Exploring Determinants of Waste Recycling Boundary

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1. Introduction

Promoting regional recycling has received great attention since 2008 when the concept was articulated in the 2nd Fundamental Plan for Establishing a Sound Material-Cycle Society. Ueda [1] explained that regional recycling could benefit from economies of scale and facilitate the application of advanced recycling technologies; however, expanding recycling boundary would result in higher transportation costs.

In terms of modeling, Habara et al. [2] showed that a large scale does not necessarily lead to cost reduction, which is contingent on types of wastes. More generally in the field of operational research, a number of modeling studies focused on optimal locations of landfills, incinerators, transfer centers and recycling centers [3-6]. However, these case studies are mostly for planning purposes and do not theoretically explore the mechanisms and factors that determine recycling boundary in regional scale. This paper quantitatively explores the mechanism and determinants for recycling boundaries in regional scale. An optimization model on recycling waste plastics is developed and applied to test impacts of influencing factors in a case study on the Tokyo Metropolitan Region (TMR) of Japan.

2. Methodology

In the case study, the number, capacities, and locations of *regional recycling centers* (RRCs) are determined so that they provide waste plastics pre-treatment services (separating, compressing, and bailing) to the whole region at the minimum cost. We designed eight sets of scenarios to test impacts of seven factors. In order to facilitate comparison, one scenario in 2025 was set as the *standard scenario*. The factors and their value in the standard scenario are summarized in Table 1. For ensuring the unit of assessment, i.e. the total amount of waste plastics in TMR, being the same under all scenarios, reduction effects and incineration of unseparated waste plastics are counted.

Under each scenario, identifying the optimal number, capacity, and locations of RRCs, namely the hosting cities of RRCs, can be seen as an uncapacitated facility location (UFL) problem on networks. Municipalities can be taken as nodes that are connected through the road network. Among *n* municipalities in total, *m* large ones with population over 100 thousand are taken as candidates for *p* hosting cities ($n \geqslant m \geqslant p$). In this study, we consider economies of scale so that the

Table 1. Factors tested and their values in the standard scenario

Parameter	Value/description
Population	Estimated in 2025
Generation rate	Per capita waste at the 2008 level (7.5% of the MSW)
Recycling rate	50%
Cost of diesel	120 JPY/l
Fuel efficiency of trucks	0.25 l/km for collection trucks; 0.5 l/km for container trucks
Loading capacity of trucks	2 t (loading factor: 0.5) for collection trucks; 10 t (loading factor: 0.8) for container trucks
Unit construction cost	482 million JPY for a recycling center with capacity of 19 t/d
Unit labor cost	4.5 million JPY per capita

construction and operation costs of an RRC are functions of the scale of that center. The problem is formed in two steps as follows: (1) to locate a pre-determined number (*p*) of hosting cities $j \in J$ (j = 1, 2 … m, $J \in I$) to serve all municipalities $i \in I$ (i = 1, 2 … n), so that the transportation cost is minimized, and (2) to identify the optimal number of hosting cities, *p**, under a given scenario so that the total cost of treating all waste plastics in the study region is minimized. The problem can be written as:

$$\min_{p} Total\ cost = \min_{i,j}\left[\sum_{i,j} TRS_{ij}^{ce} x_{ij} + \sum_{j}\left(TRS_{j}^{rf} + TRS_{j}^{if}\right)\right]$$

$$+ \sum_{j}\left(COS_{j} + OPR_{j}\right) + INCI$$

Subject to

$$\sum_{j} x_{ij} = 1, \quad \forall i,$$

$$x_{ij} \leq y_{j}, \quad \forall i, j,$$

$$\sum_{j} y_{j} = p,$$

$$x_{ij}, y_{j} \in (0, 1)$$

where TRS_{ij} = transportation cost if *i* is served by *j*; superscripts *ce*, *rf*, and *if* denote transportation to RRC, to the closest mechanical recycling facility, and to the closest industrial facility, respectively;

COS_j = construction cost of center in j;

OPR_j = operation cost of center in j;

INCI = cost of incinerating unceparated plastics;

x_{ij} = 1 if municipality *i* is served by a RRC in *j*; 0 otherwise;

A GIS based database was constructed for managing spatial data used in the model test. To ensure temporal consistency, most data were for the year of 2008. For those unavailable data in 2008 such as digital data on the road network, data in the closest time were used.

3. Results and Discussions

Under the standard scenario, the total costs at different ps form a U-shaped curve and reach the minimum point at 22.2 billion JPY/year when 13 hosting cities are planned (Figure 1). At an extreme condition where each municipality were to have a local center for the pre-treatment of waste plastics, the total costs would be close to 37 billion JPY, tow-thirds more expensive than the optimal solution. Transportation costs, operation costs of RRCs, and incineration costs of the unseparated waste plastics respectively accounts roughly one third of the total cost, whereas annual construction costs accounts for only 4%. RRCs located in relatively populous areas around the Tokyo Bay have larger capacities and smaller service areas than those located in less populous periphery (Figure 2). This is because the amount of waste plastics collected from a few municipalities in the populous region is large enough for an RRC. The additional transportation cost due to expanding the service area exceeds the benefit gained due to economies of scale.

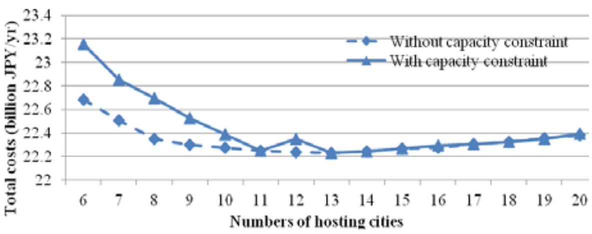

Figure 1 Total costs under the standard scenario

Note: capacity constraint: 100 kt/yr

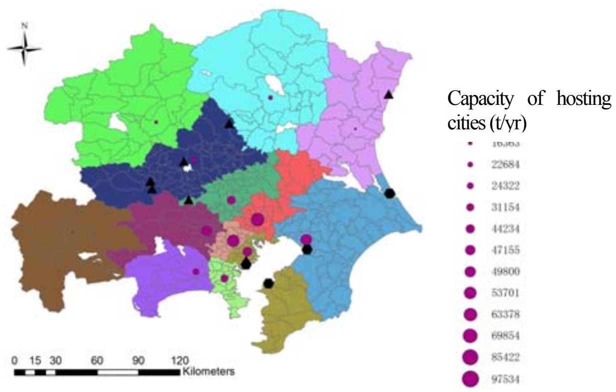

Figure 2 Location and capacity of the optimal number of RRCs under the standard scenario

The optimal numbers of hosting cities under various scenarios vary from 9 to 16 (Figure 3). This result implies significant differences in service areas of RRCs. Among all factors, recycling rate, loading capacity of trucks, and unit labor cost have heavy impacts on the service areas of RRCs. Waste generation rate and unit construction cost have moderate impacts, while diesel price has almost no impact on the optimal number of hosting cities.

The results from various scenarios imply that service areas of RRCs are determined mainly by two relatively independent factors: (1) density of separated waste and (2) the ratio of unit transportation cost to unit treatment cost (i.e. the sum of unit operation cost and construction cost). If we consider transportation cost and construction + operation costs are continuous functions of the number of hosting cities, the optimal number of hosting cities is determined when the sum of marginal cost of transportation (MCT) and the marginal costs of construction + operation (MCCO) equals to zero. For example, by plotting minus MCT and MCCO in the figure, the interest of these two curves shows the optimal number of hosting cities. When loading capacity increases, the unit transportation cost decreases, and the -MCT curve moves down, while the MCCO line remains unchanged. The optimal number of hosting cities thus decreases (Figure 4).

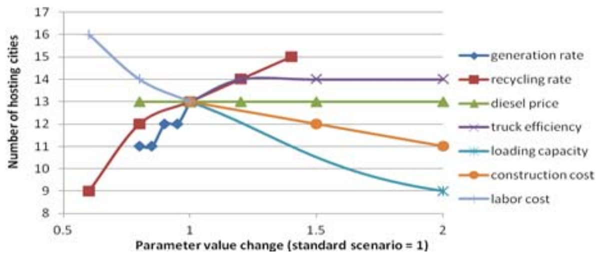

Figure 3 Impact of parameters on the optimal number of RRCs

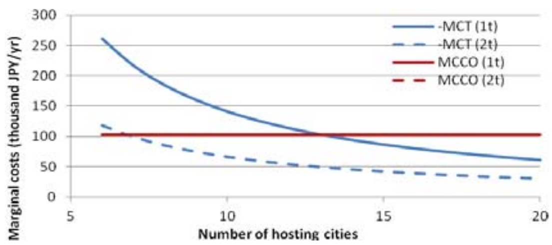

Figure 4 Impacts of unit transportation cost on marginal costs and the optimal number of hosting cities

4. Conclusions

The results imply different types of wastes should be recycled in different boundaries according to their density after separation, unit transportation cost and unit treatment costs. Such implications would contribute to the policy making for promoting regional recycling.

5. References

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