Regional and temporal simulation of a smart recycling system for municipal organic solid wastes

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A B S T R A C T

A cost-effective and robust waste treatment and recycling system is a requisite of a sustainable society. In our previous study, we proposed a “smart recycling system” that utilizes existing industrial facilities with higher energy efficiency so that a cost-effective and robust recycling system for treating municipal wastes can be established. In this study, we further develop the concept of smart recycling and propose a framework for facilitating the implementation of such a system. By making use of existing facilities and adopting both closed-loop and semi-closed-loop recycling processes, this system allows flexible adaptations on the changes of external factors. A spatially optimal scale is necessary to meet the requirements for such a smart recycling system. Thus, we develop an integrated model that combines both geographical information system based collection model and a process model for a smart recycling center. In order to test its applicability, we employ a case study approach to simulate the implementation of smart recycling in the three satellite cities of Tokyo Metropolitan Area and evaluate its effects under three different scenarios. Our simulation results show that smart recycling cannot only reduce carbon dioxide emission but also lower the overall costs. Also, by comparing with conventional waste incineration, we find that the unit cost of smart recycling is relatively stable to changes of the waste amounts due to its lower fixed costs for facilities.

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1. Introduction

With the increasing concerns on climate change and resource depletion, promotion of resource-saving through 3R (reduction, reuse and recycling) has become critical. Recycling and incineration (energy recovery) of municipal solid wastes (MSW) are useful co-benefit measures that can reduce the total amount of landfilled wastes, exhaustible resources and greenhouse gases (GHGs) emissions. Many studies have been undertaken to design an efficient waste treatment and recycling system that can address both resource consumption and environmental load (Astrup et al., 2009; Bohm et al., 2010; Chang et al., 2012; Reich, 2005). They also proposed alternative or optimal solutions so that innovative methods can be applied under different conditions. Meanwhile, when estimating the cost-effectiveness of waste treatment and recycling systems, we need to consider the potential impacts of different future development patterns. For example, potential changes on future populations and lifestyles may lead to different amounts and components of waste generation, thus, resulting in different demands on recyclable products. Under such a circumstance, it is critical to develop a robust waste treatment and recycle system so that such changes can be coped with more appropriately.

In order to fill such a gap, we recently proposed a new concept of “smart recycling” to evaluate the effects of innovative waste management on carbon dioxide (CO2) emissions and cost reductions (Fujii et al., 2012). This concept was based on “urban symbiosis” (Geng et al., 2010; van Berkel et al., 2009), which spatially expands the concept of “industrial symbiosis” (Chertow, 2000). Based on the
synergistic opportunity arising from the geographic proximity through the transfer of physical resources (waste materials) for environmental and economic benefits, urban symbiosis can be defined as “the use of byproducts (wastes) from cities (or urban areas) as alternative raw materials or energy sources for industrial operations (Geng et al., 2010). A smart recycling system refers to actual implementation of urban symbiosis since it utilizes MSW from neighboring cities as raw materials or potential fuels for existing industrial plants and power stations. Such a use of wastes as industrial inputs can greatly reduce CO₂ emissions as a result of fossil fuel resource substitution (Sekine et al., 2009). In addition, the amount of organic solid wastes used in an industry as fuels or chemical feedstock is generally smaller than the amount of original fossil resources used. This makes the recycling system more robust because it is not influenced by the changes both in the amount of waste generated and the demand for recycled wastes. Furthermore, if a considerable amount of wastes can be recycled, the number of incinerators for conventional waste treatment can be reduced. Thus, by utilizing existing and more energy-efficient industrial facilities, a smart recycling system is both cost-effective and robust, despite changes in waste generation and demand for recycled products. Such a system is similar to a smart grid system because both aim to use low-carbon but fluctuating resources to the possible extent by utilizing existing facilities.

In order to improve the cost-effectiveness of a waste treatment and recycling system, the collection of MSW from a spatially dispersed area, which accounts for a large percentage of the overall cost, should not be ignored. In this regard, the geographical characteristics of the study area should be carefully considered. Optimization of waste collection routes was studied previously (McLeod and Cherrett, 2008; Zsigraiova et al., 2013). Several recent studies conducted a comprehensive evaluation on waste management from collection to recycling and treatment in an actual or a virtual region (Chen et al., 2011; Merrild et al., 2012). In addition, the effect of geographic proximity between recycling facilities and waste generation sites (Ohnishi et al., 2012) and modeling of optimal facility location (Erkuta et al., 2008) was investigated.

Based upon these studies, the purpose of this paper is to demonstrate an innovative method to plan a smart waste treatment and recycling system, which is not only cost-effective but also robust for the changes of external factors such as population and consumption behavior. In order to test its applicability, a case study approach was employed, which can reflect more practical and geographical characteristics. The case study area is the three satellite cities within the great Tokyo region, Japan, where the treatment of MSW has been highly dependent on incinerators of the local municipalities. In our previous study (Fujii et al., 2012), an effect simulation on smart recycling was done as a function of population density and the capacity of the recycling facility (a “smart recycling center” : SRC), in which smart recycling can result in a reduction of approximately 100 kg of CO₂ emissions per capita per year without increasing costs if the capacity of the SRC was set appropriately. However, this simulation was simply based on the assumption that wastes generation is static after the implementation of the new recycling program. Also, we simply assumed that the number of incinerators would decrease in proportion to the decreased amount of incinerated wastes. In this paper, we extend the concepts from previous studies and provide more valuable policy insights. We first describe the qualitative requirements for a robust waste treatment and recycling system and then conduct a more practical simulation by applying such a system in Japanese cities. The waste collection process was evaluated more precisely by using a geographic information system (GIS). Other factors, such as location, treatment capacity and operational life, were also considered. Fixed costs for construction and maintenance, and variable costs, such as labor, electricity, industrial water and chemical agents, were separately estimated in order to undertake a dynamic simulation according to changes of the waste amounts. In addition to the SRC, which produces both recycled plastic resin and solid raw material and fuel (SMF) for material industries and power plants (SRC-A), we also tested a simplified SRC, which produces only SMF and is designed for less populated areas (SRC-B).

2. Qualitative requirements for a robust recycling system

In this section, we describe the qualitative requirements for a robust waste treatment and recycling system so that the stakeholders, such as policy makers and urban planners, can plan their waste management by considering their own situations.

2.1. Factors that influence the operation of a robust recycling system

A preferable waste treatment and recycling system should save a large amount of virgin resources and significantly reduce environmental emissions, as well as reduce the total costs. In addition, it should not be influenced by changes in the waste amounts and compositions or the demand for recycled products. Fig. 1 shows various factors that directly or indirectly influence a waste treatment and recycling system. From the waste supply point of view, future waste generation amounts will change in proportion to the local population (McBean and Fortin, 1993); therefore, the future population should be estimated. Also, per capita waste generation amounts and the waste composition may change due to income levels, consumption patterns, promotion of reduction (e.g. reduction of packaging weight) and reuse and other factors (Memon, 2010). Thus changes in population, consumption behaviors, weight reduction, product reuse and economic conditions,

Fig. 1. Factors involved in a robust waste treatment and recycling system.
indirectly influence the operation of such a system. Similarly, from the point of view of demand for recycled products, economic conditions, consumption behaviors, an increase amount and types of competitive recyclable products and the development of a social or legal system for “green” purchasing, also indirectly influence the operation of such a system. To flexibly respond to these external factors, the direct internal factors shown in Fig. 1 should be satisfied. These internal factors will be explained in the following sections.

2.2. Making use of existing facilities

A waste treatment and recycling system should be flexible in order to adapt to unpredictable changes. Making use of existing facilities can help reduce fixed cost. Furnaces in material industries and boilers in thermal power stations are typical examples where wastes such as mixed plastics and paper can be used efficiently. However, the trade-off between cost reduction by making use of existing facilities and cost increases for sorted collection and pre-treatment of recyclable wastes should be considered.

2.3. Trade-offs of using various facilities

Incinerators have both advantages and disadvantages. They can incinerate even low-quality waste materials and wastes with higher moisture contents and recover energy from them (Ning et al., 2013). However, the average power generation efficiency of incinerators in Japan is no more than 12% (MOEJ, 2013). Also, the construction cost of an incinerator is higher in terms of per unit waste weight owing to its complex equipment configuration. Wastes decrease would cause a further decrease in power generation due to the mismatch between the steam flow of boiler and the capacity of a steam turbine. Pre-processing facilities that can mechanically recycle high-quality plastics and other wastes have lower construction costs, and the processing speed can be adjusted according the waste amounts (Fujii et al., 2012). However, this kind of recycling center can only process qualified wastes with suitable levels of foreign matter contamination and energy content. Thus, there is a need to balance the treatment capacities of the incinerator and the recycling center.

2.4. Closed-loop recycling and semi-closed-loop recycling

Demand for a recycled product may change under different economic conditions. To flexibly handle this type of uncertainty, the ability to increase the demand for a recycled product is critical. Closed-loop recycling, in which waste is recycled back into the same type of product (Williams et al., 2010), can help solve this problem, especially in the case of non-durable consumer goods. However, even if the waste cannot be returned to the same kind of product, there will be a demand if the waste can be used as a substitute for fossil resources such as coal, oil and gas, which are consumed with large quantity by industries. In this regard, semi-closed-loop recycling is possible because uncertainty in the waste amount and demand for recycled products can be offset by changing the inputs of fossil resources.

3. Research methods

Since the collection process for wastes accounts for a high percentage of the waste treatment and recycling costs, it is critical to achieve the trade-off between recycling benefits and waste collection costs. In addition, a robust waste treatment and recycling system should be built on a spatially optimal scale. In this section, we present our methods on planning a smart waste treatment and recycling system and evaluating the related effects.

3.1. Outline of a smart recycling and treatment system

In a smart waste treatment and recycling system proposed in our previous study (Fujii et al., 2012), waste plastics and mixed paper are collected separately from MSW. Waste plastics with higher quality in terms of contamination level by foreign matter are processed into plastic resin or chemical feedstock for industrial use, and the rest is processed into SMF for material industries and power stations. The outline of the smart waste treatment and recycling system is shown in Fig. 2. Newspaper, magazines and PET bottles were excluded from this study because they have been efficiently recycled and are expected to continue. If this smart waste treatment and recycling system is applied across the whole Japan, the CO₂ reduction effect corresponds to a reduction of approximately 1% in GHG emissions (Fujii et al., 2012). In terms of cost, sorted collection, construction and operation of an SRC require additional investment. However, because of the significant reduction in the amount of wastes to be incinerated, the cost for construction and operation of incinerators can be reduced. If a smart waste treatment and recycling system with an appropriate spatial scale can be operated, in which the unit cost for sorted collection increases with the area of collection and the unit cost for an SRC decreases with the capacity of the SRC, such a system will have a cost advantage over a conventional waste incineration system.

3.2. A simplified model for sorted collection by using GIS

Models that can optimize the routes of waste collection vehicles have been developed (McLeod and Cherrett, 2008; Nuortioa et al., 2006). However, these models are complicated and not easily applied by policy-makers. Under such a circumstance, we employed a simple model based on the Grid City Model (Ishikawa, 1996). This model estimates the collection distance by approximating a city (or a part of one city) by a square with the same area and assuming a uniform distribution of waste generation. Our model can reflect the spatial distribution of wastes by using GIS in the following way. For every mesh (e.g. 1-km² mesh) within one city, the waste collection amount is estimated based upon the population size living in one mesh. The collection distance to waste collection points in one mesh is calculated by the same algorithm used in the Grid City Model. The round-trip distance between a facility (i.e. an incinerator or SRC) and a mesh is calculated as the required travel distance along the grid lines. The trip number taken annually between a facility and a mesh is calculated by dividing the annual waste amount in one mesh by the load capacity of an average collection vehicle. The annual total waste collection distance within one city, \( L \) (km/year), is expressed by Equation (1):

\[
L = \sum_{i=1}^{n} \left( F \times a \times \sqrt{\frac{P_i}{P_{sta}}} + W \times \sum_{j=1}^{m} (2 \times L_i + (|x_j| + |y_j|)) \right) / B,
\]

(1)

where \( n \) is the number of meshes within one city, \( F \) is collection frequency (times/year), \( a \) is the size of one side of a mesh (km), \( P_i \) is the population in the \( i \)th mesh, \( P_{sta} \) is the population size that use one collection point, \( W \) is the per capita waste amount within one year (kg/person/year), \( x_i \) and \( y_i \) (km) represent the positions of the \( i \)th mesh relative to a facility, and \( B \) is the load capacity of a collection vehicle.

The first term of the right side of Equation (1) shows travel distance within meshes, and the second term shows roundtrip
distances between one facility and the meshes. A similar concept model was tested by Murakami et al. (2008), demonstrating a good relationship between the estimated collection distances and the actual collection distances in Japanese cities. To calculate the total collection distance for sorted collection, it should be estimated for every type of waste. By combining the distance and the travelling speed of a collection vehicle and loading speed at a station, collection time can also be calculated. Similarly, the cost for labor and vehicles can be estimated by multiplying hourly cost and time. Although this model requires repeated calculations to the number of meshes, each calculation is simple. In addition, it does not need trial-and-error type calculations so that the calculation can be done by general spreadsheet software.

3.3. Smart recycling centers and incinerators

In our previous study (Fujii et al., 2012), with the close cooperation of a consulting company and an engineering company that have rich experiences in designing waste treatment and recycling facilities, we estimated the monetary cost and CO₂ emissions associated with the construction and operation of one facility as a function of the capacity of an SRC by considering plant construction, purchase and maintenance of equipment, and inputs of energy, water, chemicals and labor in each process for SRCS having different capacities. In this study, we created two different smart recycling patterns. In addition to an SRC that produces both recycled plastic resin and SMF (SRC-A), the cost and CO₂ emissions associated with the construction and operation for a simplified SRC that produces only SMF (SRC-B) were estimated. SRC-A has an advantage for the future change of resources prices which will improve competitiveness of recycled resin, but has a disadvantage associated with the construction and operation for a simplified process model enables the simulation of complicated processes. Therefore, the SRC-B was designed to fit the case for less populated areas where it is economically infeasible to install SRC-A. Thus the process model enables the simulation of smart recycling in various regions under different conditions. Fixed costs and CO₂ emissions as well as variable costs and emissions were calculated to conduct a simulation analysis for changing waste amounts. Fixed cost was calculated by dividing the sum of the initial construction cost and the cumulative maintenance cost by the lifetime of one facility (25 years). Variable costs include labor, electricity, industrial water and chemical agents. Fixed and variable CO₂ emissions were calculated in a similar way. The fixed and variable CO₂ emissions and costs for SRC-A and SRC-B are expressed by the same type of equation:

\[ Y = a \times X^b. \]  

where \( Y \) represents either fixed CO₂ emissions (t-CO₂/year), variable CO₂ emissions (t-CO₂/t), fixed cost (USD/year) and variable cost (USD/t), \( X \) represents the capacity of an SRC (t/year), and \( a \) and \( b \) are parameters (Table 1).

For an incinerator, the model developed by Matsuto (2005) was used to calculate fixed and variable CO₂ emissions and costs of incinerators with different treatment capacities. For the existing incinerators in the case study area, we assumed that the electricity production was equal to the amount required to operate each incinerator. For a new incinerator that replaces an old incinerator, the model was modified so that power generation efficiency was set as 15% and the surplus electricity can be sold. The profit from the electricity sale was subtracted from the operations cost of an incinerator.

### Table 1

| Parameters of the process equation of a smart recycling center. |
|-----------------|-----|-----|
| Type            | \( a \) | \( b \) |
| Fixed CO₂ (SRC-A) | 6.31E+1 | 0.179 |
| Variable CO₂ (SRC-A) | 3.43E+1 | −0.558 |
| Fixed cost (SRC-A) | 2.25E+5 | 0.165 |
| Variable cost (SRC-A) | 9.36E+2 | −0.192 |
| Fixed CO₂ (SRC-B) | 4.53E+1 | 0.192 |
| Variable CO₂ (SRC-B) | 5.28E+0 | −0.439 |
| Fixed cost (SRC-B) | 1.27E+5 | 0.193 |
| Variable cost (SRC-B) | 1.46E+3 | −0.285 |
external factors are dynamically changing. From such a standpoint, the case study area was chosen in Japan. Similar to many of developed countries, Japan has more aging population due to the birth rate decline, good health care and higher income level (UNDESA, 2013). The population decrease may lead to less waste generation. Also, financial burden on waste management will be increased since more budgets need to be allocated for social welfare of increasing aging population. Moreover, although Japan has been promoting recycling, the municipal waste treatment is still dominated by incinerators (Fujii et al., 2012). Consequently, it is crucial to develop a robust and cost-effective waste treatment and recycle system in Japan. Similar simulation will be applicable to other countries such as Denmark, Norway, Sweden and Switzerland, where the incineration rate of MSW is rather high (USNID, 2011). Also in a country such as China where the current landfill rate of MSW is high but is going to install more incinerators (Song et al., 2013), the simulation results may help decision-makers to seek an alternative plan.

Our study area includes three satellite cities in Tokyo, namely, Machida City, Tama City and Hachioji City (Fig. 3). The total area of these three cities is 279 km², including 181 km² of habitable land. The population density is 6400 person/km². There are two reasons to choose this study area. First, several old incinerators exist in this area, allowing us to discuss the application of alternative recycling and waste treatment plan instead of simply replacing the old ones. Second, according to the simple evaluation in our previous study (Fujii et al., 2012), it is cost-effective to construct one SRC in an area with the above population density.

3.5. Scenario setting

We set three different future scenarios for our analysis. The first one is the baseline scenario which reflects the recent trend of waste treatment and recycling policy in Japan. The other two recycling scenarios are designed to test the efficiency of smart recycling systems, namely, SRC-A and SRC-B, respectively. By comparing the CO₂ emissions and costs under different scenarios, we can judge whether the smart recycling can bring advantages or not to the conventional system. To compare these three scenarios under the same condition, the geographical boundary of waste collection, the amount of waste generation, and the total frequency of waste collection, are set as the same in three scenarios. The year of 2030 is set as our target year. The future population in the area is based on estimates by the National Institute of Population and Social Security Research, Japan, and MSW generation amount is estimated based upon population size. Waste composition is estimated based on the results of our previous study (Fujii et al., 2012). At present, Japan has a recycling scheme based on the Containers and Packaging Recycling Law, in which some containers and packaging materials made of plastic or paper are required to be recycled. However, recycled plastic and paper, which used to be incinerated, account for only about 10% of the total amount of waste plastic and paper on a heat value basis. In the baseline scenario we suppose that the recycling law would be strictly enforced and energy recovery from waste incineration would be promoted. The year 2006 was set as the reference year to quantitatively show the effect of the conventional policy in the baseline scenario because there was little recycling of containers and packaging materials at that time. As shown in Fig. 4, there are five incinerators in this area and two of them are old (built in 1981 and 1982 respectively). In the past decade, the amount of incinerated wastes decreased in Japan (although it has stabilized more recently) primarily as a result of the promotion of 3R processes, and more incinerators are gradually phased out. In the baseline scenario, one of the two old incinerators is no longer used and the other is replaced by a new incinerator with a smaller treatment capacity in 2020. Sorted collection and pretreatment of plastic containers and packaging material is implemented in each city, and the sorted materials are delivered to licensed recyclers. In the smart recycling scenarios (SRC-A and SRC-B), both old incinerators are shut down and an SRC will be constructed in 2020 at one previous site of two old incinerators. The total maximum facility capacities in each scenario are set as roughly the same. The SMF produced at the SRC is assumed to substitute for coal in local industries and CO₂ emission from the equivalent amount of coal in terms of energy value is regarded to be reduced by the use of SMF. The process of landfiling incineration ash, which is required in every scenario, is omitted from our evaluation due to the very small amount difference between scenarios.

For each of the scenarios, CO₂ emission and costs regarding with sorted collection, construction and operation of incinerators and a SRC, transportation of SMF and avoidance of fossil resources consumption achieved by recycling, are estimated for 2020 and 2030 respectively. In addition to the coal substitution by SMF, the surplus electricity generated in an incinerator is regarded to substitute electricity produced by coal fired power generation and the recycled plastic resin is regarded to substitute 90% of virgin resin in weight basis in consideration of inferior quality of recycled resin to calculate the CO₂ emission reduction through the recycling. The calculation parameters of each scenario are presented in Table 2. In the study area, a significant population decrease is not expected until 2030. However, as a whole, the population of Japan is declining. Moreover, the promotion of reduction and reuse may drastically reduce waste generation in the future. In view of these conditions, to quantitatively test the robustness of smart recycling system, our simulation is done under an assumption that the per capita waste generation decreases to 60% of the standard estimation while waste composition remains the same. This assumption has a similar effect on the results as reducing population density to 60% of its standard estimation while keeping per capita waste generation as the same.

4. Results and discussion

Costs for waste collection and facilities as well as revenues generated from the sale of recycled products are shown in Fig. 5 for three scenarios. The case study area is densely populated and accordingly is suitable for recycling. The total net costs of SRC-A and SRC-B are cheaper than the baseline scenario in both 2020 and
2030, so it is clear that smart recycling has cost advantages. Compared to the baseline scenario, both smart recycling scenarios have higher collection costs, but with lower fixed costs for the construction and maintenance of facilities.

In the two smart recycling scenarios, the revenues generated by the sale of the recycled products provide an additional advantage, but such an impact on total costs is rather limited. The total cost of the SRC-B was lower than that of SRC-A because it includes only the

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**Table 2**

Parameters for simulation of the smart recycling scenarios, the reference scenario and the baseline scenario.

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<td></td>
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<td>2020</td>
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<td>1199</td>
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<td>km$^2$</td>
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<td>Total habitable land area</td>
<td>km$^2$</td>
<td>181</td>
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<td>Amount of target waste</td>
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<td>326</td>
<td>326</td>
<td>326</td>
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<td>Number of incinerators</td>
<td>$10^3$ t/year</td>
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<td>4</td>
<td>4</td>
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<td>400</td>
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<td>Number of smart recycling centers</td>
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<td>Capacity of smart recycling center (maximum)</td>
<td>$10^3$ t/year</td>
<td>90 (135)</td>
<td>90 (135)</td>
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<td>Waste for incineration</td>
<td>$10^3$ t/year</td>
<td>301</td>
<td>315</td>
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<td>236</td>
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<td>$10^3$ t/year</td>
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<td>12</td>
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<tr>
<td>Transportation distance of SMF (from recycling center to material industry)</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>50</td>
<td>50</td>
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* Based on projections by National Institute of Population and Social Security Research, Japan.
Therefore, the CO₂ from the oxidation of waste is omitted in the burned at industries and some is burned after being recycled. Every scenario, waste is burned in the last step, although some is generated through recycling. VC represents variable costs and FC represents fixed costs, which were realized through the use of recycled materials being used to substitute for fossil resources in industries. This capacity to shift would provide stable supply-demand balance. The simulation results under different waste supply conditions are shown in Fig. 7. A decrease in the waste amount reduces operating rates at facilities, and a decrease in the waste spatial density reduces the efficiency of waste collection. These factors cause unit cost increases for both recycling and waste treatment. In the two smart recycling scenarios, however, the increased unit costs are lower due to lower fixed costs, which were realized through the utilization of existing facilities in local industries. Thus, it is preferable to build a more robust waste treatment and recycling system, although there are trade-offs between increases in the cost for sorted collection and decreases in the cost of facilities, and these trade-offs need to be carefully examined.

With the above results, we propose to plan a waste treatment and recycling system, which is cost-effective and can keep its relatively simple process of producing SMF. In addition, we set the price of recycled plastic resin produced in the baseline and the SRC-A scenarios at 0.30 USD/kg, which is much cheaper than the price of virgin plastics (around 1.7 USD/kg) because it is difficult to produce high-quality resin from mixed household waste plastics. If the price of recycled plastic were to exceed 1.3 USD/kg, the total net costs of SRC-A and SRC-B would be equal. Therefore, if conditions change, such as better waste separation by residents, improved designs for easier recycling, increased prices of virgin plastics, and improved automation of the recycling process, SRC-A may be more advantageous. Thus, in one area with a dense population, SRC-A is one reasonable choice that can adapt to the future changes, while in one area with less population, SRC-B will be a better choice in order to let the smart recycling have a cost advantage in the current situation.

Fig. 6 shows estimated CO₂ emissions for three scenarios. In every scenario, waste is burned in the last step, although some is burned at industries and some is burned after being recycled. Therefore, the CO₂ from the oxidation of waste is omitted in the figure. In the two smart recycling scenarios, plastics and mixed paper are utilized more efficiently in industries than they are in the baseline incinerators. As a result, there is a greater reduction in CO₂ emissions, primarily because of coal (or other fossil resources) substitution.

In terms of the robustness of smart recycling to changes in direct external factors, an increased demand for recycled products could be accommodated by reducing the amount of recycled materials being used to substitute for fossil resources in industries. This capacity to shift would provide stable supply-demand balance. The simulation results under different waste supply conditions are shown in Fig. 7. A decrease in the waste amount reduces operating rates at facilities, and a decrease in the waste spatial density reduces the efficiency of waste collection. These factors cause unit cost increases for both recycling and waste treatment. In the two smart recycling scenarios, however, the increased unit costs are lower due to lower fixed costs, which were realized through the utilization of existing facilities in local industries. Thus, it is preferable to build a more robust waste treatment and recycling system, although there are trade-offs between increases in the cost for sorted collection and decreases in the cost of facilities, and these trade-offs need to be carefully examined.

With the above results, we propose to plan a waste treatment and recycling system, which is cost-effective and can keep its robustness. The robustness of smart recycling which can adapt to the demand changes for recycled products and the waste supply changes, was quantitatively examined thorough our simulation process. Those outcomes are different from other relevant studies (e.g. Koroneos and Nanaki, 2012; Reich, 2005) which aimed to assess a waste management system in a given, rather steady external factors. Besides, the model used for the simulation in a specific area was simply calculated, which can facilitate the use of such a recycling system within one city or several cities. Actually, it is difficult to deal with the future waste generation changes by simply upgrading and merging the existing incinerators, as it was shown by the baseline scenario. Policymakers should prepare strategies for adapting to the future changes. The robustness of the planned recycling system is attractive to the investors for low carbon technologies since such investors tend to have longer investment recovery term. Consequently, promotion of CO₂ emission reduction through smart recycling can be expected, coupled with the higher probability of CO₂ emission reduction by smart recycling not only in the short term but also in the long term. For instance, as an economically feasible way to promote urban symbiosis (Geng et al., 2010; van Berkel et al., 2009), smart recycling will be effective. Our study area is located in Japan, a developed country with decreasing population. However, in developing countries, the waste amounts will continue to increase because of population increases and improved living standards. Therefore, different development patterns should be considered when developing waste treatment and recycling systems. If the total waste amount increases, more waste treatment and recycling facilities should be planned and constructed so that there will be adequate treatment capacities. However, due to limited budgets and lower awareness, currently it may not be easy to promote smart recycling in developing countries although such a system can better utilize existing industrial facilities and thereby lower the overall costs.

5. Conclusions

With increasing global concerns on climate change and resource depletion, it is crucial to improve the overall material efficiency so that the related environmental emissions and costs can be reduced. In this paper we proposed a smart recycling model that can adapt to changes induced by external factors. To test its feasibility, a case study approach was adopted in three satellite cities in the great Tokyo region, Japan. Based on the results of our previous study...
using a simpler model (Fujii et al., 2012), the expected advantages of smart recycling include not only the reduction of CO₂ emissions but also the reduction of the overall cost. These advantages were confirmed in this simulation analysis.

A sensitivity analysis on the waste amounts was also conducted to test the effects of changes induced by an external factor. A decrease in the waste amount resulted in increased unit costs in all three scenarios, but the increase was less for the two smart recycling scenarios because of lower fixed costs for facilities. Consequently, this type of waste treatment and recycling system is more robust and should be promoted in both developed and developing countries.

In general, the smart recycling has great potential to reduce the consumption of fossil resources and resulting CO₂ emission from industries through urban symbiosis where the MSW is used as industrial inputs as much as possible. These effects play a catalyst role to drive the industries toward a more sustainable and industrial inputs as much as possible. These effects play a catalyst role to drive the industries toward a more sustainable and environmentally-sound direction. The property of the smart recycling, which is economical as well as high efficient, will contribute to maximize the CO₂ emission reduction through the recycling of MSW and will promote appropriate treatment of MSW. The method for evaluating a smart recycling in a certain region we demonstrated in this paper will help to explore the possibilities of promoting smart recycling in cities, especially in industrial cities with existing facilities, not only in Japan but also in many other countries, although the waste sorting and collection needs to be further improved.

Acknowledgments

This research was supported by the Environment Research and Technology Development Fund (1E-1105, K113002 and K2351) of the Ministry of the Environment, Japan, the Chinese Academy of Sciences (2008–318), the National Natural Science Foundation of China (71033004, 71325006, 7131140172) and Ministry of Science and Technology (2011BAJ06B01).

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