



Regional optimization model for locating supplemental recycling depots

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ABSTRACT

In Taiwan, vendors and businesses that sell products belonging to six classes of recyclable materials are required to provide recycling containers at their local retail stores. The integration of these private sector facilities with the recycling depots established by local authorities has the potential to significantly improve residential access to the recycling process. An optimization model is accordingly developed in this work to assist local authorities with the identification of regions that require additional recycling depots for better access and integration with private facilities. Spatial accessibility, population loading and integration efficiency indicators are applied to evaluate whether or not a geographic region is in need of new recycling depots. The program developed here uses a novel algorithm to obtain the optimal solution by a complete enumeration of all cells making up the study area. A case study of a region in Central Taiwan is presented to demonstrate the use of the proposed model and the three indicators. The case study identifies regions without recycling points, prioritizes them based on population density, and considers the option of establishing recycling centers that are able to collect multiple classes of recycling materials. The model is able to generate information suitable for the consideration of decision-makers charged with prioritizing the installation of new recycling facilities.

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1. Introduction

Researchers have acknowledged that the success of municipal solid waste (MSW) recycling schemes is highly dependent upon the active participation of residents, which, in itself, is critically influenced by the proximity of drop-off depots (McDonald and Ball, 1998; Tilman and Sandhu, 1998). Speirs and Tucker (2001) have analyzed the behavior of recycling participants and have concluded that only 22% will make extra trips to drop-off depots, and that more than 50% of the participants' recycling efforts are primarily inspired by the convenience of drop-off depots. González-Torre and Adenso-Díaz (2005) also maintain that the distance between a drop-off depot and a residence has an impact on the frequency of recycling: a shorter distance between the two significantly improves the participation in MSW recycling and increases the quantity of materials recovered.

Due to the recent trend towards extended producer responsibility in waste management, along with increased regulatory requirements in Taiwan, vendors of products with stipulated recyclable materials assume responsibility for the provision of drop-off containers/depots that are essential for the recycling of goods after their useful life. These recyclables have either (or both) of the following properties: they are arbitrarily discarded (e.g., beverage

bottles) and contain hazardous materials (e.g., batteries and fluorescent lights). Table 1 displays eight types of recyclable materials and six types of businesses required to provide drop-off containers for them (for readability, some types of businesses/categories of recycling materials have been modified from the original regulation). Although private containers are in widespread use and have proven effective for collecting designated recyclables, they have not been uniformly installed. In order to achieve higher recycling rates, local governments have become interested in providing additional recycling depots in regions with poor access to recycling facilities.

The problems associated with drop-off depots have been long studied by researchers in the MSW management field. For example, Chang and Wei (2000) applied a non-linear integer programming model aided by a genetic algorithm to simultaneously determine depot locations and associated collection routing. Their goal was to minimize both the walking distance required by residents, and the costs of collection routes. Kao and Lin (2002) compared three models in siting waste/recyclable material pickup points. They concluded that the model that minimized the walking distance required by residents significantly improved their access to collection points. Gantam and Kumar (2005) utilized a maximal-coverage model incorporating a geographical information system (GIS) to generate the locations of MSW recycling stations. All of the models in these studies were able to simulate the pickup and collection services provided by local authorities. A primary

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Table 1
Recycling materials and stipulated business.

	A1/A2/A3	B1	C1	D1	E1	F1
Hypermarkets/supermarkets	X	X	X	X		
Convenience stores/cosmetics retailers	X	X	X			
Gas stations					X	
Photographic and mobile communication device retailers			X			
Fast food restaurants		X		X		
Fluorescent lamp stores						X

(A1) Metal containers: steel containers, aluminum containers, other metal containers.

(A2) Plastics containers: PET bottles, PE bottles, PVC bottles, PP bottles, PS bottles, other plastic bottles.

(A3) Glass: glass containers, beer bottles, cosmetics containers.

(B1) Paper containers: paper cartons, paper containers, wastepaper, cardboard.

(C1) Battery: waste dry batteries, cordless phone batteries, camcorder batteries, button batteries.

(D1) Disposable tableware: wastepaper tableware, plastic tableware, styrofoam tableware.

(E1) Automobile accessories: waste lubricating oil containers, tires, sealed rechargeable batteries.

(F1) Fluorescent lamps.

factor analyzed in these models was spatial proximity, which was indicated by the distance a resident had to walk to reach a collection point. Other factors, including collection costs and service vehicle capacities, were then accounted for in determining the optimal recycling system.

The application of these models requires, *a priori*, a list of plausible candidate locations, thus requiring a large amount of investigation and planning (an amount that increases sharply with the size of the area under study). The work involved in screening candidate locations can be mitigated by identifying existing recycling locations provided by the private sector, as only those regions with poor access to recycling facilities need to be analyzed. This paper develops a methodology for identifying the regions that are most in need of recycling facilities, instead of looking for the optimal combinations of locations.

The use of GIS enables a clear and progressive analysis of the factors that influence participation in a given recycling scheme. Studies that have heretofore incorporated GIS in MSW management make reference to landfill siting (e.g., Kao and Lin, 1996; Lin and Kao, 2005; Chang et al., 2008), collection routing (Ghose et al., 2006; Karadimas et al., 2007; de Oliveira Simonetto and Borenstein, 2007) and recycling depots (Caterina et al., 1998;

Clarke and Maantay, 2006). In these studies, raster GISs were most popularly applied to the study area, which was divided into a number of equally-sized cells. Most of these studies include mathematical models of very similar structures that have constraints on decision variables that can be compared across all cells and exploited to ease the solution process. Unfortunately, the amount of time required to yield a solution with these models is often prohibitively long, thereby precluding their application in some real-life scenarios. With a view to addressing these concerns, the work presented here proposes a methodology incorporating a customized computer program aimed at the facilitation of data compilation and to reduction of the problem-solving time associated with the modeling of MSW recycling depots.

2. Methodology

The analytical steps associated with the methodology are: (1) collating MSW data for GIS application and calculation, (2) defining recycling performance indicators, (3) implementing the model to locate the recycling facilities, and (4) evaluating the optimal solution for the study area. A detailed explanation of each step follows.

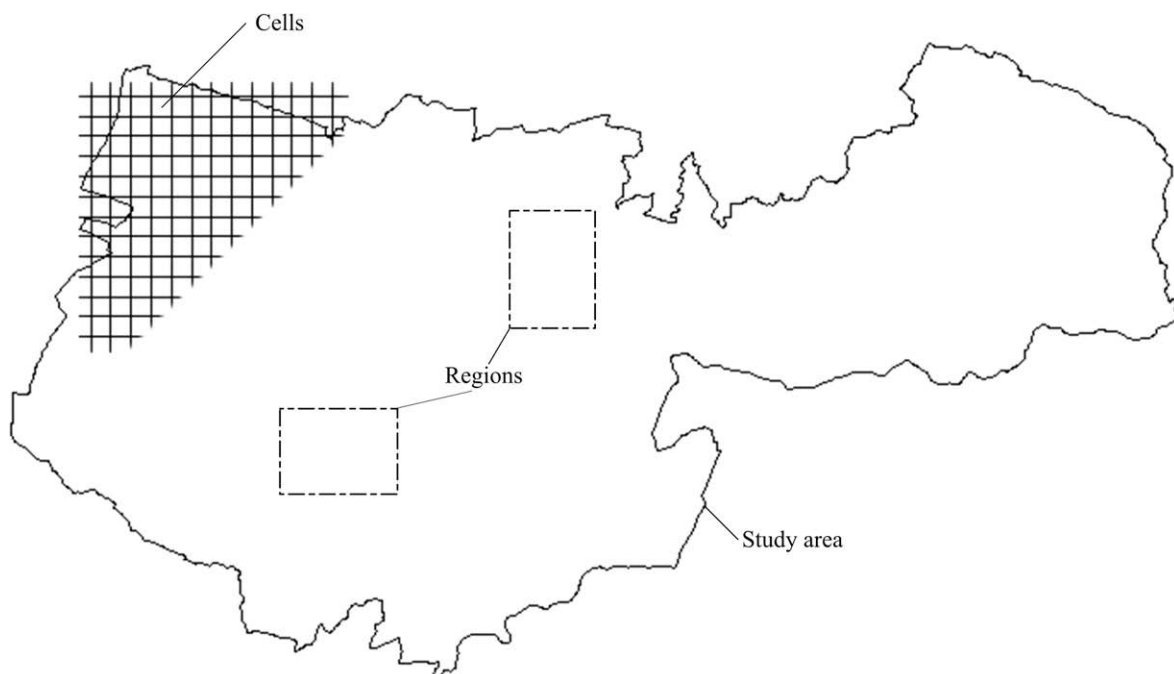


Fig. 1. The relationship between cells, regions, and the study area.

2.1. Collation of MSW recycling data

Population statistics were utilized to estimate the quantities of potentially recyclable material generated, which in turn were compared with the statistics on actual collected recyclables to determine any potential for increased recycling participation. Relevant data considered included the population density and the quantities of recyclable materials being collected in each administrative tract. In addition, data for the location and allowable recycling materials of private recycling facilities were also collected (in this study such data were acquired from local authorities).

These data were then transformed into raster GIS map-layers for use in the ensuing analysis. A “cell” is a geo-referred object, which represents a small square area in reality, and is the elementary unit of a raster GIS map-layer (cf. Fig. 1). To locate areas in need of additional recycling facilities, “regions” are defined as random rectangular zones of similar size, containing groups of adjacent cells. The size of a region, which represents the service area of a recycling depot, is specified by the decision-makers. A region is a subset of the entire study area, so multiple regions can be found in a given study area.

2.2. Indicators for recycling facility analysis

A number of researchers have examined a multitude of indicators for the assessment of accessibility of facilities to the public (e.g., Smoyer-Tomic et al., 2004; Talen and Anselin, 1998). The model outlined in this paper uses three indicators: spatial accessibility (SA), population loading (PL), and integration efficiency (IE). SA is defined as the ratio of cells with at least one recycling point, over the total number of cells in the region. PL is used to evaluate the capacity of the recycling facilities in a given region and is defined as the ratio formed by dividing the total number of recycling points by the total population in the region being analyzed. IE is given by

$$IE = \sum_{k=1}^K (SA_k / SA_k^{max}) \tag{1}$$

Herein, k represents the k_{th} recycling material in the study area; K is the total number of categories of recyclable materials; SA_k is the SA indicator value of k_{th} recyclable material in the region; and (SA_k / SA_k^{max}) represents the maximum SA indicator value of the k_{th} recyclable material among all regions in the study area.

A detailed description of these indicators can be found in Supplementary data.

2.3. The proposed model

The model is built upon a previous model (Lin and Kao, 2005), a detailed description of which is given in Supplementary data. The goal of this model is to find a region larger than a specified size (A_{size}) that has the fewest total accessible cells inside. In addition to using accessibility analysis (SA) to locate the regions, two other indicators, PL and IE , can also be used by the model.

2.4. The customized program for the proposed model

The model uses integer programming, which can consume a large amount of computing time for the solution of even modestly-sized problems. To enable solution time savings, a customized program, written in C++, has been developed to solve the model by enumeration. The algorithm followed by the customized program is described as follows.

Two cells are selected in each iteration. The first cell is chosen to be the upper-left corner of a region, and is selected one by one in sequence from all cells of the study area. The second cell marks the lower-right corner of a region, which is selected only from the cells whose row and column indices (i, j) are greater than those of the first cell. The area of the region is then calculated from the position of the two cells; if the value is larger than the specified area constraint (A_{size}), the program then computes an objective value for this region and compares it with the minimum value previously recorded. If the new value is smaller than the existing record, the record will be replaced by the new value. For a study area with T cells, the number of computational iterations is C_2^T , which is sig-

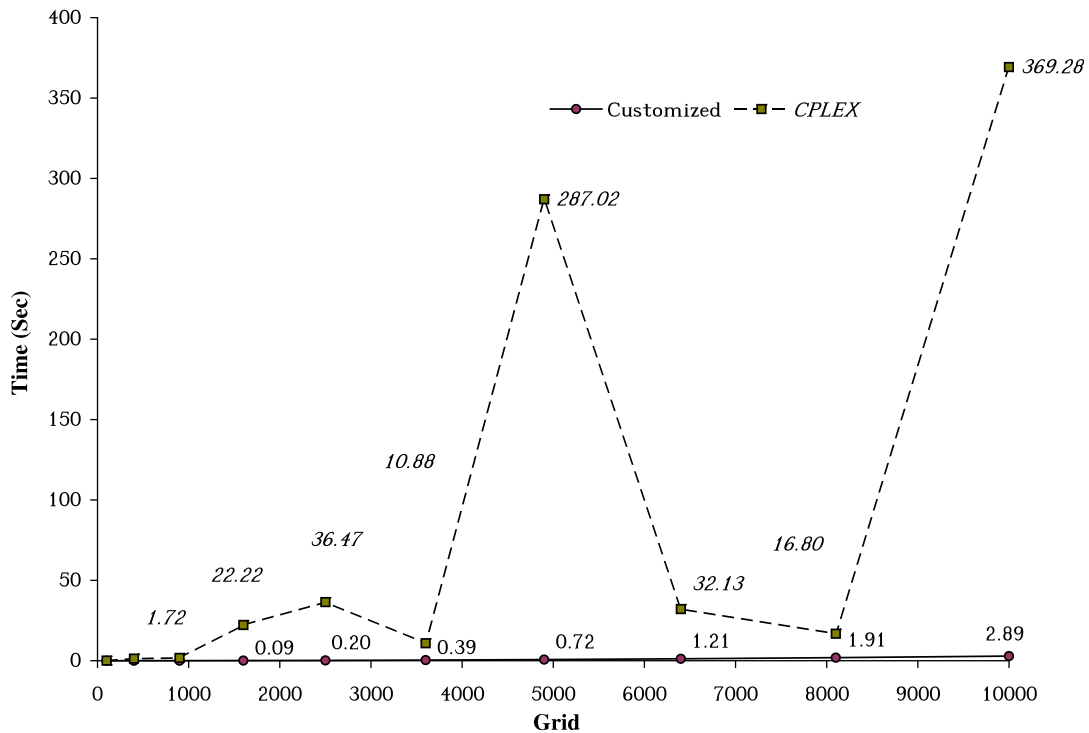


Fig. 2. Time taken for different analytical tools to solve test cases.

nificantly less than 2^7 , the maximum number of iterations required by typical branch and bound methods. Fig. 2 presents the solution time for test cases with problem size varying from 10 to 10,000 cells, employing both the customized program and an optimization software package CPLEX (ILOG Inc., 1997). The customized program used by our model requires less computation time than the CPLEX package in all of the test cases considered. As the number of cells increases, the difference in solution time between the two solving methods becomes increasingly larger. These experiments on test cases strongly support the hypothesis that the customized program is superior in computation time, especially when applied to large-scale problems.

3. Case study

In order to demonstrate the applicability of the proposed model and the associated customized program, a case study is presented. Taichung City is the third largest metropolis in Taiwan. It has an area of approximately 163 km², and it has a population of more than one million inhabitants. In 2003, the total recyclable material collected from Taichung City was around 88,000 tons, which was about 33% of the total MSW generated by the city (Environmental Protection Agency, Republic of China, 2004). There were 1,573 private recycling points accepting eight different recyclable materials in Taichung City. The three indicators used in the model to evaluate the recycling access are discussed below.

3.1. Scenario A: SA indicator analysis of glass recycling points in the downtown area of Taichung City

The downtown area of the city includes three districts: North District, East District and Center District. The area under study is

in the heart of Taichung City and has approximately 260,000 residents annually generating 76,000 tons of MSW. The ratio of recycled material collected to total MSW generated in this area is 27%, which is less than the average for Taichung City (33%). The recycling points for glass containers, categorized as A3 in Table 1, are assessed in this scenario. There are 239 recycling points accepting A3 category materials in the downtown area. To analyze the proximity of these recycling facilities to residents, the SA indicator was applied. A cell in a GIS map-layer was defined as a square of size 50 × 50 m²; there were 14,352 cells of this size in the downtown area. The cells containing recycling points are classified as ‘accessible’. The acceptable walking distance for a recycling participant was set at 350 m, which was roughly estimated as the length covered by a person walking slowly along a street for 5 min. Other values of distance could be selected if desired. A ‘region’ was therefore defined as an area of size 0.12 km² (A_{size}), the square of the acceptable walking distance, and the length or width of a region is confined to be less than twice the acceptable walking distance, 700 m. These measurement criteria ensure that the new recycling points, as well as existing ones, will be accessible to residents living within the region. Fig. 3 presents the distribution of these points and the result of SA analysis for this scenario. Existing recycling points in the Center District, which are marked by solid circles, are located with slightly higher density than those in the other two districts. After application of the model of the downtown area, 35 regions without access to recycling depots were identified and are marked by dashed-line rectangles in the figure. They were therefore highlighted as requiring new A3 recycling facilities. If the budget for MSW management allows, the local authority can set up recycling facilities for the A3 category within all of these regions, which would result in a significant improvement in access for residents in these regions. One problem with this approach, however,

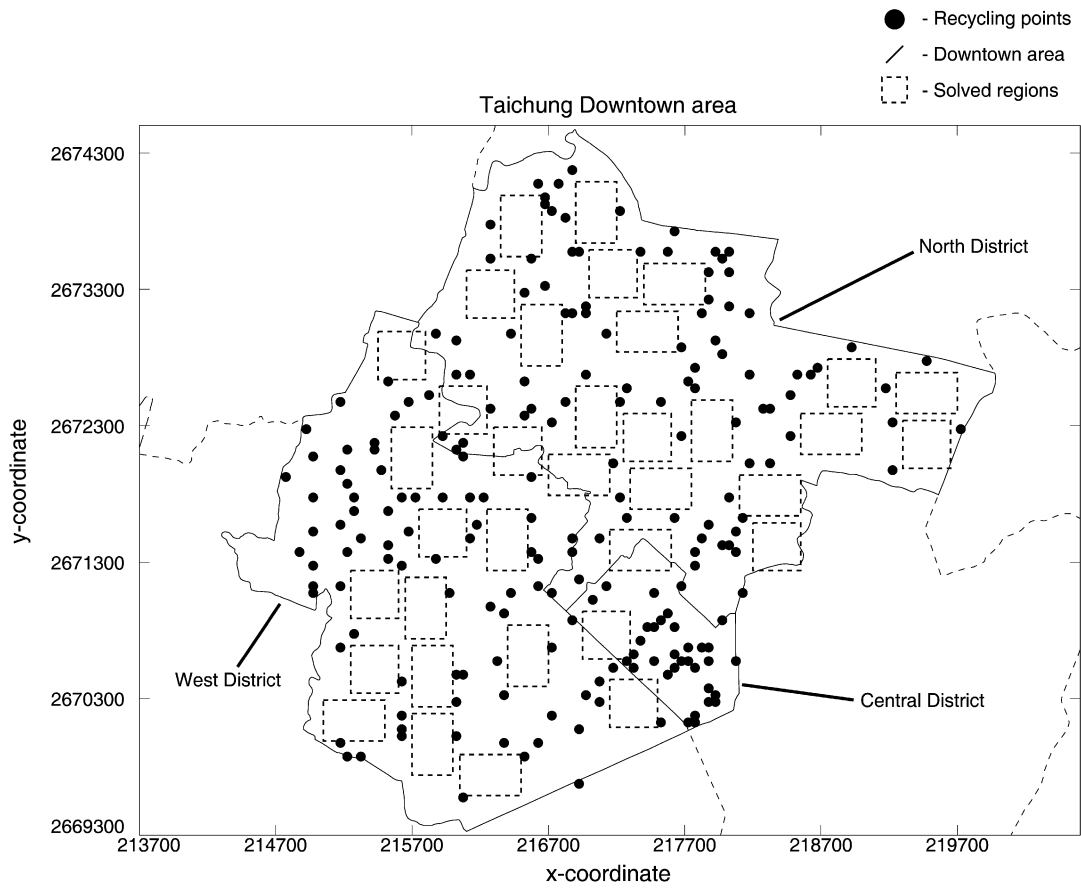


Fig. 3. Model results of SA analysis of Scenario A.

is that SA analysis provides no information about the priority for setting up new recycling facilities in these regions. An alternative that addresses this is to apply the PL indicator, as described in Scenario B.

3.2. Scenario B: PL indicator analysis of glass recycling points in the downtown area of Taichung City

If two regions both lack suitable access to recycling collection points, the region containing more residents should be given a higher priority when determining the location of new recycling facilities. The PL indicator is able to reflect this priority. To illustrate the difference between SA and PL, the A3 category recycling points of the downtown area were re-evaluated using the proposed model, incorporating the PL indicator. Fig. 4 presents the distribution of population and recycling points in the downtown area after applying the model with the PL indicator. Each color in the figure represents a different cell population density, and existing recycling points are marked by a solid circle. In addition to this, the regions identified as requiring new recycling points are marked by rectangles with dashed lines and a priority number. A lower priority number (lower PL indicator value) indicates a more urgent need for new recycling points. In cases where the same PL value occurs in different regions, the priority numbers of these regions are then assigned by ranking the population densities only; that is, a lower priority number is assigned to a more populated region.

In this scenario, as shown in Fig. 4, there are ten regions without access to the A3 category recycling points and, consequently, the PL values of these regions are null (given that the priority numbers are assigned in accordance with the region's population density).

Table 2 lists the properties of the ten regions, including their priority number, population, area and population density. Comparing the results of the two scenarios, most of the regions selected in Scenario B are subsets of those selected in Scenario A. However, consideration of the PL indicator value will be potentially helpful to local authorities when making more cost effective and flexible decisions. This is particularly useful if the budget for locating new recycling points is limited, as the model with the PL indicator will generate a priority list for implementation.

3.3. Scenario C: IE indicator analysis of Taichung City

In addition to the 1573 recycling points that cover a range of different recyclable materials, 9 recycling centers that accept the entire range of stipulated recyclable materials operate in Taichung

Table 2
The results of Scenario B after applying the PL indicator.

Priority	Population	Region area (# of cells)	Population density (people per cell)
1	6755	49	137.86
2	6354	49	129.67
3	5989	49	122.22
4	5996	49	122.37
5	5317	54	98.46
6	4799	49	97.94
7	4737	49	96.67
8	4582	49	93.51
9	4427	49	90.35
10	4801	54	80.91

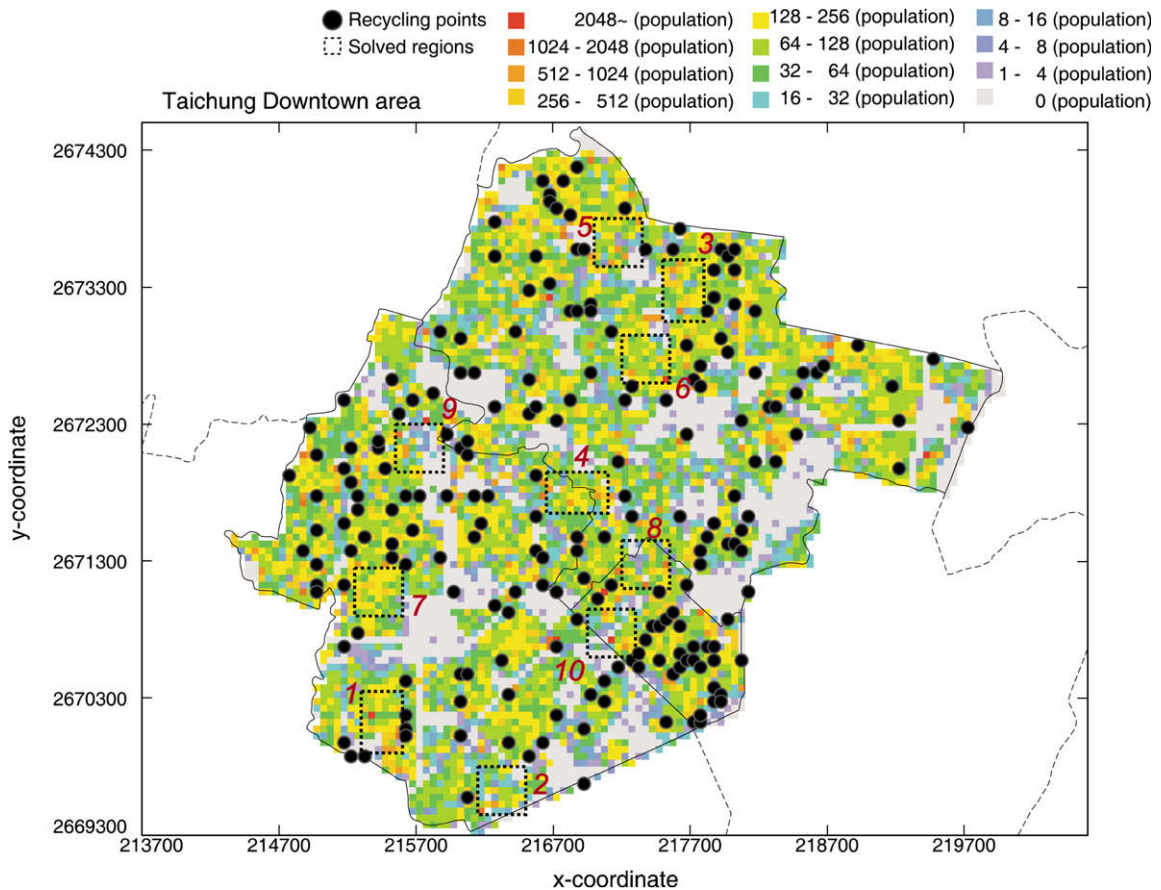


Fig. 4. Model results of PL analysis of Scenario B.

City. A recycling center can differ from a recycling point insofar as it may be operated by private firms or charities, and is therefore more likely to accept all categories of recyclables and to sell them onto the material-recovery companies before its storage space is exhausted. To help analyze preferred locations for these full-range recycling centers, the model with *IE* indicator was applied. In general, it is considered that recycling participants who send material to the full-range recycling centers are more strongly motivated, either as a result of money or good intentions, than those using smaller recycling points. They usually accumulate materials for recycling, up until a certain manageable amount, and then transport them to a recycling center. The acceptable traveling distance is defined as 2500 m in this scenario; a vehicle traveling at a speed of 30 km/h would take 5 min to travel this distance. The corresponding region size (*A*_{size}) value is defined as 6.25 km², or 2500 cells in total. In addition, the length or width of a region is confined to be less than twice of the acceptable traveling distance. Fig. 5 presents the entire area of Taichung City, which is comprised of 120,744 cells in total. The locations of recycling points and of full-range recycling centers are marked by dots and boxes, respectively. Existing recycling centers are located in the north and southwest areas of Taichung City.

Fig. 5 also presents the results of modeling with the *IE* indicator. Ten regions requiring additional recycling center access, with priority numbers, are marked by dashed rectangles. The priority numbers of these regions are based on their *IE* indicator values, with the number “1” representing the highest priority level. For evaluation of the cost effectiveness of a given location for a new recycling center, an alternative ranking method can be achieved by dividing the *IE* indicator values by the population density of the regions, accordingly. Table 3 presents the priority number, population, area, and the alternative priority ranking method of *IE* values for each region. The regions identified as first and second priority levels were the same using both ranking approaches. This would seem to indicate

Table 3
The results of Scenario C after applying the *IE* indicator.

Priority by <i>IE</i>	<i>IE</i> value	Population	Region area (# of cells)	Population density (people per cell)	<i>IE</i> /population density	Priority by <i>IE</i> /population density
1	0.00	1016	2500	0.406	0.0	1
2	13.85	23,087	2538	9.100	1.5	2
3	30.08	5571	2508	2.221	13.5	8
4	56.08	25,492	2508	10.164	5.5	3
5	127.20	45,430	2500	18.172	7.0	4
6	358.28	105,377	2508	42.016	8.5	5
7	535.00	109,185	2520	43.327	11.3	7
8	537.67	125,039	2508	49.856	10.9	6
9	681.75	13,394	2508	5.341	127.7	9
10	1383.72	20,319	2508	8.107	170.7	10

that new recycling centers in these two regions should be given precedence over all other regions. The priority numbers of the other regions are, however, slightly different after the two approaches are applied. This is because the *IE* indicator priority emphasizes the access ratio of a region without considering population factors, whereas the alternative priority ranking method considers population. In order to obtain the best coverage of recycling depots for the maximization of public benefits, the *IE* indicator priority approach is suggested. The use of additional priority rankings in the approach will be more cost effective if the budget for recycling centers is limited.

4. Conclusions

This paper develops a methodology for identifying regions that are most in need of recycling facilities, as opposed to concentrating on any optimal combination of locations. One inherent advantage

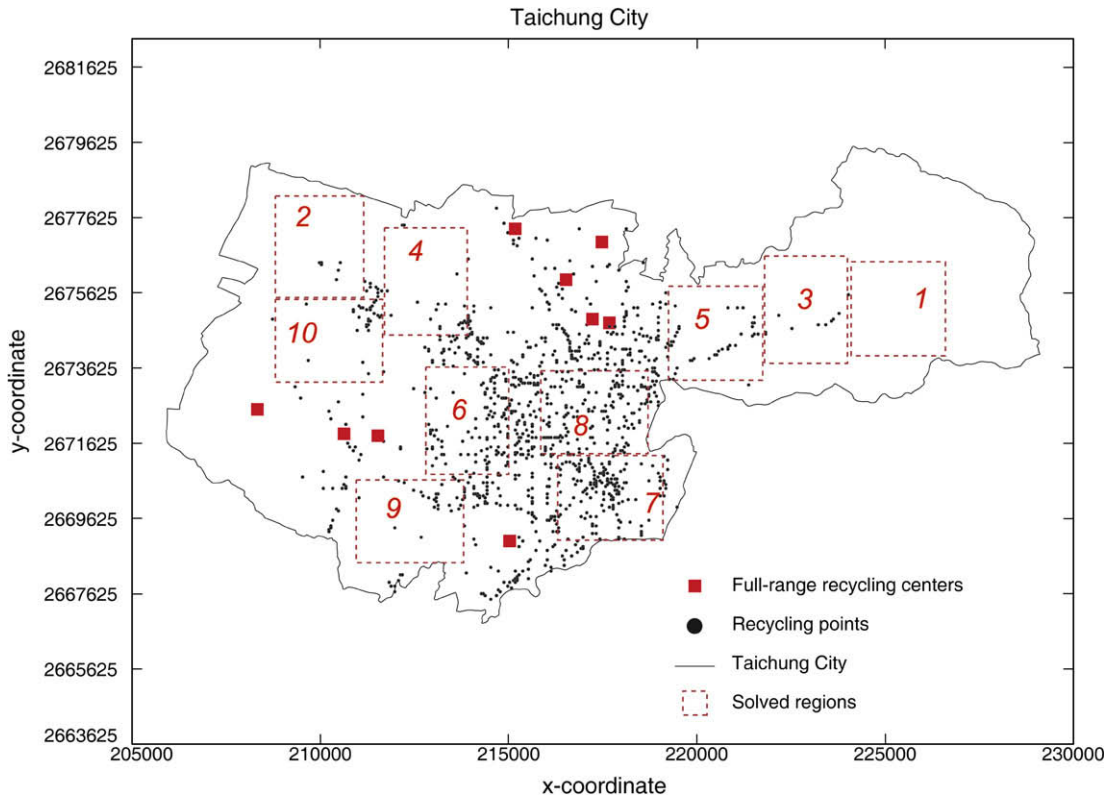


Fig. 5. Model results of *IE* analysis of Scenario C.

of this approach lies in the flexibility provided by expeditious computational evaluation of competing design solutions. The proposed model and program aim to find regions requiring new recycling facilities to supplement existing recycling points. For a local authority responsible for the provision and management of recycling facilities, the major attraction of this method is the flexibility inherent in the process of identifying potential recycling points. In this sense, the model is a dynamic management tool, able to proactively engage the everyday contingencies that might have otherwise negatively impacted the selection of ideal sites (for example, the cooperation of landowners and navigation of land-use restrictions, which are common stumbling blocks in the process). Once suitable regions have been identified by the model, locations for supplemental recycling points within these regions can be easily determined using the experience of local authorities.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.wasman.2008.10.012.

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