Service Distance and Ratio-Based Location-Allocation Models for Siting Recycling Depots

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Abstract: Siting appropriate locations for placing recycling depots is essential for promoting an efficient recycling program. This study develops three optimization models to facilitate siting analysis for district-based, district open, and nondistrict situations. An enhanced model to improve drawbacks of locating recycling depots that mainly serve residents in adjacent districts using the district open model is also proposed. Three factors of service distance, local service ratio, and service ratios for different distance ranges are used to compare the effectiveness of alternatives obtained from different models. A case study involving 16 city districts is implemented to demonstrate the applicability of the proposed models. Findings show that the district-based alternatives have best overall service distance and service ratio, but with a poor local service ratio. The enhanced model obtains alternatives that achieve good local service ratio with acceptable service distance and service ratios for different distance ranges.

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Introduction

Recycling using recycling depots is a commonly adopted approach for recyclable material collection (e.g., Apotheker 1997; Sparks 1998; Valeo et al. 1998; Flahaut et al. 2002). Some local environmental authorities in Taiwan are exploring the possibility of adopting such an approach to replace or enhance the original curbside recycling approach. However, the locations of recycling depots can significantly affect the performance of a recycling program. Various factors should be evaluated for selecting proper locations for establishing recycling depots. For example, a recycling depot without a convenient road access, far from the central population or without sufficient lighting will discourage the residents from dropping off their recyclable materials. Siting appropriate locations for placing the recycling depots is therefore important. This study develops optimization models to facilitate the decision analysis for siting appropriate recycling depot locations.

Although a comprehensive model such as the life-cycle-based model proposed by Solano et al. (2002a,b) is available, it is too complex to be used for this siting problem. Several simple decision factors are thus adopted or developed. The distance between a house or apartment and the closest recycling depot is an essential factor for evaluating recycling depot efficiency. A short service distance will likely increase the recycling rate. Researchers frequently adopt the service distance as a major evaluating criterion in many siting researches (e.g., Berman et al. 1991; Gerrard and Church 1995; Kao and Lin 2002; Farhan and Murray 2006; Aras and Aksen 2008). This study therefore selects the service distance as one of the major decision factors.

However, if only the service distance was considered, most depots would be located at places near high population density areas, and the disproportional allocation would cause disparity among different regions (Church 1990). To improve regional equity, depots should also be placed in the districts with low population density to avoid significantly long service distances. The regional equity issue should be simultaneously evaluated in developing the siting optimization model.

For a low population density district, selecting total service distance as the objective to minimize for this siting problem will locate a recycling depot close to the adjacent district with high population density. As a result, a recycling depot will primarily serve households located in the adjacent district instead of those in the same district the depot belongs to. The current study therefore introduces the local service (LS) ratio for the ratio of local households in the same district where the recycling depot is located as another major siting factor. Similar to the method proposed by Kao and Lin (2002), this study computes the service ratio by counting households being served in the same district and the distribution of households with different service distances from the closest recycling depot.

Although previous researches rarely address the problem of siting recycling depots, many studies investigate similar location siting problems. For example, many researchers explored the p median problem for minimizing the overall average distance for selecting p depots in an area (e.g., Hakimi 1964, 1965; Teitz and Bart 1968; Järvinen et al. 1972; Narula et al. 1977; Neebe 1978; ReVelle and Elzinga 1989; Church 1990; Gerrard and Church 1995; Figueiredo and Mayerle 2008). The siting problem in this

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study is a p median problem if only considering one district.

However, the siting problem this study explores is not restricted to a single area, but also applies for multiple districts. Recycling performances among different administrative districts are competitive and frequently compared by the local environmental authority and the general public. Therefore, a method for siting recycling depots in multiple districts is desired. ReVelle and Elzinga (1989) developed a two-stage algorithm for selecting facility locations in multiple regions. The first stage solves a p median model for each district. The second stage applies a greedy algorithm to allocate facilities with the sum of weighted distances being minimized. However, the solution obtained from this method may not be the global optimum. Church (1990) developed a mixed-integer programming (MIP) model to solve a p median problem with limits on the maximal and minimal desired numbers of facilities, and Gerrard and Church (1995) modified the model further and developed another MIP model that allows demand to cross zonal boundaries. Recycling depots generally allow service to residents in adjacent districts; therefore, this study adopts siting models that also allow service demand to cross zonal boundaries.

The following sections first discuss factors for evaluating siting location effectiveness. Four recycling depot siting models are then described. The application of the models to an illustrative case for 16 districts in Hsinchu City in Taiwan is demonstrated. Finally, modeling results are compared for their differences, advantages, and disadvantages.

Evaluating Factors

Previous location allocation models generally evaluated total service distance without considering spatial equity and distribution efficiency. Based solely on service distance, most depots would be located near high population density areas, causing disparity among different regions. The regional equity issue should be simultaneously assessed in developing a recycling depot siting optimization model. Therefore, besides service distance, this study proposes LS ratio for evaluating spatial distribution equity and service ratios for different distance ranges in evaluating spatial distribution efficiency. This study uses these three major factors to evaluate effectiveness of results obtained from the siting models presented in the next section. The three factors are described respectively as follows.

Average Service Distance

The service distance for a household is the distance between the household and the closest recycling depots. This study uses the average service distance for all households as a major evaluating factor. However, the average service distance does not reflect the spatial distribution of recycling depots. Therefore, two other factors are proposed, as described below.

LS Ratio

If total service distance is the major objective function to minimize it for applying the siting models, some districts with low population density may not be allocated any recycling depot. Each district should have at least one recycling depot as the minimal requirement. A large area with low population density may not be allocated enough recycling depots and subsequently some residents may not have service within a reasonable distance to an adjacent recycling depot. Subsequently, the residents may not be willing to cooperate with the recycling program. Therefore, this study proposes the LS ratio for evaluating this spatial distribution equity problem. The LS ratio is the ratio of local households receiving service. If such a ratio for a district is too low within an acceptable distance, placing at least one additional recycling depot to improve service quality should be considered.

Service Ratios for Different Distance Ranges

This study assumes that each household is served by the nearest depot. According to this assumption, the service ratios for different distance ranges and the LS service ratios for different distance ranges are determined. These ratios can be used to evaluate the spatial distribution efficiency of recycling depots to serve local and all households.

Models

This study applies four models for siting recycling depots: district-based (DB), district open (DO), nondistrict (ND), and enhanced district open (EDO) models. The first three models are used to optimize depot allocation for the DB, DO, and ND strategies, respectively, and the EDO model is developed to obtain the best compromise solution. The objective functions of the models all aim to minimize the sum or average distances between each household to the closest recycling depot, although their constraint sets are different. These models are respectively described as follows.

DB Model

The DB strategy assumes that residents use only the depots located in their own districts. Thus, the objective function of the model is to minimize the sum of the distances between each household and its nearest recycling depot in the same district. The model is formulated as follows:

$$\text{Min} \quad \sum_i W_i d_i \tag{1a}$$

Subject to

$$\sum_{j \in M_i \cap C_i} (D_{ij} y_{ij}) \le d_i \quad \forall\, i \tag{1b}$$

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

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

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

$$x_j = (0,1) \quad \forall\, j \tag{1f}$$

where i=index of a household group, and each group includes a different number of households; W_i=number of households in household group i; d_i denotes the average distance to the nearest recycling depot that serves household group i; j represents the index of a candidate recycling depot location; M_i=set of candidate recycling depots in the same district with household group i; C_i=set of the candidate depots that can serve household group i; D_{ij}=average distance between household group i and recycling

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depot j; y_{ij}=variable that can be 1 and 0 only, for which 1 indicates that household group i is served by recycling depot j; x_j =binary integer variable, for which 1 indicates that a recycling depot is placed at candidate location j; r=index of a district; N_r =set of all candidate recycling depots in district r; and R_r =desired number of recycling depots in district r.

Eqs. (1b) and (1c) determine the nearest recycling depot location serving each household group. Eq. (1d) ensures that y_{ij} must be smaller than x_j, and combined with the driving force provided by the objective function and Eq. (1d), y_{ij}'s will be either 0 or 1. Thus, there is no need to set them as [0,1] binary integer variables, that can significantly save model solving time. Eq. (1e) sets the desired number of recycling depots in each district. Eq. (1f) defines all x_j's to be [0,1] integer variables.

DO Model

This model assumes that the residents always choose the nearest recycling depot for recycling, without considering whether the nearest recycling depot belongs to the same district or not. The model is formulated and described as follows:

$$\text{Min} \quad \sum_i W_i d_i \tag{2a}$$

Subject to

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

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

$$\text{Same as Eqs. } 1(d) - 1(f)$$

Eqs. (2b) and (2c) are different from Eqs. (1b) and (1c), for which household group i and recycling depot j need not be in the same district. Other constraints are the same as those used in the DB Model.

ND Model

The ND model regards the entire area as one single region and attempts to select proper locations for establishing recycling depots without considering the district regions.

$$\text{Min} \quad \sum_i W_i d_i \tag{3a}$$

Subject to

$$\sum_{j \in J} x_j = R \tag{3b}$$

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

where j=set of all candidate depots; and R=desired number of recycling depots. Eq. (3b) sets the desired number of recycling depots. All other constraints are the same as those used in previous models.

EDO Model

The DO model may place recycling depots at locations that can serve most residents in adjacent districts, instead of those in the local district. An enhanced DO model is thus developed by adding constraints to set the limit for the minimal acceptable district LS ratio. Although these new constraints set all LS ratios to be larger than a prespecified limit, it may drive some y_{ij}'s to be values between 0 and 1. Setting all y_{ij}'s as a binary integer variable can resolve this problem, but significantly increases the number of binary integer variables that make the problem hard to solve in a timely manner. Thus, these variables are not set to be binary integer variables. Any existing y_{ij} equal to a value between 0 and 1 in the solution can be resolved either selecting the better one of the two new solutions obtained by setting the variable to be 1 and 0, or implementing a branch-and-bound procedure. This model is formulated as below.

$$\text{Min} \quad \sum_i W_i d_i \tag{4a}$$

Subject to

$$\sum_{i \in O_r} \sum_{j \in M_i \cap C_i} W_i y_{ij} \ge S^* WI_r \quad \forall\ r \tag{4b}$$

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

where O_r=set of the household groups in district r; S=minimal limit for LS ratios; and WI_r=number of households in district r. Eq. (4b) lets the LS ratio of each district to be larger than the prespecified limit. All other constraints are the same as those used in previous models.

Case Study

This study applies the models to the 15 districts in the east region and one district in the north region of the Hsinchu City, totaling 16 districts. Fig. 1 illustrates district locations. A district is a municipal administrative unit in a local city. Each district has its own office to handle district issues. Districts in Taiwan typically derive from small villages, covering relatively large areas, and gradually dividing into multiple smaller but highly populated districts as their population grew. The entire study area comprises 18,008 households, 58,518 residents, and 21.18 km^2. Recyclable materials in most districts are collected with a recycle truck following a garbage truck along the streets. Local residents are required to physically bring out their recycling materials and hand the materials the collector on the truck, with the truck stopping at each collection point for just a few minutes. This collection method is expensive and inconvenient for residents who are unable to bring out their recyclable materials at the collection time. Although increasing the collection frequency or providing a convenient container may increase the participation rate (Noehammer and Byer 1997), the associated cost may be more than the local authority can bear. This work thus assesses the applicability of the alternative for providing recycling depots.

Each model is applied to optimize the depot allocation for a specific recycling depot collection strategy. The DB strategy assumes that the residents in each district use only the depots located in their own district. Currently, the recycling rates of all districts are individually calculated and regularly announced to the general public. The DO strategy allows residents to bring their recycling materials to the closest recycling depot in an adjacent district. The ND strategy assumes that the recycling program is managed by the city government instead of by individual district

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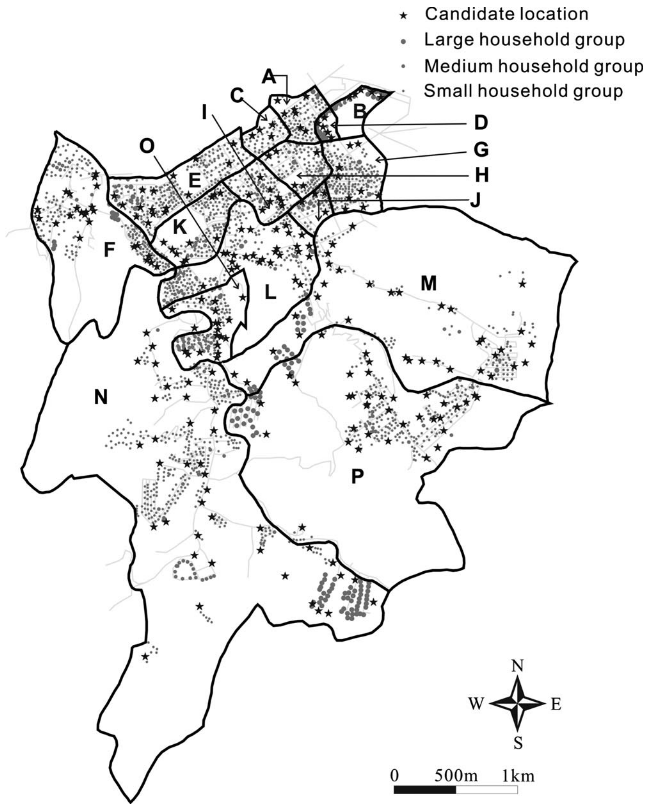

Fig. 1. Study area, household groups, and candidate locations

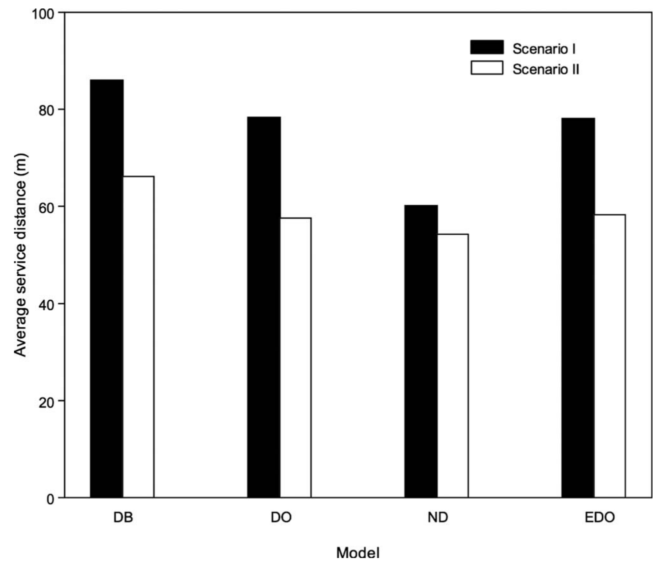

Fig. 2. Average service distances (m) of the results obtained from different models for both scenarios

offices. Furthermore, the EDO strategy can resolve the regional disparity problem and enable most residents to access a depot within a reasonable distance.

In this study, each household represents a typical local family, but households are not individually processed because most families in Taiwan live in a building or apartment with others. Instead, they are grouped with their neighbors from aerial photographs, with 16 households at most in a group. In total, there are 2,437 household groups. From the same set of aerial photographs, 253 sites are selected as candidate locations for placing recycling depots. Fig. 1 illustrates locations of the household groups and candidate sites. To avoid wasting time checking inappropriate service distance between a household group and a recycling depot, the maximal acceptable service distances are set as 2,220 m for districts M, N, and O, and 820 m for the other 13 districts. The distance is measured as the Euclidean distance between two given locations, although it slightly differs from the street distance.

After gathering the data for household groups, candidate recycling depot locations, and preparing the distance between each household group and each recycling depot, this study applies and solves the models by CPLEX (ILOG 2007). Two scenarios are evaluated. Scenario I establishes one depot per district for a total number of 16 recycling depots. Scenario II adds three extra depots because of the sparse population distribution in the three large districts, M, N, and P. If only one depot is established for these three large districts, the service distances would be significantly longer than those in other districts and thus Scenario II adds three extra depots.

Results and Discussion

The proposed models are applied to both scenarios. Each model represents a different recycling depot collection strategy. And the three factors of service distance, LS ratio, and service ratios for different distance ranges are applied to measure the performance of each strategy. The results are compared based on the three factors, as discussed below.

Service Distance

Fig. 2 shows average service distances from results obtained by different models, ranging from 60 to 80 m for Scenario I. The shortest one, 60 m, is for the ND result that is about 26 m shorter than that for the DB result, that is about 30% less. However, the same figure shows that the ND result does not place any recycling depot for several districts and thus has poor spatial distribution equity. The DB result has the longest average distance because it only allows the recycle depot to be used within its own district, and residents cannot use the closest depots located in adjacent districts. The average distances of DO and EDO results are quite close and about 8 meters shorter than that of DB because it allows the resident to drop off recycling materials at the depot located in an adjacent district. The average service distances of the results obtained for Scenario II range from 54 to 66 m and are predictably less than those for Scenario I because three additional depots are placed in three districts with sparse population distribution. The ND and DB results have the shortest and longest average service distances of 54 and 66 m, respectively. However, the difference is only 12 meters, much smaller than the 26 meters for Scenario I.

LS Ratio

A higher LS ratio implies better local depot placement. Fig. 3 shows the LS ratio of each district and the service ratio of the entire region. For Scenario I, the highest LS ratio of 73% is observed for the DB result, because the DB model allows each recycling depot to serve local residents only. Therefore, the depots are placed at locations that can serve as many local households as possible. Most districts have high LS ratios except for District L, having only 25% because of the spare population distribution and irregular shape of the district, as shown in Fig. 4(a), and most local residents live close to the recycling depots in

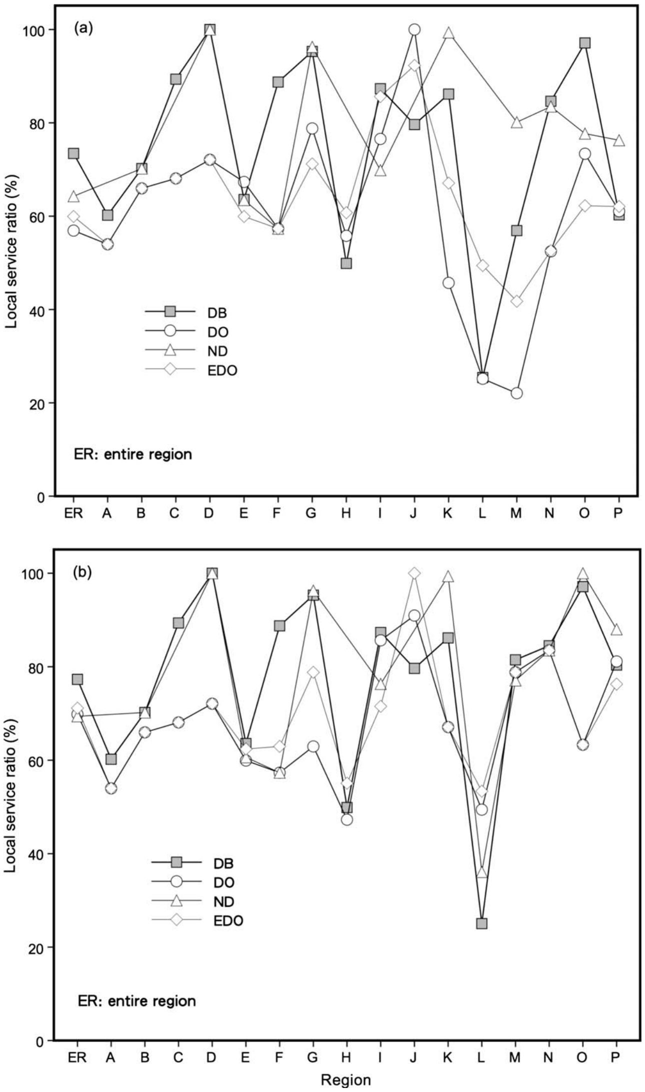

Fig. 3. LS ratios of the results for (a) Scenario I; (b) Scenario II

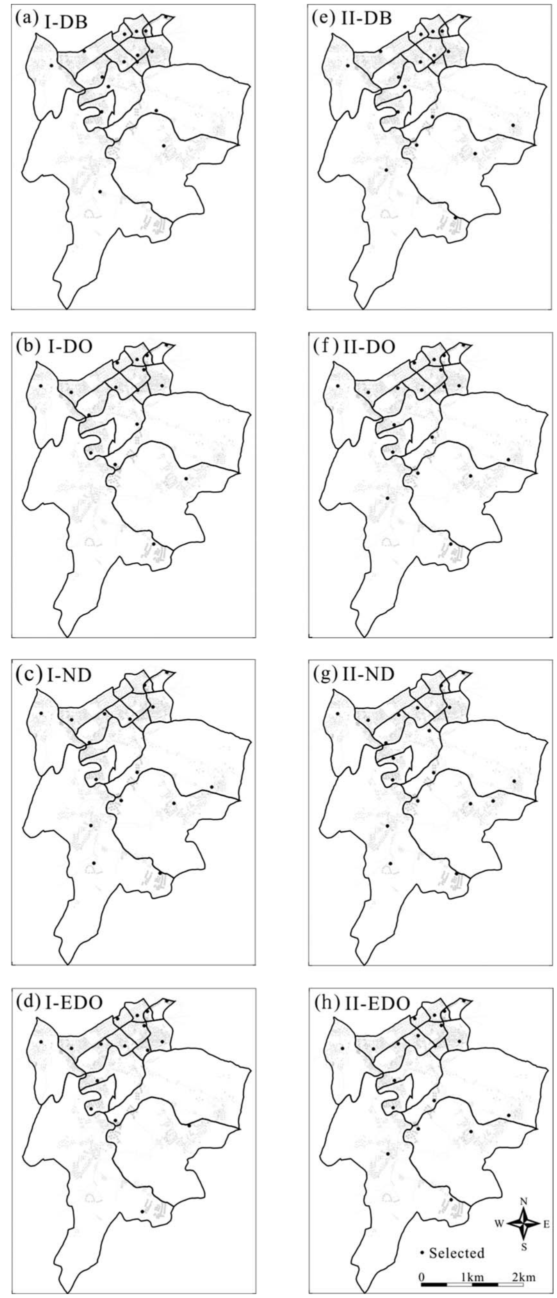

Fig. 4. Solutions obtained for both scenarios using different models: (a) I-DB; (b) I-DO; (c) I-ND; (d) I-EDO; (e) II-DB; (f) II-DO; (g) II-ND; and (h) II-EDO

Districts K and O. For Scenario II, according to Figs. 3(b) and 4(e), the DB result again has the highest LS ratio of 78%, while the LS ratio for District L is only 22%.

The DO results in Figs. 3(a) and 4(b) show that the LS ratios of Districts K, L, and M are all less than 50%, because residents from districts adjacent to these districts are allowed to drop their recycles into the depots located in these districts. These depots are used mostly by residents in adjacent districts rather than local residents. For Scenario II, Figs. 3(b) and 4(f) show improved LS ratios because of three additional recycling depots, although the LS ratios of Districts H and L are still low.

Figs. 4(c and g) show the spatial results obtained from the ND model. The objective of the ND model is to minimize total distance; therefore, the recycling depots are mainly located at places with high population density. Although the ND model obtains results with shortest average distances, Districts A, C, H, J, and L for Scenario I and Districts A, C, H, and J for Scenario II do not have any recycling depot in these districts. Subsequently, residents not living close to highly populated areas will not be served and the LS ratio is thus low for these districts.

Figs. 3(a) and 4(d and h) show that the EDO results significantly improved the LS ratios of Districts L and M, as compared to the DO results, although they are still below 50%. The spatial inequity problem also improves. Fig. 3(b) illustrates that the EDO results for Scenario II have high LS ratios exceeding 50%. The recycling depots move to locations that can serve local residents better. The EDO model proves able to significantly improve the low LS ratio problem for the DO results.

Service Ratios for Different Distance Ranges

Although the LS ratios for different distance ranges of the DB results are superior to other results, as Fig. 5(a) shows, the ratio of residents living in the service distance within the range of 1,001 to 1,500 m is significantly high, about 8%. However, Fig. 5(b) shows no similar situation for Scenario II. One additional depot for these districts with low population density can significantly

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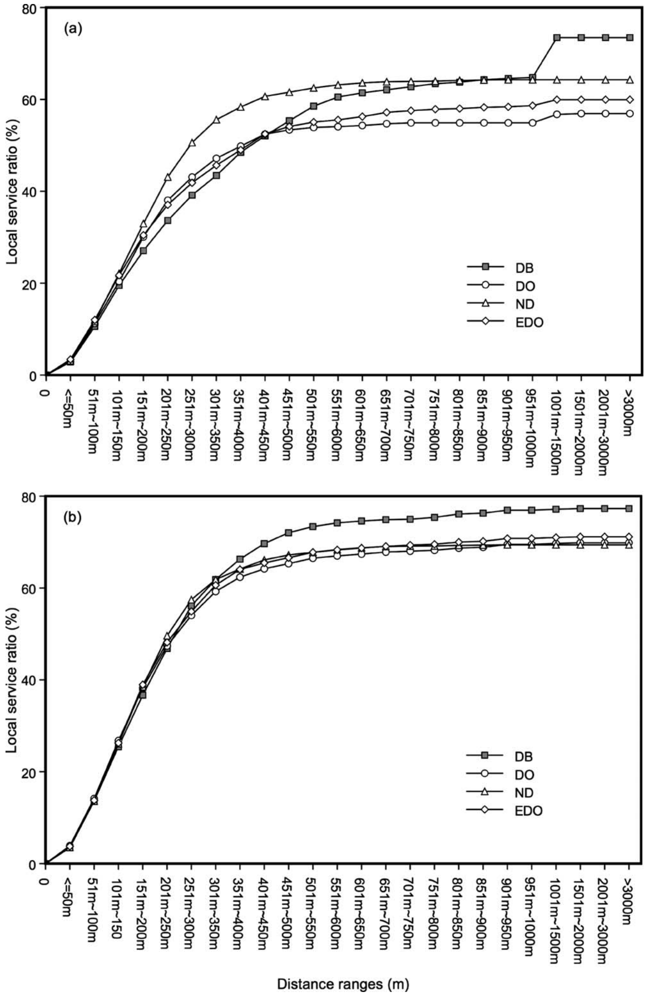

Fig. 5. LS ratios within varied distance ranges for (a) Scenario I; (b) Scenario II

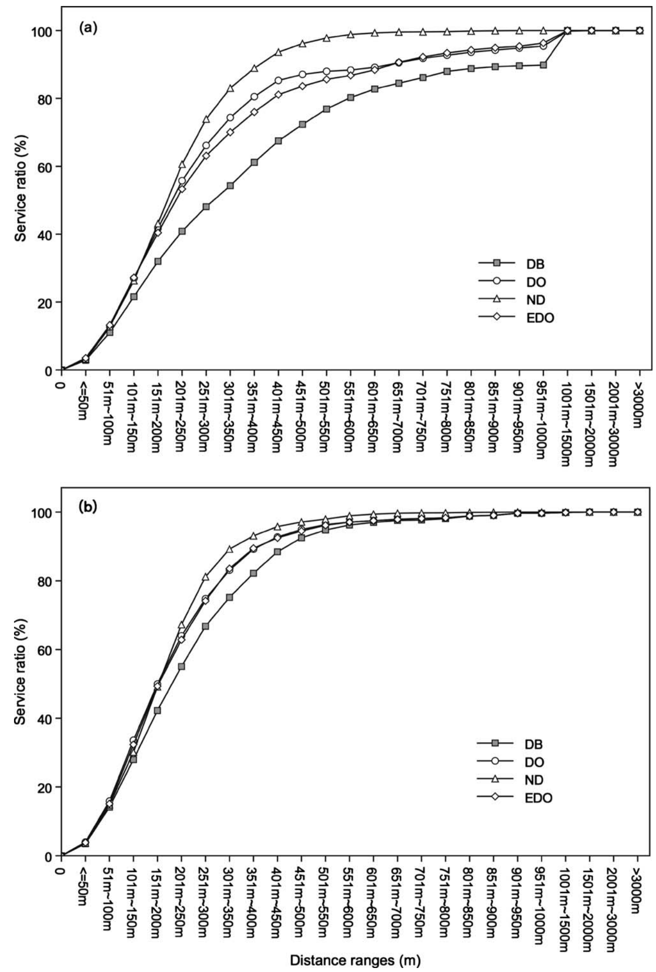

Fig. 6. Service ratios within varied distance ranges for (a) Scenario I; (b) Scenario II

improve service quality. Fig. 6 presents service ratios within varied distance ranges for different results for both Scenarios. Fig. 6(a) shows substantial increase in the range of 1,001 to 1,500 m, about 10% for the DB results and about 5% for the DO and EDO results. According to Scenario I, results shown in Figs. 5(a) and 6(a), service ratios for different distance ranges are good for the DB results, but a significant portion of local residents living far from the recycling depots are not served.

For Scenarios I and II, Figs. 6(a and b) show that service distances for the ND results are all shorter than 1 km. Although more recycling depots can be established to further improve the LS ratios, the cost of establishing additional depots also increases.

Conclusion

This study develops optimization models to find appropriate locations for installing recycling depots in a city. The performances of the DB, DO, ND, and EDO models for resolving the recycling depot siting problem are compared in terms of the three factors of service distance, LS ratio, and service ratios for different distance ranges. According to the results obtained for the Hsinchu City study area, the LS ratio for DB results is high at 73%, because the DB strategy restricts residents to using depots in their own district and thus the DB model identifies the depot locations to maximize the LS ratio of each district. However, the average service distances, 86 m for Scenario I and 60 m for Scenario II, for DB results are not as good as those for other solutions due to the irregular shape of District L whose LS ratio is quite low. The average service distances, 60 m for Scenario I and 44 m for Scenario II, for ND results are superior to those obtained from the other three models, but the spatial equity problem exists with some districts, e.g., Districts A, C, H, K, and L for Scenario I and Districts A, C, H and K for Scenario II, having no recycling depot. The ND strategy tends to place depots near high population density areas to minimize total service distance and thus leads to some districts having poor LS or no recycling depot. This result thus reveals significant spatial disparity among districts. The DO results compromise the tradeoff between service distance and the LS ratio, and also improve the spatial distribution equity, although the service distance distribution is slightly worse than those of other solutions due to the sparse population distribution in the case study area. After providing additional recycling depots, the difference of average distances and LS ratios among DB, DO, ND, and EDO results is not significant, and thus the LS ratio becomes the essential decision factor. The EDO model provides results with better spatial equity, when no significant difference exists from the other results for the other factors.

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