Spatial Analysis and Evaluation System for the Planning of Regional Recycling Network: Empirical and Modeling Analyses in Japan

（地域循環ネットワークの計画のための空間分析・評価システムに関する研究

—日本における実証及び事例研究）

CHEN，Xudong

（陳　旭東）

Spatial Analysis and Evaluation System for the Planning of Regional Recycling Network: Empirical and Modeling Analyses in Japan

（地域循環ネットワークの計画のための空間分析・評価システムに関する研究
—日本における実証及び事例研究）

Chen, Xudong

（陳　旭東）

Doctor of Environmental Studies

Graduate School of Environmental Studies, Nagoya University

（名古屋大学大学院環境学研究科　博士（環境学））

2012 年 1 月

Spatial Analysis and Evaluation System for the Planning of Regional Recycling Network: Empirical and Modeling Analyses in Japan

地域循環ネットワークの計画のための空間分析評価システムに関する研究
ー日本における実証及び事例研究

CHEN Xudong

陳　旭東

Summary

In recent years, urban development caused multiple, comprehensive environmental problems simultaneously, such as resource depletion, shortage of waste disposal space, and global warming, which in turn hindered further development of cities. Owing to the limit of resources and carrying capacity of the natural environment and people's desire of maintaining, or even upgrading, the living environment, urban systems must be converted from the conventional "mass production-consumption-disposal" style towards high resource efficiencies and less disposal of wastes so as to reduce the environmental burden of urban activities. Actions need to be taken in all processes of material flows through urban systems, including production, logistics, consumption, and treatment of wastes. Among numerous approaches, recycling through industrial symbiosis, namely using municipal solid waste (MSW) as raw materials in industrial production, is an effective one to mitigate the pressures. Research efforts have been made on the operational level, such as increasing recycling rates and developing and assessing new recycling technologies.

Managing MSW as a resource requires an emphasis on the efficiency of recycling, which has counted on technology progress. A scope exclusively on "waste" limits the search for potentials of waste utilization in energy intensive industries with high efficiencies. Moreover, municipalities in Japan, as well as in many other countries, are assuming the responsibility for collecting and pre-treating recyclable municipal solid waste. Most municipal recycling centers are in small scales (i.e. small treatment capacity) and of high costs. Enlarging the scale of recycling centers leads to the establishment of a regional recycling network, which bridges spatially diffuse sources of wastes and agglomerated clusters of industrial facilities.

Determining appropriate boundaries of recycling for different types of wastes becomes important and necessary in planning for regional recycling. However, both empirical and modeling studies are lacking in the literature.

This doctoral dissertation aims to quantitatively explore the mechanism and key factors that determine the proper boundary of regional recycling through industrial symbiosis by both empirical studies and a case study on waste plastics recycling in the Tokyo Metropolitan Region in Japan. It has three tightly linked objectives. Towards this goal, this dissertation has the following three objectives: (1) to identify features of existing recycling facilities in different scales and types in Japan; (2) to develop models for optimizing the number, capacity, and locations of regional recycling centers (RRCs) and assessing the environmental benefits and eco-efficiency of regional recycling through industrial symbiosis; and (3) to design regional recycling networks with multiple layers for different types of wastes according to their properties and promotion policies.

This paper is organized as follows:

Chapter 1 introduces the background of this dissertation. It notes that given the limitation in the carrying capacity of our “spaceship”, earth, in terms of resource supply and waste disposal, in order to maintain or even upgrade the urban living environment, the efficiencies of utilizing resources must be increased. For closing the material-loop in urban systems, a possible approach is to utilize waste as resource directly in industrial facilities. To materialize this concept in practice, both technologies (hardware) and a supporting social system (software) are required. Three problems need to be addressed for further improving recycling. First, it is necessary to address not only the amount of recycling, but also the efficiency of utilizing wastes. Second, the scale of recycling centers in municipalities for pre-treatment (e.g. separation, compressing, or bailing) is usually small so that the average cost of pre-treatment is relatively high. Third, planning for regional recycling through IS, including the design of regional recycling networks and promoting policies, requires sound supports of scientific studies. Therefore, it is important to study the mechanisms and factors that determine appropriate recycling boundaries of different types of wastes. The research objectives and dissertation structure are also introduced.

Chapter 2 reviews relevant literature to identify research gaps and solidify the theoretical foundation of this study. Because topics concerning recycling have long been regarded as a part of waste management in both practice and research, Chapter 2 begins with a brief review on how waste management has been evolved in the recent history. It then reviews models often employed in waste planning and management to identify the gaps in research for improving the efficiency of recycling, establishing regional recycling networks, and issuing comprehensive policies for promoting regional recycling through industrial symbiosis. The review finds that most widely adopted models focus exclusively on managing waste, which is a limited scope not looking at the potential of industries. They also focused mainly at the municipal level. Regional recycling is not a main topic in research and practices. To resolve these issues requires knowledge beyond the scope of conventional waste management and planning. As propositions, studies related to industrial symbiosis, regional recycling, and socio-technical transition for policy-making are reviewed.

Chapter 3 introduces empirical studies on recycling activities in Japan. With its achievements in recycling and industrial symbiosis and high accessibilities to relevant data, Japan offers a precious opportunity for empirical study on recycling. Chapter 3 first examines recycling boundary and facility scale at the project level, analyzing first hand survey data acquired from recycling facilities to identify relationships between scale, recycling boundary, waste type, and performances of recycling facilities. Next, it zooms out to the national scale, examining the spatial distribution and clustering of waste generation, incineration, separate collection, and recycling processing. The empirical studies find that large recyclers appear to be more stable in operation; agglomeration of recycling facilities in eco-towns does not appear to have advantages over dispersed eco-towns; recycling boundary differs for different types of waste – transportation cost is likely to affect the result; and for processing waste plastics, clusters are present.

Chapters 4 and 5 present the case study on recycling of waste plastics in the Tokyo Metropolitan Region of Japan. Chapter 4 introduces general methodologies in terms of a planning model, scenario design, modification of an optimization model to count economies of scale when determining number, capacity, and location of RRCs, and a life cycle assessment (LCA) model for assessing environmental benefits of regional recycling networks.

Chapter 5 details out the background of the case study region, model parameters, results, and theoretical discussions. The modeling aims not only at finding optimal solutions for the case study, but also at generalizing the results to other types of wastes and other regions. To do so, scenarios are designed to test various factors to identify key factors by comparing the results from all scenarios. The modeling results reveal two key factors that determined the proper boundary of recycling spatially diffused waste, density of recyclable wastes, and the ratio of unit transportation costs to unit treatment costs. In a given region where all municipalities are serviced, considering cost as a function of the number of hosting cities, i.e. the recycling boundary, the optimal solution is determined when the sum of marginal cost of transportation (MCT) and the marginal costs of construction + operation (MCCO) equals to zero.

Discussions about generalization of findings and policies implications are elaborated in Chapter 6. By identifying the two determinants for different types of wastes, proper recycling boundaries for them can be estimated. Such a theoretical deduction is verified by the empirical findings in Chapter 3. The findings lead to a design of regional recycling networks with multiple layers for different types of wastes. To establish such a regional recycling network requires coordinated efforts of various stakeholders. Comprehensive policies are discussed based on a model of socio-technical transition management in two aspects. First, policies need to identify the extent to which pressures are oriented coherently in a particular direction and translate pressures into a form that prompts and enables responses by the regime, referred as pressure articulation. Second, policies should contribute to the adaptive capacity of a regime, the capacity and resources to respond to the pressures bearing it, referred to as Resource coordination.

Finally, Chapter 7 draws conclusions on the major findings, contributions to literature and practices, and future studies.

CONTENTS

ABBREVATIONS

3Rs	Reduce, Reuse, and Recycling
CDM	Clean Development Mechanism
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
IE	Industrial Ecology
IS	Industrial Symbiosis
ISW	Industrial Solid Waste
JCPRA	The Japan Containers and Packaging Recycling Association
LCA	Life Cycle Assessment
LQ	Location Quotient
MCT	Marginal Cost of Transportation
MCCO	Marginal Costs of Construction and Operation
METI	Ministry of Economy, Trade and Industry
MOE	Ministry of the Environment
MRC	Municipal Recycling Center
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NIPSSR	National Institute of Population and Social Security Research
OR	Operation Rate
PE	Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
RCRA	Resource Conservation and Recovery Act
RCM	Rational Comprehensive Model
RDF	Refuse Derived Fuel
RPF	Refuse Plastic & Paper Fuel
RRC	Regional Recycling Center
TMR	Tokyo Metropolitan Region
UFL problem	Uncapacitated Facility Location problem
VSM	Virgin Material Saving
WEEE	Waste Electronic and Electrical Equipment

Chapter 1 Introduction

1.1 Background

Our cities, which have supported and cultivated the present human civilization, are an inseparable part of the natural environment on Earth. On the one hand, urban activities and development rely upon the surrounding natural environment for resources and energy inputs. On the other hand, cities also take advantage of the natural environment for storing and decomposing wastes emitted from cities. Due to increasingly intensified urban activities and limited carrying capacity of the natural environment, urban development recently has caused serious, complex environmental problems, such as air and water pollution, shortage of waste disposal space, resource depletion, and global warming. These problems in turn hindered further development of cities. For example, they threatened public health, raised the costs of urban activities, and increased the frequencies of natural disasters.

Given the limitation in the carrying capacity of our “spaceship”, the Earth, in terms of resource supply and waste disposal, in order to maintain or even upgrade the urban living environment, the efficiencies of utilizing resources must be increased (Hayashi, 2010). Typically, material flows in an urban system pass through several major processes from industrial production to final disposal of wastes (Figure 1.1). Approaches in each of these processes could contribute to a high efficiency of resources, such as process integration and clean production, efficient logistics, dematerialization of products, design for environment, reuse, recycling, and efficient energy recovery. These approaches actually imply a conversion of urban system from the conventional “mass-production-consumption-disposal” type towards a more sustainable one. One approach to which this research pays attention is utilizing “discards” directly in industrial production. This approach is often referred to as industrial symbiosis or, as an extension, urban symbiosis in the field of industrial ecology, which is reviewed in detail in the next chapter (Figure 1.1). The discards are often taken as *wastes* as they have no value to the original owners. They become *resources* when users exist.

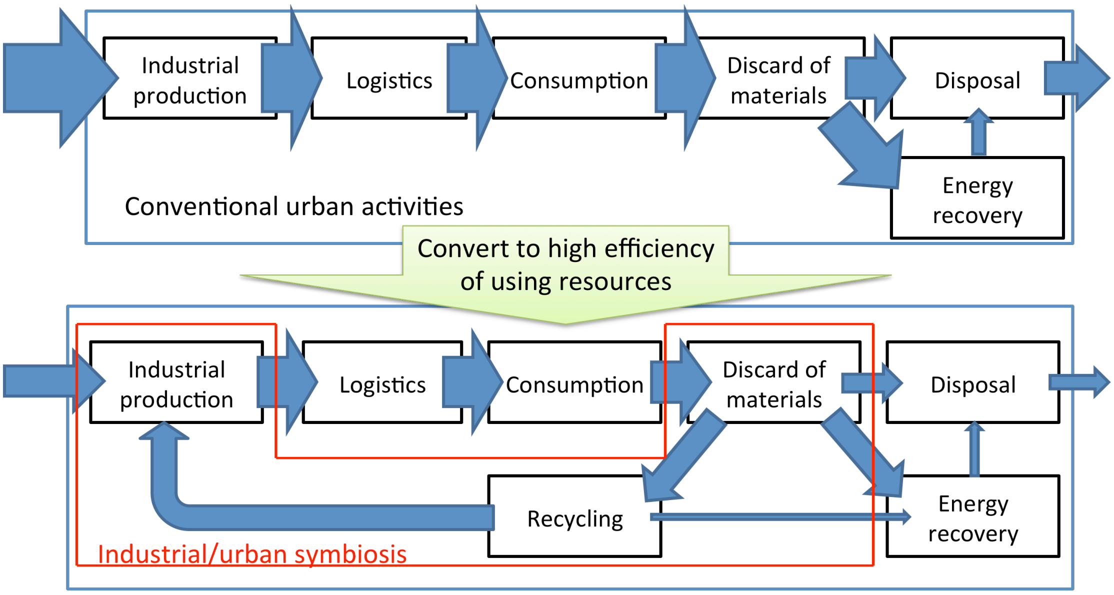


Figure 1.1 Conversion of urban system towards higher efficiency of using resources

Both technologies (hardware) and a supporting social system (software) are needed to realize industrial and urban symbiosis. Japan already accumulated valuable experiences in recycling concerning both advanced technologies and the supporting social system. As a result, out of 591 million tons of wastes generated (including both industrial and municipal solid wastes) in 2007, 41% of recyclable wastes were recycled, whereas only 2% were directed disposed (Figure 1.2). A combination of technologies and supporting social systems made this a reality. The national government encouraged and subsidized leading recycling technologies in eco-towns. Cases of innovative recycling through industrial and urban symbiosis in Japan were studied in eco-towns (Geng et al., 2010; Hashimoto et al., 2010; JCPRA, 2007; van Berkel et al., 2009). In terms of legislation, the national government issued the Fundamental Law for Establishing a Sound Material-Cycle Society, as well as specific recycling laws on recycling packaging and containers, construction and demolition wastes, end of life vehicles, waste home appliances, and food wastes. Governments and civil society initiated various public education programs on waste reduction and recycling. Ministry of the Environment (MOE) of Japan has been presenting commendations and prizes to organizations that contribute to establishing the sound material-cycle society (MOE, 2010).

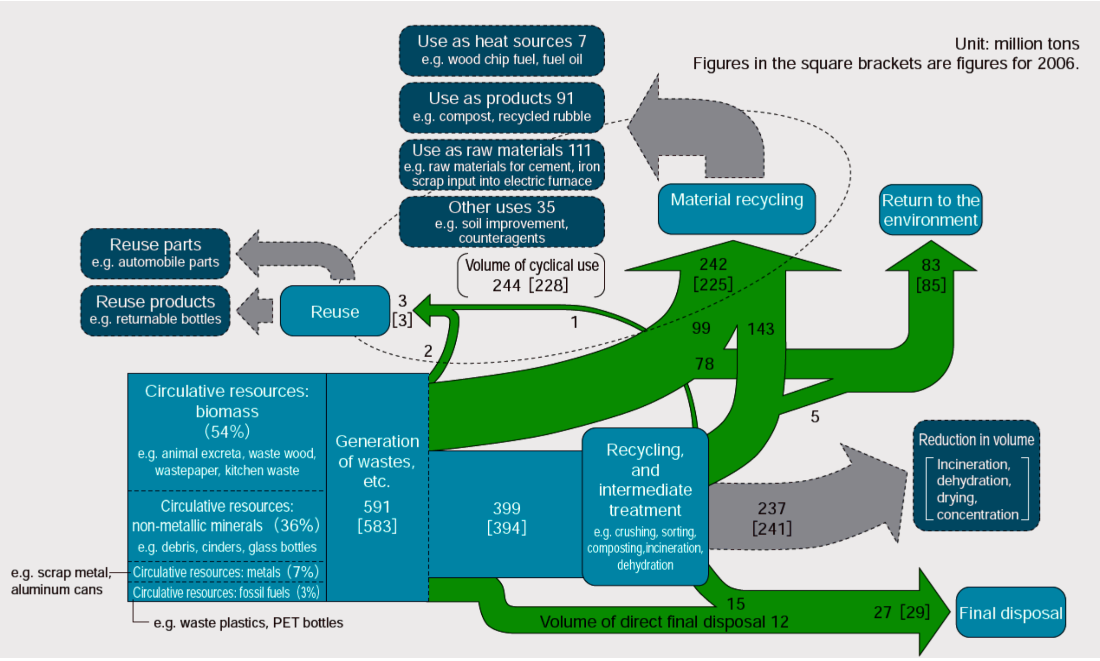


Figure 1.2 Flow of recyclable wastes in Japan in 2007

Source：(MOE, 2010).

The achievements in waste reduction, reuse, and recycling (3Rs) in Japan offer precious opportunities for empirical and case studies. Critical analyses can shed lights on further promoting 3Rs, which other countries and regions may face in the future. First, managing wastes as a resource requires emphases on not only the amount of recycling, but also the efficiency of utilizing wastes. As the goals in the current plans for establishing sound material-cycle society are mainly concerning rates, the efficiencies of recycling have not been addressed sufficiently. Efficiencies here refer to environmental benefits gained per unit weight of waste recycled and per unit cost of recycling, namely resource efficiency and eco-efficiency (Huppes & Ishikawa, 2005). Industrial symbiosis showed in many cases the potential for high environmental benefits and low costs. For assessing the environmental benefits of industrial symbiosis, only a few credible quantitative studies can be found in the literature, which are discussed in section 2.3. How industrial symbiosis could be integrated in municipal solid waste management and contribute to high efficiencies of recycling still demand for detailed quantitative studies.

Second, the scale of recycling centers in municipalities for pre-treatment (e.g. separation, compressing, or bailing) is usually small so that the average cost of pre-treatment is relatively high. Compared with recycling technologies and source separation programs, the collection and pretreatment processes have received much less attention in research. On the one hand, recycling centers in large scales would enjoy low average costs for economies of scale. On the other hand, large scales require collecting recyclable wastes in long distances, resulting in increases in transportation costs. Although such a concept is not novel, robust empirical and modeling studies on facility scale and recycling boundary at the regional level are rarely found in the literature.

Third, planning for regional recycling through IS, including modeling and designing regional recycling networks and promoting policies, requires sound supports of scientific studies. The 2nd Fundamental Plan for Establishing a Sound Material-Cycle Society in Japan recognized that "recycling blocks" should be established according to the characteristics of wastes. However, with a few case studies and empirical evidence in the literature, the determining mechanisms and factors for recycling boundaries are not clearly identified. In research, planning and evaluation of industrial symbiosis focus mostly on symbiotic networks among firms in industrial parks. Due to uneven performances of planning and governmental intervention in different countries with some successful cases in East Asia and failed cases in North America, studies on exploring the key factors contributing to the success and failure of industrial symbiosis are still needed. Planning for regional recycling through industrial symbiosis and design of promotion policies are rarely discussed. Theoretically, the mechanisms and factors that determine appropriate recycling boundaries of different types of wastes are still unclear. More theoretical studies are needed.

1.2 Goal, Objectives and Originalities

The problems and proposed solutions discussed in the preceding section are summarized in Figure 1.3. A core research question is what mechanism and factors determine a proper boundary of regional recycling through industrial symbiosis? There are two approaches in research, among others, to explore answers to this question (Figure 1.3). First, *empirical studies* can be conducted to summarize the general pattern from observations. "The adjective empirical, in its combinations with various nouns, appears to denote observations and propositions primarily based on sense experience and/or derived from such experience by methods of inductive logic, including mathematics and statistics (p.237). … 'Empirical research' excludes knowledge obtained by consulting authorities, i.e. books or in person. It includes only knowledge obtained from data resulting from first-hand observations, either by you or by someone else (p.6)" (Simon, 1978 cited in Aquino, 2000, pp. 85-86). In this research, both first-hand survey data and statistical data are used in empirical studies.

Second, *case studies* can provide an in-depth analysis to test and extract key factors for answering the research question. "Case connotes a spatially delimited phenomenon (a unit) observed at a single point in time or over some period of time. It comprises the type of phenomenon that an inference attempts to explain. Thus, in a study that attempts to elucidate certain features of nation-state, cases are comprised of nation-states (across some temporal frame); in a study that attempts to explain the behavior of individuals, cases are comprised of individuals, and so forth. …A case study may be understood as the intensive study of a single case where the purpose of that study is – at least in part – to shed light on a larger class of cases (a population)" (Gerring, 2007, pp. 19-20). In this research, the object of research is regional recycling network, so a case study on the Tokyo Metropolitan Region of Japan is conducted. In order to explore key determinants for recycling boundary, modeling is applied on the study region to test the impacts of various factors. After answering the research question, its practical meaning, the policy implications, are discussed.

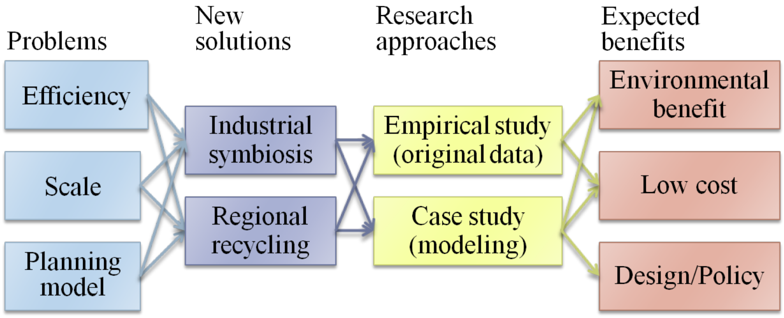


Figure 1.3 Research framework

These two approaches form the goal of this dissertation: To quantitatively explore the mechanism and factors that determine the proper boundary of regional recycling through industrial symbiosis by both empirical studies and a case study on recycling of waste plastics in the Tokyo Metropolitan Region (TMR) in Japan.

Towards this goal, this dissertation has the following three objectives:

- To identify features of existing recycling facilities in different scales and types in Japan;
- To develop models for optimizing the number, capacity, and locations of regional recycling centers (RRCs) and assessing the environmental benefits and eco-efficiency of regional recycling through industrial symbiosis; and
- To design regional recycling networks with multiple layers for different types of wastes according to their properties and promotion policies.

This dissertation includes original contributions in the following areas:

- Data originality: analyzing first-hand survey data obtained from recycling facilities to identify the relationships between features of recycling facilities (recycling boundary, scale, and type of waste treated) and their performances (virgin material saving and operating rate);
- Model modification and application: taking into account in optimization models economies of scale and industrial symbiosis for locating RRCs and their service areas;
- Theoretical finding: revealing the mechanism and key factors that determine appropriate recycling boundaries according to properties of wastes; and
- Proposal: proposing a design of regional recycling network with multiple layers for different types of wastes and promoting policies.

1.3 Dissertation Structure

Employing both empirical and case study approaches, this dissertation is organized as shown in Figure 1.4. Following Chapter 1 of introduction, Chapter 2 reviews relevant literature to identify research gaps and solidify the theoretical foundation of this study. Because topics concerning recycling have long been regarded as a part of waste management in both practice and research, Chapter 2 begins with a brief review on how waste management has been evolved in the recent history. It then reviews models often employed in waste planning and management to identify the gaps in research for improving the efficiency of recycling, establishing regional recycling networks, and planning models for promoting regional recycling through industrial symbiosis. To resolve these issues requires knowledge beyond the scope of conventional waste management and planning. As propositions, studies related to industrial symbiosis, regional recycling, and socio-technical transition for policy-making are reviewed.

Chapter 3 introduces empirical studies on recycling activities in Japan. With its achievements in recycling and high accessibilities to relevant data, Japan offers a precious opportunity for empirical study on recycling. Chapter 3 first examines the relationships among projects' features (waste type, recycling boundary, and facility scale) and their performances (virgin material saving and operating rate), analyzing first hand survey data acquired from recycling facilities in eco-towns. Next, it zooms out to the national level, examining the spatial distribution and clustering of waste generation, incineration, separate collection, and recycling processing. The empirical findings help to justify the theory that transportation costs and facility scale are important for the formation of spatial pattern of recycling network.

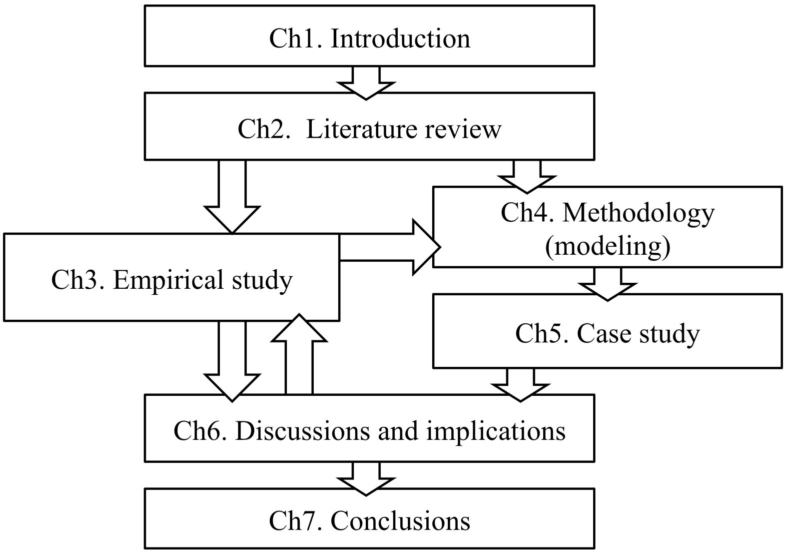


Figure 1.4 Contents and structure of the dissertation

Chapters 4 and 5 present the case study on recycling of waste plastics in the TMR of Japan. Chapter 4 introduces general methodologies in terms of a planning model, scenario design, modification of an optimization model to count economies of scale when determining number, capacity, and location of RRCs, and an LCA model for assessing environmental benefits of regional recycling networks. Chapter 5 details out the background of the case study region, model parameters, results, and theoretical discussions. The modeling aims not only at finding optimal solutions for the case study, but also at generalizing the results to other types of wastes and other regions. To do so, scenarios are designed to test various factors to identify key factors by comparing the results from all scenarios.

Discussions about generalization of findings and policies implications are elaborated in Chapter 6. By generalizing results from the case study, proper recycling boundaries for different types of wastes can be estimated. Such a theoretical deduction is verified by the empirical findings in Chapter 3. The findings lead to a design of regional recycling networks with multiple layers for different types of wastes. To establish such a regional recycling network requires coordinated efforts of various stakeholders. Comprehensive policies are discussed based on a model of socio-technical transition management. Finally, Chapter 7 draws conclusions on the major findings, contributions to literature and practices, and future studies.

Reference

Aquino, G. (2000). *Educational Management: Principles, Functions, and Concepts*: Rex Bookstore, Inc.

Geng, Y., Fujita, T., & Chen, X. (2010). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production, 18*(10-11), 993-1000.

Gerring, J. (2007). *Case Study Research: Principles and Practices*. New York, NY, USA: Cambridge University Press.

Hashimoto, S., Fujita, T., Geng, Y., & Nagasawa, E. (2010). Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki. *Resources, Conservation and Recycling, 54*(10), 704-710.

Hayashi, Y. (2010). Can We Design the Future of Human Life and the Environment? In Y. Hayashi, R. Tabuchi, S. Iwamatsu & M. Morisugi (Eds.), *Sustainability: Future Balance between Nature and Civilization* (pp. 16-26). Tokyo, Japan: Akashi Shoten.

Huppes, G., & Ishikawa, M. (2005). Eco-efficiency and its terminology. *Journal of Industrial Ecology, 9*(4), 43-46.

JCPRA (The Japan Containers and Packaging Recycling Association). (2007). *The Environmental Impacts of Plastic Containers and Packaging Recycling (in Japanese)*. Tokyo, Japan: JCPRA.

MOE. (2010). Annual Report on the Environment and the Sound Material-Cycle Society in Japan 2010 [Electronic Version]. Retrieved Oct., 2011, from http://www.env.go.jp/en/wpaper/

van Berkel, R., Fujita, T., Hashimoto, S., & Fujii, M. (2009). Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. *Environmental Science & Technology, 43*(5), 1271-1281.

Chapter 2 Literature Review on Municipal Waste Management and on Propositions for Improving Recycling Efficiency

The way by which people dealt with wastes has caused various problems in the recent history. Prior to discussing industrial symbiosis and regional recycling, this chapter begins with a brief review on the history of waste management, which serves to provide the background in terms of problems and solutions in the past, and to identify the challenges to further improvement of recycling. It then reviews the models which researchers and planners usually employ to resolve waste problems. By such a review, issues and challenges that have not been sufficiently addressed could be identified. This chapter finally proposes three propositions for resolving these issues and challenges. Recent progress in research related to these propositions is reviewed.

2.1 Historical Review: Paradigm Shifts in Waste Management

Sloping and open dumping (prior to the 20th century)

Waste is an inevitable by-product of human lives and activities. The earliest record of organized "municipal dump" for refuse and the first known edict against littering streets dated back to 500 BC in Greek (Louis, 2004). In most European and colonial American cities, dumping on farmland and rivers, animals slopping in the streets and scavenging dominated until well into the 19th century (Rathje, 1992). Rapid industrialization and urbanization resulted in excessive emission of wastes in cities. In most time of the 19th century, the "anti-contagionist theory", also known as the "filth theory", dominated in explaining the cause of epidemics. This theory believed that diseases were caused by decaying organics, sewer gas and other offensive odors, or "misasmas", and could not be transmitted between humans (Louis, 2004; Tarr, 1985). For preventing epidemic diseases, the UK initiated the Sanitary Movement to cleanse the cities in the 19th century for a healthy living environment (Tarr, 1985). In major US cities, either local governments or hired private companies also started to provide waste collection and disposal services such as dumping or mass burn (Louis, 2004). Since these services were for better human health, state or local Boards of Health in most cases were responsible for managing wastes at this time (Louis, 2004; Tarr, 1985).

In Japan, due to limited availability of land and relatively rapid development in the Edo period (1603-1868), managing wastes became an important issue. In Kyoto, dumping in rivers and ditches polluted driving water sources and impeded waterway transportation. In 1649, the *Bakufu* (a tent government run under a commander, or a *Shogun* in Japanese) banned dumping waste on open spaces known as Kaisyochi (Mikami, 2003). The designation of dumping sites appeared as early as in 1655 in *Fukagawa Eitai-Ura* (Matsutou, 2007). Waste collection and hauling services were provided in 1662 (Mikami, 2003). In addition, wastes were considered material for reclaiming land from shallow shores (Matsutou, 2007; Mikami, 2003).

Engineering-based landfill and incineration (1900s – 1960s)

After entering the 20th century, the germ theory replaced the filth theory in explaining the cause of diseases. With the development in bacteriology, the responsibility of managing wastes gradually shifted from health departments to sanitation departments (Louis, 2004). From the 1920s to the 1960s, waste management was strongly engineering-based, emphasized on record keeping, applying motorized equipments in collection, and managed landfill and incineration in the US. Landfill, the cheapest disposal method, became the most widely adopted method in this period of time (Rathje et al., 1992). Incineration was also developed as an effective method for volume reduction. In places where land is scarce such as the Northeast of the US, incineration has become, and still are, popular (Louis, 2004). However, incineration has not been a perfect solution of waste problems: It requested heavy capital investment, and small incinerators failed to meet the strengthening air quality standards and resulted in strong public opposition, known as the not-in-my-back-yard (NIMBY) syndrome (Louis, 2004; Tarr, 1985).

In a similar trajectory, waste in Japan in this period was managed for the purpose of better public health and treated mainly by landfill and incineration. The Refuse Cleansing Act was in 1900 partially for preventing epidemics (Ishii, 1997). In 1897, the first waste incinerator was installed in Tsuruga-shi, Fukui Prefecture. Incinerators were first built in western Japan and gradually seen in Tokyo area by the late 1920s (Matsutou, 2007). By 1970, over 60% municipal solid waste was treated by incineration in Japan (Matsutou, 2007). However, similar to the NIMBY syndrome in western countries, public opposition to incineration was also reported in 1933 (Ishii, 1997).

Recycling and recovery (1970s – 1990s)

Another shift in people's attitude towards waste management emerged in the 1970s at which time the focus gradually moved to recycling and energy recovery rather than simply dumping or burning municipal wastes. Recycling had been long practiced prior to this period of time. The first recycling center in the US was established in 1898 in New York City (Louis, 2004). During the World War II, recycling prevailed in the US, led by the War Production Board (Louis, 2004). However, recycling did not receive consistent attention in the US until the 1970s after the passage of Resource Recovery Act in 1970 and Resource Conservation and Recovery Act (RCRA) in 1976. The original intents of RCRA aimed to increase solid waste disposal capacity by utilizing waste-to-energy facilities, to close open dumps and establish disposal standards, and make recycling and source reduction more competitive because of higher disposal costs (Kovacs, 1993). At the same time, the proportion of recyclable paper and other low density packaging materials increased in the garbage stream (Louis, 2004). Recycling also became an approach to release the political pressure raised by waste managed. As growing public opposition against locating new landfills and incinerators, waste management literally became a "political crisis" in the US. By the early 1990s, over 2000 bills were introduced every year by state legislatures and every state had a solid waste management program and an office of recycling (Kovacs, 1993).

Recycling and reuse in Japan had a long history. In the Edo period, there were specialized merchants and mechanics recycling and repairing used products, such as cooking pans and knifes, candle stands, and ceramics (Mikami, 2003). Specialized recycling workshops were commonly seen in

Tokyo in the late 19th century (Matsutou, 2007). These practices were basically market based, recycling and repairing products that had demands in the market. Current style of source separation and separated collection were first conducted in Numatsu-shi, Shizuoka Prefecture in 1975, developing from 3 categories and as many as 15 categories (Ishii, 1997). The first piece of legislation on recycling in Japan was enacted in 1991, and in the following decade, specific recycling laws on containers and packaging, construction and demolition wastes, end-of-life vehicles, food waste, and home appliances were issued respectively (Ishii, 1997; van Berkel et al., 2009b).

Integrated waste management (since the mid-1990s)

A recent shift in waste management emerged in the mid-1990s, placing more emphases on an integrated approach in waste management, i.e. simultaneously managing wastes in various media (air, liquid, and solid), using various methods (reduction, reuse, recycling, recovery, and disposal) and management instruments (regulatory, economic, and informational), and with collaboration among multiple stakeholders (governments, the private sectors, professionals and planners, and the public) (Clarke et al., 1999; Guerini et al., 2006; Seadon, 2006). Waste management extended from simply managing "waste" to managing the whole process from product design to consumption and then to final disposal and inevitably became an interdisciplinary filed. Innovative recycling activities received more attention, such as industrial and urban symbiosis, namely exchanging wastes among firms as well as adjacent urban areas (Chertow, 2007; van Berkel et al., 2009b). Drivers for waste reduction, reuse, recycling and safe disposal became more diversified than ever before (Figure 2.1). As Tanaka (1998) noted that it had been recognized since the 1980s that "mass-production and mass-disposal society caused various environmental problems such as depletion of forest and mineral resources, global warming and acidic rain, damage of the ozone layer, and pollution of oceans, and that waste management would contribute significantly to sustainable development (p.10)." , The pressures that used to drive the transitions in waste management remained. For example, the impact on public health continued to receive great attention. Wastes that contain hazardous materials, such as WEEE, automobile, and medical waste, were required for special treatment and disposal (Achillas et al., 2010; K. C. Chen et al., 2010a; Jang et al., 2006). The shortage of disposal capacity, especially landfilling capacity, continued to be a major driver for volume reduction and waste diversion from landfill (Bai & Sutanto, 2002; Geng et al., 2010; Jin et al., 2006). In spite of the progress in technologies and strengthening of environmental standards, NIMBY syndrome and political pressure remained unsolved. For example, due to insufficient public participation in the planning stage, siting new landfills in Ontario, Canada appeared to be difficult and exporting waste to Michigan, the US for landfilling caused political attention of the two countries (Hostovsky, 2006). In Beijing, China, public opposition resulted in a cancelation of constructing a new incineration plant in 2007 (SEPA, 2007).

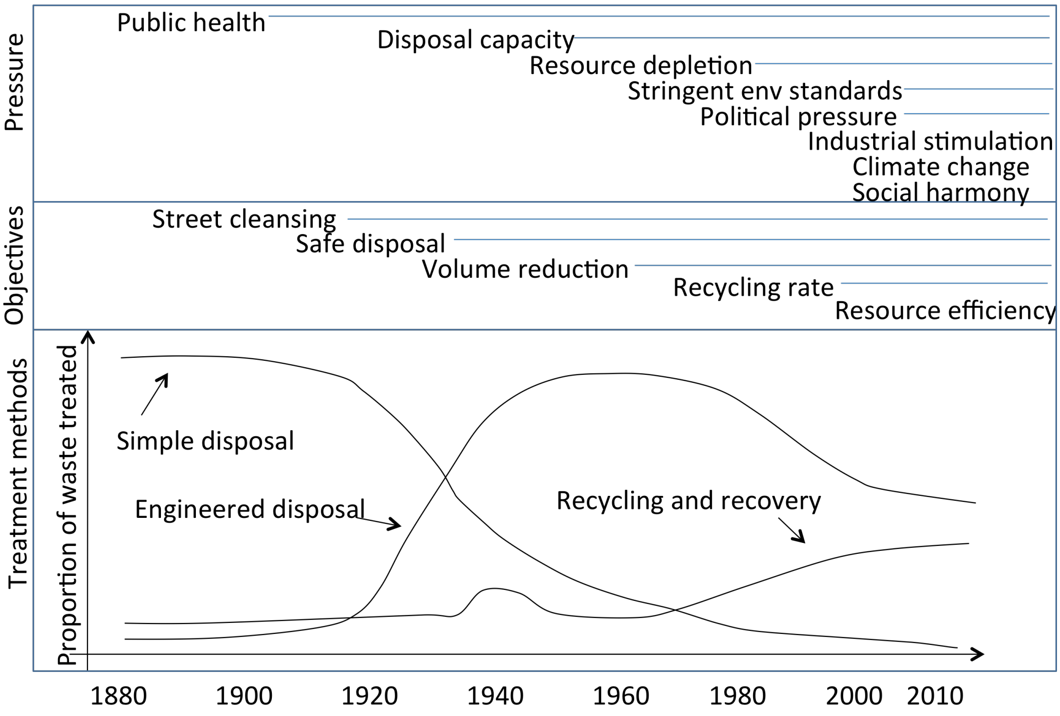


Figure 2.1 Treatment methods, objectives, and pressures during the paradigm shifts in municipal solid waste management

Source: summarized by the author based on literature review.

In addition, pressures due to present environmental and economic problems emerged rapidly in recent years and became new contributors to further waste reduction, reuse and recycling. Resource depletion encourages recycling scarce materials from wastes (e.g. rare metals), or urban mining, i.e.

recycling resources from urban stock (Klinglmair & Fellner, 2010; Ongondo et al., 2011). As the development of recycling market created new business opportunities, economic drivers came into sight. For example, eco-industrial development, including encouraging industrial symbiosis and the development of eco-industrial parks, in the US was originally considered an economic development strategy (Deppe et al., 2000). The eco-town program in Japan had a dual objective of solving waste management problems and stimulating industrial development (van Berkel et al., 2009b). In China, circular economy, whose core was reduction, reuse, and recycling, appeared to be a strategy for sustainable development of economy and society (Yuan et al., 2006). Recently, climate change mitigation affected decisions on a wide range of environmental and economic activities. Waste management was not an exemption. Cleary (2009) reviewed 20 life cycle assessment (LCA) studies on waste management recently published in English-language peer-reviewed journals and found that 19 studies assessed global warming potential (i.e. anthropogenic greenhouse gas (GHG) emissions) in their studies. Practically, carbon credits provided incentives for waste disposals that reduce GHG emissions in comparison with conventional practices. For example, as of Feb 24, 2011, out of 2845 project registered to the clean development mechanism (CDM), 516 (18%) were waste handling and disposal projects, which was the second largest category following the energy industry[1].

By reviewing the history of waste management, three points are worth noticing as they need to be addressed in current waste management and planning. First, waste problems were chronologically parallel to urbanization. Similarly to many other environmental problems, a main cause of waste problems is urban development. Waste problems first received great attention in the 19th century in large cities. During that time, megalopolis started emerging due to industrialization (Figure 2.2). Recent cases also shows that population and economic growth appear to be two major contributors of increase in waste generation (X. Chen et al., 2010b; Wang & Nie, 2001). These environmental problems in turn hindered further development of cities. They threatened public health and constrained supplies of clean water and resources that are indispensable for urban activities.

---

[1] Referring to http://cdm.unfccc.int/Projects/projsearch.html

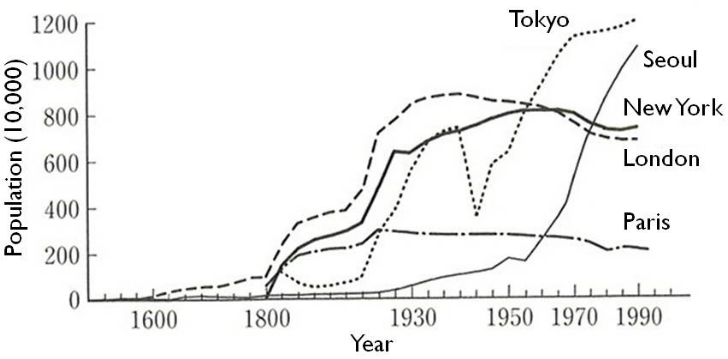


Figure 2.2 Population growth in megalopolis
Source: (Lee, 1998) cited in (Takeuchi & Hayashi, 1998, p. 5)

The second point that needs to be addressed is the waste treatment technologies evolve together with the social system. Major changes corresponded to the application of new waste disposal and treatment technologies, as well as changes in people's attitudes towards waste management, the drivers to the evolution of waste management systems, and the objectives of waste management (Figure 2.1). In other words, waste management is embedded in a complex social context and involves complex interactions among stakeholders. The processes of transitions in waste management are rather slow. No one party is likely competent to initiate such transitions unless the external conditions have created the context ready for transition. Therefore, planning for waste programs needs to consider the whole system and the mechanisms of such transitions and then to design necessary instruments towards to desired objectives.

Third, waste management system has become comprehensive as embedded in complex social, environmental, and economic context of our society. Since waste management has been driven by various environmental, economic and political factors, simply diverting wastes from landfills and increasing recycling rates could no longer be sufficient responses. Effective responses require efficient utilization of wastes as resources to fulfill multiple purposes, i.e. seeking co-benefits of waste management (Chen et al., 2011c). Admittedly, different regions may have different priorities due to specific local conditions. In spite of the differences, it is the common goal to improve the efficiency of processing and utilization of recyclable wastes for more environmental and economic benefits .

2.2 Recent Models for Waste Planning

Waste planning typically deals with the processes of facility siting, selection of appropriate treatment methods, waste management program design and evaluation, policy making. Various models have been developed and applied in waste planning. Have these model sufficiently addressed the current challenges to waste management and planning? This section briefly reviews major planning, economic and marketing models of waste planning and identifies the needs for further research.

2.2.1 Planning Models

Hostovsky (2000) summarized five types of planning models applied in waste planning since the 1970s: rational comprehensive model (RCM), participatory model, advocacy model, incremental model, and adaptive model. The RCM was a major model employed by planners in waste planning, partly because the model had been the predominant model in land use planning (Hostovsky, 2000; Seasons, 2003). In waste planning, RCM focuses on optimizing facility siting (e.g. Albakri et al., 1988; Chang & Davila, 2007; Frantzis, 1993) and treatment methods (e.g. Powell, 1996; Zhao et al., 2009). Evaluation and optimization follow a 'top-down' approach and rely heavily on quantitative methods and rational processes. The criteria for evaluation could be comprehensive, including environmental, social, and economic aspects.

The second planning model is the participatory model. As opposed to RCM, the public is incorporated into the decision making process, ideally in the early stages, to make plans through dispute resolution, mediation, and negotiation (Hostovsky, 2000; Rowe, 1992). In the participatory process, information is shared with the public, and, ideally, decisions are made collectively. An example of substantial public participation in waste planning is the "willing host" siting process. Instead of proposing optimal locations, whichever community is willing to be the host of treatment and disposal facilities will become the candidate for the host and will recieve financial compensations. The plan for a hazardous waste treatment facility in Alberta demonstrated that by the willing-host siting process, “a strong connection was made between the scientific and cultural aspects (McQuaidcook & Simons, 1989, p. 220).”

The third planning model is referred to as the advocacy model. The advocacy model proposes that planning should be congruent with clients’ values and goals, and the outcome is the “survival of the fittest” (Hostovsky, 2000). In waste management and planning, a wide range of values and goals of particular stakeholders have been advocated. For example, Lang (1990) argued for social equity; Kovacs (1993, p. 113), who supported waste industries, suggested that “political leadership is urgently needed to ensure increased disposal capacity, … notwithstanding the objections of the NIMBYists”; Burkart (1994) argued that waste planning should divert attention to public relations, and the NIMBY syndrome could be solved by communication; and Robert (2004) discussed the important role of environmental industries and suggested promoting them by new attitudes and practices, and financial incentives.

The fourth planning model is the incremental model. It is highly political and focuses on crisis management and responses to fragmented environmental regulations (Hostovsky, 2000). Reviewing the history of municipal solid waste and hazardous waste disposal in the US, Tarr (1985) found that research on contaminations caused by solid waste disposal, as a result of public policy, often developed only after the occurrence of crises. Changes in waste managment also are often correlated with the introduction of environmental regulations. For example, legislation in the 1960s and 1970s inspired state government activities, and resulted in new attitudes towards waste management and increasing waste diversion rates (Tarr, 1985).

The final type of model reviewed in this section is the adaptive model. The adaptive model is usually anticipatory and relies heavily on mathematic modeling and computerized techniques (Hostovsky, 2000). A variety of decision making and evaluation models are in this category. Widely cited decision-making models include integer linear programming (Abou Najm et al., 2002a, 2002b), the artificial intelligence system (Cortes et al., 2000), the multiple mixed integer programming model (Chang & Wang, 1996), geographic information system integrated with multi-objective programming

(Chang et al., 1997), and the gray integer-programming (Huang et al., 1997). Some new models were developed based on a combination of multiple models to simulate more complicated situations (Li et al., 2007; Nie et al., 2007). Common evaluation models include modified input-out analysis (Huang et al., 1994), economic evaluation models such as cost-benefit analysis and life cycle costing (Reich, 2005), and life cycle analysis for evaluating different treatment technologies in various secenarios (Finnveden, 1999; Thomas & McDougall, 2005) .

2.2.2 Economic Models

In economic models, waste services are regarded as a result of equilibrium between market supply and demand. Waste services, similar to other commodities and services, should be accordingly priced. Porter (2002) argued that excessive waste generation is caused by under- or un-priced collection and disposal services. In theory, the amount of waste generated, as a by-product of consumption, is determined when the marginal utility (MU) of consuming certain goods is equal to the marginal private cost (MPC) of consuming such goods. The MPC is the sum of the price of both goods and waste services (Choe & Fraser, 1998). If waste services are under- or un-priced, then the MPC decreases and thus the amount of waste generated increases (Figure 2.3). In practice, among the most common financial tools to reduce garbage generation is unit-based pricing of services (by purchasing special bags or stickers for collection, or subscribing to a specific cart volume). Case studies in the US have shown that the introduction of unit-based pricing reduces waste disposal and increases diversion (Miranda & Aldy, 1998). Various empirical studies have estimated the price elasticity of waste services in a wide range from 0 to 0.77 (summarized in Morris & Holthausen, 1994). These results showed a statistically significant effect of service price on the amount of waste generated, but the wide range also indicated that “the context, including the availability and cost of alternative disposal options, is important to community response to changes in price and the estimation of any welfare effects associated with changing conditions of service and price (Morris & Holthausen, 1994).”

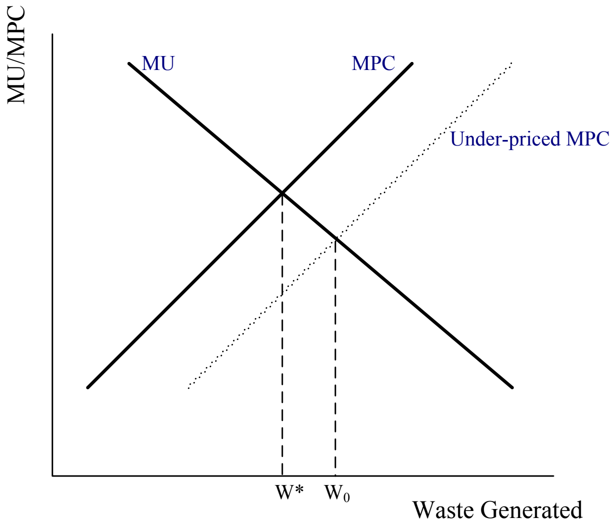


Figure 2.3 Service Price and Waste Generation

Source: by author.

Another common tool is taxation such as waste tax or virgin material tax to prevent waste from being generated at early stages (Bruvoll, 1998; Hagelstam, 2001). Similar to taxes are subsidies. For example, subsidies for advanced recycling technologies in Japanese eco-town projects encouraged application and accumulation of such technologies (Fujita, 2006). Subsidies on products that use recycled materials can encourage green purchase and recycling (Anex, 1995). Other financial tools include user fees, deposit-refunds, and advance disposal fees (Ferrara & Missios, 2005; Palmer et al., 2003; Shinkuma, 2003).

2.2.3 Marketing Models

If waste recycling programs are regarded as services, then promoting such programs is to market the services to the customers, i.e., residents. Shrum et al (1994) proposed a framework to analyze recycling services as a marketing problem and explored four aspects for research: consumer, pricing, distribution, and promotion and communication. These four aspects are consistent with the four Cs (consumer, cost, channel, and communication) (Lauterborn, 1990) or the four Ps (product, price, place, and promotion) in the marketing mix applied for general products and services marketing (McCarthy & Shapiro, 1983).

Consumer research focuses on socio-demographics and psychographics. Equivocal evidence made demographics a poor predictor for waste separation behaviors (Barr, 2004; Shrum et al., 1994). Attitudes towards the environment or environmental values are widely stated as a major factor influencing the participation in recycling programs (Barr, 2004; Qu, 2007; Shrum et al., 1994; Taylor & Todd, 1995). Some motives are intrinsic, e.g., ecological self realization and selfish environmental value (Meneses et al., 2005; Qu, 2007). Other motives are extrinsic. Taylor and Todd (1995) and Chan (1998) demonstrated both perceived behavior control and subject norms exerted influences on the participation in recycling programs. Social norm is also an important factor: Recycling behaviour could be encouraged by friends' and neighbours' recycling behaviours (Hopper & Nielsen, 1991; Oskamp et al., 1991). Other factors include environmental knowledge and involvement (Gamba & Oskamp, 1994; Meneses et al., 2005; Qu et al., 2007; Vining & Ebreo, 1990) and environmental citizenship (Selman, 1996 in Barr, 2004).

Pricing research focuses on the major cost of participation in waste diversion programs, which mainly is economic disincentives or taxes that are, as discussed previously, directly related to economic tools. Distribution research touches upon the channel and the entities of service delivery and the distance and frequency of service access (Goldsby, 1998). It examines the convenience of waste diversion programs. Pieters (1991 in Goldsby, 1998) proposed three "convenience strategies": closer proximity, higher availability, and minimal complexity in sorting and storage for consumers. Finally, research on communication and promotion studies approaches of promoting recycling programs to residents. Publicity was identified as an influencing factor for household waste management behavior (Qu et al., 2007). A communication campaign in the UK, *recycling2go*, was found to contribute to the increase in the curbside recycling rate from 9.7% to nearly 50% in two years (Mee et al., 2004). The authors also found marketing and communication activities had encouraged about 75% of the residents to recycle more. Another study in the UK revealed that a useful tool for promoting recycling programs was door-to-door communication which, compared with flyers and news paper advertisements, could increase public concern in a shorter period of time (Read, 1999).

2.2.4 Summary of Review on Waste Planning Models

A summary of waste planning models is shown in Table 2.2. These models are employed for assisting decision-making in waste management and planning at both the strategic and operational levels. Strategic planning determines types of treatment facilities (i.e. treatment technologies), location and scale of these facilities; while operational planning designs the format of daily services, such as frequency of collection, transportation and routing, responsibilities of crews (Barros et al., 1998). The participatory planning model, economic models, and marketing models can be employed for operational planning and management. Studies applying these models pay particular attention on providing better services, improving recycling rates and reducing waste generation. Because such studies mostly focus on the operational level, they rarely address how source separated wastes could be treated more efficiently. Moreover, operational planning is mostly for waste management issues at the local level since waste service as a public service is usually provided to each household by municipalities or contracted companies.

Table 2.1 Summary of waste planning models reviewed

Model	Major Issues	Features
RCM	Facility siting, treatment methods	"Top-down" approach, rely on quantitative methods
Participatory	Public participation, 'willing host'	Participatory, collective decision making
Advocacy	Social equity, tax policy, environmental industry	Congruent with concerned clients
Incremental	Legislation, public policy	Response to crises, policy-driven
Adaptive	Treatment method, virgin material substitution, energy recovery, transportation, uncertainty	Optimized by mathematical and computer based model,
Economic	Service fee, waste tax, virgin material tax, subsidy, waste diversion, disposal	Aiming to internalize externalities associate with waste and encouraging waste reduction and diversion by economic incentives
Marketing	Social norm, knowledge, experience, cost, convenience, education, communication, promotion	Waste diversion and reduction programs as services marketed to consumers

RCM, adaptive, and incremental models are more suitable for strategic waste planning. RCM emphasizes more on the rational process of preparing plans; incremental models focus more on policies and regulations; and adaptive models are more proactive to future challenges. It should be noted that application of these models are not exclusive from one another in real planning projects. Different models can be applied for different purposes, complementing one another.

One of the shortcomings of these models, however, is that their focus is exclusively on managing waste, which limits the scope to search for more efficient ways by which wastes can be used as resources. In recycling, wastes are treated and ultimately utilized by industries, which can create new value of the materials once discarded by the previous owners. The shorter the treatment process, and the more industrial processes considered, especially those that demand for a large amount of energy and materials, the higher possibility that new value of discarded materials could be discovered. For example, mixed paper and plastics, such as courier envelopes, can hardly be recycled by mechanical processes for recovering paper or plastic resin and usually end up being incinerated. Options of recycling such wastes exist, such as shaping them into refuse plastics and paper fuel (RPF) to substitute fossil fuels if facilities such as paper mills or cement kilns are willing to accept them. Industrial activities typically are not in the scope of waste planning models. Therefore, these models can not sufficiently explore the opportunities fostered in the production stage.

Another shortcoming of these models is that their focus is mainly at the municipal level, because in most countries it is the municipal government who takes the responsibility for waste disposal and recycling. Although there are some theoretical proposals on recycling at the regional level, waste planning models, especially quantitative models, are rarely applied in planning for recycling networks in the regional level. Waste planning needs to be conducted at the regional level, because industrial facilities are usually agglomerated in industrial centers, whereas wastes are generated from spatially diffuse municipalities. How to resolve this spatial mismatch is a key object in planning for recycling of municipal solid waste through IS.

Industrial symbiosis and regional recycling are proposed to overcome these shortcomings. In the remainder of this chapter, research progress in these two fields is reviewed in order to understand the existing knowledge and to form the theoretical foundation of this research. In addition, designing policies for promoting recycling goes beyond the realm of conventional waste management and municipal boundary is a challenging work. It involves a transition in current socio-technological regime, including policies and regulations, cognitive routines of waste management, and attitude towards recycling to view "discards" as "resources" in industrial production. Therefore, socio-technological transition models are reviewed for guiding the discussion on policy recommendations.

2.3 Proposition 1: Utilizing Wastes as Resources in Industrial Facilities

From a system perspective, recycling concerns closing the material cycle in an urban system. Research on optimizing the material flow in a system has been the focus of industrial ecology (IE), a burgeoning field in the last two decades. With its system view on material cycles, IE influences a wide range of issues concerning environmental management, economic development, and planning (Deppe et al., 2000; Graedel & Allenby, 2010; Jouni et al., 2004; Korhonen, 2004; Korhonen et al., 2004). Among the topics discussed in IE, industrial symbiosis (IS) is one of the practical measures to achieve loop-closing of the materials cycle. Chertow (2000) defined industrial symbiosis as the activity that "engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (pp. 313)." As an extension for IS, van Berkel et al. (2009b) proposed another term, urban symbiosis (UrS), referring to "the use of by-products (wastes) from cities (or urban areas) as alternative raw materials or energy source in industrial operations (pp.1545)." IS and UrS can be considered a series of innovative recycling activities. While recycling of industrial and municipal solid wastes have been practiced for a long time, IS recognizes the exchanges of wastes and by-products between firms that conventionally do not exchange them, and UrS recognizes the use of municipal solid waste as inputs to industries that conventionally do not accept it. In other words, wastes are recycled as resources in industrial facilities. Because UrS is an extension of IS, this dissertation hereafter does not distinguish these two terms for the sake of simplification, and refers to them as IS.

IS can offer apparent benefits to the environment and companies in terms of saving virgin materials and reducing waste emissions and costs by utilizing wastes and by-products and cascading use of energy and water. Detailed case studies can be found in the literature on Kalundborg, Denmark (Jacobsen, 2006), Rotterdam Harbour and Industrial Complex, The Netherlands (Baas & Boons, 2007), United Kingdom (Harris & Pritchard, 2004; Mirata, 2004), Kwinana and Gladstone, Australia (van Beers et al., 2007), Puerto Rico, USA (Chertow & Lombardi, 2005), and Guigang, China (Fang et al., 2006). Some results of quantitative evaluations are given in Table 2.2. Examples of recycling MSW through IS include recycling waste plastics in iron and steel plants as feedstock in coke ovens and blast furnaces. Waste plastics can also be treated to replace coal as fuel in kilns for cement production, and be gasified to produce hydrogen as feedstock for ammonia production (JCPRA, 2007). These industrial facilities are usually more efficient than waste treatment facilities. Converting the efficiency into equivalent power generation efficiency in terms of effective use of the potential heat value of waste plastics, Fujii et al. (2010) showed that the efficiencies of plastic recycling in these industrial facilities are relatively high (Figure 2.4). If waste plastics are incinerated, the energy recovery efficiency is usually around 10%.

Because of the potential of environmental benefits and industrial competitiveness by utilizing wastes in industrial facilities, a number of countries launched programs in the past two decades to foster Eco-Industrial Parks (EIPs) with IS/UrS being one of their features (Chertow, 2007; Chiu & Geng, 2004; Costa et al., 2010; Geng et al., 2007; Gibbs & Deutz, 2007; Shi et al., 2010; van Berkel et al., 2009b). This concept can be and should be considered carefully when planning for recycling of municipal solid waste.

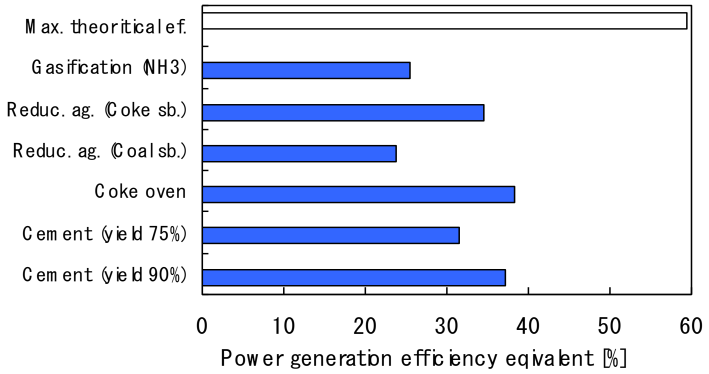


Figure 2.4 Efficiency of waste plastic recycling in industrial facilities

Source: (Fujii et al., 2010).

Table 2.2 Major environmental benefits documented in literature

Case studied	Environmental benefit	Quantity	Note	Reference
Kawasaki	Landfill avoidance	565 kt/yr	Five by-product exchanges and two recycling industries	(van Berkel et al., 2009a)
	Raw material saving	490 kt/yr		
Guayama	Reduction in SO_2	1978 t/yr	Exchange of steam	(Chertow & Lombardi, 2005)
	Reduction in NO_x	211 t/yr		
	Reduction in PM_{10}	123 t/yr		
	Reduction in CO	-15 t/yr		
	Reduction in CO_2	51000 t/yr		
Kalundborg	Conservation of surface water	500,000 m^3/yr	Using cooling water for steam production	(Jacobsen, 2006)
	Reduction in CO_2	154788 t/yr	Steam and heat cogeneration	
	Reduction in SO_2	-304 t/yr		
	Reduction in NOx	389 t/yr		

2.4 Proposition 2: Expending Recycling Network to the Regional Scale

In order to take advantage of existing industrial facilities, the recycling network needs to be planned at the regional level because waste generation is spatially diffuse but industrial facilities, especially energy intensive industries, are located at a limited number of industrial centers. Spatial boundary is one of the influencing factors of IS discussed in the literature. Geographical proximity offers opportunities for IS, especially for exchanges of materials that are not suitable for long distance transportation, such as steam (i.e. energy) and water. Recycling of other materials suitable for transportation can be, in fact some are already being, operated in a larger scale. Because wastes are materially heterogeneous and spatially diffuse, certain minimum thresholds are necessary for viable recycling businesses (Lyons, 2007). A large scale is usually associated with relatively a large recycling boundary that could be benefited from increasing supply and demand, greater economic of scale, and easier and greater supply of secondary raw materials etc, as observed in Rhine-Neckar region, Germany (Sterr & Ott, 2004). Regional scale is argued to be a proper scale for IS (Desrochers, 2002; Sterr & Ott, 2004). Theoretically, with increasing geographical scale, the "problem-solving competence" in terms of the diversity of wastes increases, whereas the degree of "societal control" over and "personal affectedness" of ecologically unfavorable behavior decreases. The medium regional scale thus becomes a "promising host for eco-industrial developments" (Sterr & Ott, 2004). Historically, evidence has also been found to bear the argument that by-product exchanges among firms have long been practiced in the regional scale (Desrochers, 2002). However, having found exchanges taking place in the regional scale does not mean that it is necessary to be organized only at the regional level for all types of wastes. Lyons (2007) also argued that there is no preferable geographical scale for recycling and remanufacturing. The recycling boundary varies for different types of waste and is rather dependent on the demand side in terms of where the recycled products are utilized (Lyons, 2007).

In Japan, national policies have already articulated regional recycling. For example, the 2nd Fundamental Plan for Establishing a Sound Material-Cycle Society already recognizes the need for regional recycling, as establishing sound-material cycle "blocks". The Plan also noted that "the scale of the cycles for different CRs [circulative resources] must necessarily differ depending on the individual characteristics of these CRs (MOE, 2008)." Researchers have also paid attention on the proper scale of waste treatment and recycling. Yasuda (1998) argued that waste treatment planned in the regional scale could offer several benefits: (1) improving recycling, (2) reducing emissions of dioxin gases due to stable incineration in a large scale, (3) reducing CO_2 emissions by heat recovery, and (4) reducing public expenses on waste management. Ueda (2000) pointed out that establishing a sound material-cycle society should recognize that recyclable wastes were generated from a large region and policy-making should consider proper scales of recycling. He further explained that regional recycling could enjoy the scale merits and facilitate the introduction of advanced recycling technologies; however, expanding recycling boundary would increase in transportation costs. So promoting regional recycling should take into account both technologies and social systems.

Although regional waste management and recycling are theoretically advocated, quantitative studies are rare in the literature and offered somewhat plausible evidence. Only a limited number of empirical studies on recycling boundaries can be found in the literature. Among empirical studies, Togawa (1994) found that waste paper collection businesses tended to locate in populous areas (i.e. the source of waste paper), whereas scrap iron collection business tended to locate close to electric furnaces (i.e. end users of scrap iron). Lyons (2007) analyzed recycling and remanufacturing facilities in Texas, the US and showed differences in recycling boundaries of different types of wastes. Fujiyama and Matsumoto (2009) studied the transportation of industrial wastes in Japan and showed the difference between the optimal solution and the current situation.

In terms of modeling, Habara et al. (2002) showed that a large scale does not necessarily lead to cost reduction. For treating bulky wastes (e.g. furniture), composting, and producing refuse derived fuel (RDF), expanding to the regional scale would increase the total cost. Then the question becomes what types of wastes are suitable for regional recycling, and how wide should the region be? These are no clear answers to these questions yet. More generally in the field of operational research, a number of modeling studies touched upon issues concerning scale and boundaries of waste management. Many of them focused on modeling optimal location of landfills, incinerators, transfer centers and recycling centers (Caruso et al., 1993; Erkut et al., 2008; Farhan & Murray, 2006; Flahaut et al., 2002). However, most of these models deal with only siting waste separation, collection and disposal facilities and sties, but not particular facilities processing recyclable wastes and connections with existing industrial facilities at the regional level. Both empirical studies and modeling are needed for better understanding and planning for regional recycling and for exploring the mechanism and factors that determine proper boundaries for recycling.

2.5 Proposition 3: Socio-Technical Transition towards Regional Recycling

In most countries, it is the municipalities that assume the responsibility and prepare plans for municipal solid waste management. To realize regional recycling through IS involves remarkable modifications of the current management system in terms of administrative institutions, stakeholders involved, as well as their attitude for dealing with wastes. Therefore, a comprehensive framework of transitions is needed when designing policies to promote regional recycling.

According to the theory of socio-technical transitions, transitions in technologies do not emerge alone but usually together with a series of changes in our society such as user practices, regulation, industrial networks, infrastructure and symbolic meaning (Geels, 2002). Geels and Schot (2007) defined a socio-technical regime as “an extended version of Nelson and Winter’s (1982) technological regime, which referred to shared cognitive routines in an engineering community and explained patterned development along ‘technological trajectories’ (p. 399-400)”. Geels and Schot (2007) continued that “sociotechnical regimes stabilise existing trajectories in many ways: cognitive routines that blind engineers to developments outside their focus (Nelson and Winter, 1982), regulations and standards (Unruh, 2000), adaptation of lifestyles to technical systems, sunk investments in machines, infrastructures and competencies (Tushman and Anderson, 1986; Christensen, 1997) (p. 400).” However, the socio-technical regimes do change over time. The change from one socio-technical regime to another is referred to as a socio-technical transition (Geels & Schot, 2007).

A multi-level perspective of socio-technological transitions was introduced to interpret past socio-technological transitions (a research branch known as system in transition) and to design interventions for steering future transitions (known as transition management) (Geels, 2002; Genus & Coles, 2008; Smith et al., 2005). The multi-level perspective distinguishes three levels from micro to macro: niche-innovations, socio-technical regime, and socio-technical landscape. Technological niches form the micro-level where radical novelties emerge, while the socio-technical landscape forms an exogenous environment beyond the direct influence of niche and regime actors (Geels & Schot, 2007). Socio-technical transition can be seen as a result of interactions between the three levels. Changes in the socio-technical regime level (i.e. socio-technical transition) would evolve in different pathways depending on the type of changes at the landscape level (i.e. pressures) and the state of the niches level. Such changes are often a very slow process because the existing regime tends to stabilize itself. Geels and Schot (2007) further proposed four typical paths of socio-technical transitions compared with a stable reproduction path to interpret the mechanisms of transitions. Some recent examples using the multi-level perspective include analyzing transitions in the electricity system in the UK, sustainability experiments in Asian countries, the shrimp aquaculture industry in Thailand, higher education in the US, introduction of hydrogen and battery-electric vehicles, sustainable mobility transitions in the UK and Sweden, transport fuels in Sweden (Berkhout et al., 2010; Foxon et al., 2010; Geels, 2005, 2006; Hillman & Sanden, 2008; Lebel et al., 2010; Nykvist & Whitmarsh, 2008; Stephens & Graham, 2010; van Bree et al., 2010).

Based on the multi-level perspective, we can define a socio-technical regime of waste management as the widely applied waste treatment and disposal technologies, together with the social context in which they embedded, such as institutional regime, relevant policies and regulations, and people’s attitude towards waste and waste management. In this case, the landscape pressures are those beyond the control of waste managers but exerting serious impacts on waste management. Examples include the pressures shown in Figure 2.1, such as public health, shortage of disposal capacity, resource depletion, and climate change. Niches innovations include innovative waste treatment technologies and methods.

The multi-level perspective was also criticized. Geels and Schot (2007) addressed three major criticisms concerning empirical and analytical levels, the neglect of agencies, and too much emphasis on technological niches. Some of the criticisms remain unsolved, including implicit definition of the model in case study, unclear definition of transition, credibility of data sources, and subjective interpretation of data in analysis (Genus & Coles, 2008). With these criticisms in mind, the multi-level perspective is employed here not for the purpose to interpret the socio-technological transitions in waste management, but for transition management, i.e. designing policies to orient a transition to more efficient utilization of waste at the regional scale. Details of the transition management model are introduced in Chapter 6 prior to the discussion about policy recommendations.

2.6 Summary

The history of waste management showed a co-revolution of urban development and waste management: urban development has been the major cause of waste problems and waste problems, together with many other environmental problems, has hindered further development of cities. Due to complex economic, social, and environmental pressures in cities today, wastes need to be managed as resources with high efficiencies. Because conventional waste planning and management models focus exclusive on managing waste, their scope is so narrow that the potential of efficient use of waste by industries are overlooked. These models also focus mainly at the municipal level, which limits the possibility to take advantage of infrastructures in the region and leads to small scale and high cost of pre-treatment centers.

Aiming at the high efficiency of utilizing wastes as a resource, three interconnected propositions are proposed (Figure 2.5). In the literature, numerous studies focused their attention on issues related increasing recycling rate, reducing waste generation, and developing and assessing recycling technologies, as reviewed in section 2.2. The propositions complement previous research by expanding the scope to include industrial symbiosis and, expanding the boundary to the regional scale. These concepts would contribute to the strategic planning for waste management and loop-closing of materials in urban systems. The propositions also take in account the implementation stage in terms of design policies for promoting regional recycling through IS.

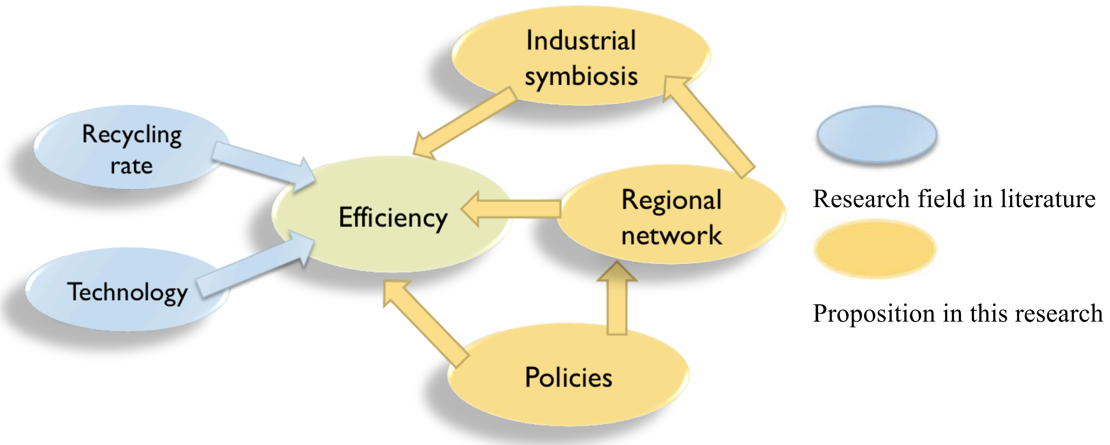


Figure 2.5 Relationships between research propositions and existing research topics

As Ehrenfeld (2008) noted that reducing unsustainability would not create sustainability. The "out-of-sight, out-of-mind" doctrine and the scope only on end-of-pipe technologies can not realize sustainable waste management. Improving recycling requires creating value of "discards", converting them from "wastes" to "resources". Such a process involves the application of recycling and industrial symbiotic technologies, as well as a supporting social system to encourage and facilitate better waste separation, collection, and pre-treatment.

Reference

Abou Najm, M., El-Fadel, M., Ayoub, G., El-Taha, M., & Al-Awar, F. (2002a). An Optimisation Model for Regional Integrated Solid Waste Management II. Model Application and Sensitivity Analyses. *Waste Management & Research, 20*(1), 46-54.

Abou Najm, M., El-Fadel, M., Ayoub, G., El-Taha, M., & Al-Awar, F. (2002b). An Optimisation Model for Regional Lintegrated Solid Waste Management I. Model Formulation. *Waste Management & Research, 20*(1), 37-45.

Achillas, C., Vlachokostas, C., Moussiopoulos, N., & Banias, G. (2010). Decision support system for the optimal location of electrical and electronic waste treatment plants: A case study in Greece. *Waste Management, 30*(5), 870-879.

Albakri, D., Shublaq, W., Kittaneh, W., & Alsheikh, Z. (1988). Site Selection of a Waste-Disposal Facility in Kuwait, Arabian Gulf. *Waste Management & Research, 6*(4), 363-377.

Anex, R. P. J. (1995). *Systems and Economic Analysis of Municipal Solid and Hazardous Waste Management.* University of California, Davis, Davis.

Baas, L., & Boons, F. (2007). The introduction and dissemination of the industrial symbiosis projects in the Rotterdam Harbour and Industry Complex. *International Journal of Environmental Technology and Management, 7*(5-6), 551-577.

Bai, R. B., & Sutanto, M. (2002). The practice and challenges of solid waste management in Singapore. *Waste Management, 22*(5), 557-567.

Barr, S. (2004). What We Buy, What We Throw Away and How We Use Our Voice. Sustainable Household Waste Management in the UK. *Sustainable Development, 12*(1), 32-44.

Barros, A. I., Dekker, R., & Scholten, V. (1998). A two-level network for recycling sand: A case study. *European Journal of Operational Research, 110*(2), 199-214.

Berkhout, F., Verbong, G., Wieczorek, A. J., Raven, R., Lebel, L., & Bai, X. M. (2010). Sustainability experiments in Asia: innovations shaping alternative development pathways? *Environmental Science & Policy, 13*(4), 261-271.

Bruvoll, A. (1998). Taxing Virgin Materials: An Approach to Waste Problems. *Resources, Conservation and Recycling, 22*(1-2), 15-29.

Burkart, R. (1994). Consensus Oriented Public-Relations as a Solution to the Landfill Conflict. *Waste Management & Research, 12*(3), 223-232.

Caruso, C., Colorni, A., & Paruccini, M. (1993). The Regional Urban Solid-Waste Management-System - a Modeling Approach. *European Journal of Operational Research, 70*(1), 16-30.

Chan, K. (1998). Mass Communication and Pro-Environmental Behaviour: Waste Recycling in Hong Kong. *Journal of Environmental Management, 52*(4), 317-325.

Chang, N. B., & Davila, E. (2007). Minimax regret optimization analysis for a regional solid waste management system. *Waste Management, 27*(6), 820-832.

Chang, N. B., Lu, H. Y., & Wei, Y. L. (1997). GIS Technology for Vehicle Routing and Scheduling in Solid Waste Collection Systems. *Journal of Environmental Engineering-Asce, 123*(9),

901-910.

Chang, N. B., & Wang, S. F. (1996). Solid Waste Management System Analysis by Multiobjective Mixed Integer Programming Model. *Journal of Environmental Management, 48*(1), 17-43.

Chen, K. C., Huang, S. H., & Lian, I. W. (2010a). The development and prospects of the end-of-life vehicle recycling system in Taiwan. *Waste Management, 30*(8-9), 1661-1669.

Chen, X., Geng, Y., & Fujita, T. (2010b). An Overview of Municipal Solid Waste Management in China. *Waste Management, 30*, 716-724.

Chen, X., Fujita, T., Geng, Y., & Xi, F. (2011c). Exploring and Assessing Innovative Approaches to Utilizing Waste as a Resource: toward Co-Benefits. In *Waste Management* (pp. 83-96): InTech.

Chertow, M. R. (2000). Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment, 25*, 313-337.

Chertow, M. R. (2007). "Uncovering" industrial symbiosis. *Journal of Industrial Ecology, 11*(1), 11-30.

Chertow, M. R., & Lombardi, D. R. (2005). Quantifying economic and environmental benefits of co-located firms. *Environmental Science & Technology, 39*(17), 6535-6541.

Chiu, A. S. F., & Geng, Y. (2004). On the industrial ecology potential in Asian Developing Countries. *Journal of Cleaner Production, 12*(8-10), 1037-1045.

Choe, C., & Fraser, I. (1998). The economics of household waste management: a review *42*(3), 269-302.

Clarke, M. J., Read, A. D., & Phillips, P. S. (1999). Integrated Waste Management Planning and Decision-Making in New York City. *Resources, Conservation and Recycling, 26*(2), 125-141.

Cleary, J. (2009). Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environment International, 35*(8), 1256-1266.

Cortes, U., Sanchez-Marre, M., Ceccaroni, L., Roda, I. R., & Poch, M. (2000). Artificial Intelligence and Environmental Decision Support Systems. *Applied Intelligence, 13*(1), 77-91.

Costa, I., Massard, G., & Agarwal, A. (2010). Waste management policies for industrial symbiosis development: case studies in European countries. *Journal of Cleaner Production, In Press, Corrected Proof.*

Deppe, M., Leatherwood, T., Lowitt, P., & Warner, N. (2000). *A Planner's Overview of Eco-Industrial Development.* Paper presented at the APA National Planning Conference, New York, New York.

Desrochers, P. (2002). Regional development and inter-industry recycling linkages: some historical perspectives. *Entrepreneurship and Regional Development, 14*(1), 49-65.

Ehrenfeld, J. (2008). *Sustainability by Design*: Yale University Press.

Erkut, E., Karagiannidis, A., Perkoulidis, G., & Tjandra, S. A. (2008). A multicriteria facility location model for municipal solid waste management in North Greece. *European Journal of Operational Research, 187*(3), 1402-1421.

Fang, Y., Cote, R., & Qin, R. (2006). Industrial Sustainability in China: practice and prospects for eco-industrial development. *Journal of Environmental Management, 83*, 315-328.

Farhan, B., & Murray, A. T. (2006). Distance decay and coverage in facility location planning. *Annals of Regional Science, 40*(2), 279-295.

Ferrara, I., & Missios, P. (2005). Recycling and Waste Diversion Effectiveness: Evidence from Canada. *Environmental and Resource Economics, 30*(2), 221-238.

Finnveden, G. (1999). Methodological Aspects of Life Cycle Assessment of Integrated Solid Waste Management Systems. *Resources Conservation and Recycling, 26*(3-4), 173-187.

Flahaut, B., Laurent, M. A., & Thomas, I. (2002). Locating a community recycling center within a residential area: A Belgian case study. *Professional Geographer, 54*(1), 67-82.

Foxon, T. J., Hammond, G. P., & Pearson, P. J. G. (2010). Developing transition pathways for a low carbon electricity system in the UK. *Technological Forecasting and Social Change, 77*(8), 1203-1213.

Frantzis, I. (1993). Methodology for Municipal Landfill Sites Selection. *Waste Management & Research, 11*(5), 441-451.

Fujii, M., Fujita, T., Chen, X., Ohnishi, S., & Yamaguchi, Y. (2010). *Efficient use of organic municipal solid waste in a sound material-cycle society.* Paper presented at the ISIE Asia-Pacific Meeting & ISIE MFA-ConAccount Meeting, Tokyo, Japan.

Fujita, T. (2006). *Eco-Town Projects/Environmental Industries in Progress*: The Ministry of Economy, Trade and Industry, Japan.

Fujiyama, A., & Matsumoto, T. (2009). Current Situation Factor Analysis on Wide-Area Transportation with Industrial Waste (in Japanese). *Environmental System, 37*, 331-338.

Gamba, R., & Oskamp, S. (1994). Factors Influencing Community Residents'Partipation in Commingled Recycling Programs. *Environment and Behavior, 26*, 587-612.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31*(8-9), 1257-1274.

Geels, F. W. (2005). The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860-1930). *Technology Analysis & Strategic Management, 17*(4), 445-476.

Geels, F. W. (2006). The hygienic transition from cesspools to sewer systems (1840-1930): The dynamics of regime transformation. *Research Policy, 35*(7), 1069-1082.

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy, 36*(3), 399-417.

Geng, Y., Fujita, T., & Chen, X. (2010). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production, 18*(10-11), 993-1000.

Geng, Y., Haight, M., & Zhu, Q. H. (2007). Empirical analysis of eco-industrial development in China. *Sustainable Development, 15*(2), 121-133.

Genus, A., & Coles, A. M. (2008). Rethinking the multi-level perspective of technological transitions.

Research Policy, 37(9), 1436-1445.

Gibbs, D., & Deutz, P. (2007). Reflections on implementing industrial ecology through eco-industrial park development. *Journal of Cleaner Production, 15*(17), 1683-1695.

Goldsby, T. J. (1998). *Consumer recycling programs: The marketing and logistics implications.* Unpublished Dissertation, Michigan State University.

Graedel, T. E., & Allenby, B. R. (2010). *Industrial Ecology and Sustainable Engineering*. Upper Saddle River, NJ, USA: Prentice Hall.

Guerini, G., Maffeis, P., Allievi, L., & Gigliotti, C. (2006). Integrated Waste Management in a Zone of Northern Italy: Compost Production and Use, and Analytical Control of Compost, Soil, and Crop. *Journal of Environmental Science and Health Part B-Pesticides Food Contaminants and Agricultural Wastes, 41*(7), 1203-1219.

Habara, H., Matsuto, T., Tanaka, N., & Inoue, M. (2002). Comparative study on regional solid waste management system in terms of cost and energy consumption (in Japanese). *Environmental Systems Research, 30*, 323-332.

Hagelstam, J. (2001). Ecotaxes in Finland. *European Environmental Law Review, 10*(3), 80-86.

Harris, S., & Pritchard, C. (2004). Industrial Ecology as a Learning Process in Business Strategy. *Progress in Industrial Ecology, 1*(1), 89-111.

Hillman, K. A., & Sanden, B. A. (2008). Exploring technology paths: The development of alternative transport fuels in Sweden 2007-2020. *Technological Forecasting and Social Change, 75*(8), 1279-1302.

Hopper, J., & Nielsen, J. (1991). Recycling as Altruistic Behavior: Normative and Behavioral Strategies to Expand Participation in a Community Recycling Program. *Environment and Behavior, 23*, 195-220.

Hostovsky, C. (2000). Integrating Planning Theory and Waste Management: An Annotated Bibliography. *Journal of Planning Literature, 15*(2), 305~332.

Hostovsky, C. (2006). The Paradox of the Rational Comprehensive Model of Planning: Tales from Waste Management Planning in Ontario, Canada. *Journal Of Planning Education And Research, 25*(4), 382-395.

Huang, G. H., Anderson, W. P., & Baetz, B. W. (1994). Environmental Input-Output-Analysis and Its Application to Regional Solid-Waste Management Planning. *Journal of Environmental Management, 42*(1), 63-79.

Huang, G. H., Baetz, B. W., Patry, G. G., & Terluk, V. (1997). Capacity Planning for an Integrated Waste Management System under Uncertainty: A North American Case Study. *Waste Management & Research, 15*(5), 523-546.

Ishii, I. (1997). *Waste Treatment: Environmental Protection and Recycling (In Japanese)*. Tokyo, Japan: Morikita Press, Inc.

Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg, Denmark - A quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology, 10*(1-2), 239-255.

Jang, Y. C., Lee, C., Yoon, O. S., & Kim, H. (2006). Medical waste management in Korea. *Journal of*

Environmental Management, 80(2), 107-115.

JCPRA (The Japan Containers and Packaging Recycling Association). (2007). *The Environmental Impacts of Plastic Containers and Packaging Recycling (in Japanese)*. Tokyo, Japan: JCPRA.

Jin, J. J., Wang, Z. S., & Ran, S. H. (2006). Solid waste management in Macao: Practices and challenges. *Waste Management, 26*(9), 1045-1051.

Jouni, K., Fredrik von, M., Peter, A. S., & John, R. E. (2004). Management and policy aspects of industrial ecology: an emerging research agenda. *Business Strategy and the Environment, 13*(5), 289.

Klinglmair, M., & Fellner, J. (2010). Urban Mining in Times of Raw Material Shortage. *Journal of Industrial Ecology, 14*(4), 666-679.

Korhonen, J. (2004). Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology. *Journal of Cleaner Production, 12*(8-10), 809-823.

Korhonen, J., Huisingh, D., & Chiu, A. S. F. (2004). Applications of industrial ecology - an overview of the special issue. *Journal of Cleaner Production, 12*(8-10), 803-807.

Kovacs, W. L. (1993). Solid-Waste Management - Historical and Future Perspectives. *Resources Conservation and Recycling, 8*(1-2), 113-130.

Lang, R. (1990). equity in siting solid waste management facilities. *Plan Canada, 30*(2), 5~13.

Lauterborn, B. (1990). New Marketing Litany: Four P's Passe; C-Words Take Over. *Advertising Age[Chicago], vol.61, no.41, pp.26, 1990.*

Lebel, L., Mungkung, R., Gheewala, S. H., & Lebel, P. (2010). Innovation cycles, niches and sustainability in the shrimp aquaculture industry in Thailand. *Environmental Science & Policy, 13*(4), 291-302.

Li, Y. P., Huang, G. H., Nie, S. L., & Qin, X. S. (2007). ITCLP: An inexact two-stage chance-constrained program for planning waste management systems. *Resources, Conservation and Recycling, 49*(3), 284-307.

Louis, G. E. (2004). A Historical Context of Municipal Solid Waste Management in the United States. *Waste Management and Research, 22*(4), 306-322.

Lyons, D. I. (2007). A spatial analysis of loop closing among recycling, remanufacturing, and waste treatment firms in Texas. *Journal of Industrial Ecology, 11*(1), 43-54.

Matsutou, T. (2007). *Solid Waste Management [In Japanese]*. Tokyo: Gihoudo Shubbansha.

McQuaidcook, J., & Simons, C. S. (1989). Development and Operation of a Waste Management-System in Alberta, Canada. *Waste Management & Research, 7*(3), 219-227.

Mee, N., Clewes, D., Phillips, P. S., & Read, A. D. (2004). Effective implementation of a marketing communications strategy for kerbside recycling: a case study from Rushcliffe, UK. *Resources, Conservation and Recycling, 42*(1), 1-26.

Meneses, G. D., x, az, Palacio, A., x, & n, B. (2005). Recycling behavior: A multidimensional approach. *Environment and Behavior, 37*(6), 837-860.

Mikami, S. (2003). Waste issues in the Edo period. In Hokkaido University of Education Asahikawa Sociology Research Lab (Ed.), Thinking about Waste Problems [in Japanese].

Miranda, M. L., & Aldy, J. E. (1998). Unit pricing of residential municipal solid waste: lessons from nine case study communities. *Journal of Environmental Management, 52*(1), 79-93.

Mirata, M. (2004). Experiences from early stages of a national industrial symbiosis programme in the United Kingdom: determinants and coordination challenges. *Journal of Cleaner Production, 12*(8-10), 967-983.

MOE. (2008). *The 2nd Fundamental Plan for Establishing a Sound Material-Cycle Society*. Tokyo: Ministry of the Environment.

Morris, G. E., & Holthausen, D. M. (1994). The Economics of Household Solid-Waste Generation and Disposal. *Journal of Environmental Economics and Management, 26*(3), 215-234.

Nie, X. H., Huang, G. H., Li, Y. P., & Liu, L. (2007). IFRP: A hybrid interval-parameter fuzzy robust programming approach for waste management planning under uncertainty. *Journal of Environmental Management, 84*(1), 1-11.

Nykvist, B., & Whitmarsh, L. (2008). A multi-level analysis of sustainable mobility transitions: Niche development in the UK and Sweden. *Technological Forecasting and Social Change, 75*(9), 1373-1387.

Ongondo, F. O., Williams, I. D., & Cherrett, T. J. (2011). How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Management, 31*, 714-730.

Oskamp, O., Harrington, M., Edwards, T., Sherwood, D., Okuda, S., & Swanson, D. (1991). Factors Influencing Household Recycling Behavior. *Environment and Behavior, 23*, 494-519.

Palmer, K., Sigman, H., & Walls, M. (2003). The Cost of Reducing Municipal Solid Waste. In T. C. e. Kinnaman (Ed.): International Library of Environmental Economics and Policy. Aldershot, U.K. and Burlington, Vt.: Ashgate.

Porter, R. C. (2002). *The Economics of Waste*. Washington, DC: Resources for the Future.

Powell, J. C. (1996). The evaluation of waste management options. *Waste Management & Research, 14*(6), 515-526.

Qu, Y. (2007). *The Study on Residential Behavior for Source Separation of Household Waste.* Dalian University of Technology, Dalian, China.

Qu, Y., Zhu, Q., & Haight, M. E. (2007). A Survey of the Influencing Factors and Models for resident's household waste management behavior. *Ecological Economy*(3), 336-344.

Rathje, W. L. (1992). *Rubbish! : the archaeology of garbage* New York: HarperCollins Publishers.

Rathje, W. L., Hughes, W. W., Wilson, D. C., Tani, M. K., Archer, G. H., Hunt, R. G., et al. (1992). The Archaeology of Contemporary Landfills. *American Antiquity, 57*(3), 437-447.

Read, A. D. (1999). "A weekly door-step recycling collection, I had no idea we could!" - Overcoming the local barriers to participation. *Resources Conservation and Recycling, 26*(3-4), 217-249.

Reich, M. C. (2005). Economic assessment of municipal waste management systems - case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production, 13*(3), 253-263.

Roberts, P. (2004). Wealth from waste: Local and regional economic development and the environment. *Geographical Journal, 170*(2), 126-134.

Rowe, S. (1992). Landfill planning in Ontario: bringing in the public. *Plan Canada, 32*, 22-25.

Seadon, J. K. (2006). Integrated waste management - Looking beyond the solid waste horizon. *Waste Management, 26*(12), 1327-1336.

Seasons, M. (2003). Monitoring and evaluation in municipal planning - Considering the realities. *Journal of the American Planning Association, 69*(4), 430-440.

Selman, P. (1996). *Local Sustainability: Planning and Managing Ecologically Sound Places*. London: Chapman.

SEPA. (2007). The Resolution on Administrative Review Requested by Qian Zuosheng, Li Huilan et al. (in Chinese) [Electronic Version]. Retrieved Nov. 2008, from http://www.mep.gov.cn/law/fzjs/xzfy/200706/t20070612_105077.htm

Shi, H., Chertow, M., & Song, Y. (2010). Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China. *Journal of Cleaner Production, 18*(3), 191-199.

Shinkuma, T. (2003). On the second-best policy of household's waste recycling. *Environmental and Resource Economics, 24*(1), 77-95.

Shrum, L. J., Lowrey, T. M., & McCarty, J. A. (1994). Recycling as a marketing problem: A framework for strategy development: US: John Wiley & Sons.

Smith, A., Stirling, A., & Berkhout, F. (2005). The governance of sustainable socio-technical transitions. *Research Policy, 34*(10), 1491-1510.

Stephens, J. C., & Graham, A. C. (2010). Toward an empirical research agenda for sustainability in higher education: exploring the transition management framework. *Journal of Cleaner Production, 18*(7), 611-618.

Sterr, T., & Ott, T. (2004). The industrial region as a promising unit for eco-industrial development - reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production, 12*(8-10), 947-965.

Takeuchi, K., & Hayashi, Y. (1998). *Global Environment and Megalopolis*. Tokyo, Japan: Iwanami Shyoten.

Tanaka, M. (1998). *Outline of Waste Management (in Japanese)*. Tokyo, Japan.

Tarr, J. A. (1985). Historical Perspectives on Hazardous Wastes in the United-States. *Waste Management & Research, 3*(2), 95-102.

Taylor, S., & Todd, P. (1995). An Integrated Model of Waste Management Behavior - a Test of Household Recycling and Composting Intentions. *Environment and Behavior, 27*(5), 603-630.

Thomas, B., & McDougall, F. (2005). International expert group on life cycle assessment for integrated waste management. *Journal of Cleaner Production, 13*(3), 321-326.

Togawa, K. (1994). The recycling system of waste paper and scrap iron in today's Japanese economy: An introduction to the location theory of 'venous industry' (in Japanese). *Annals of the Association of Economic Geographers 40*(3), 241-255.

Ueda, K. (2000). Public Policy for Sound Material-Cycle Society (in Japanese). *Policy Science, 7*(3),

77-88.

van Beers, D., Corder, G., Bossilkov, A., & van Berkel, R. (2007). Industrial Symbiosis in the Australian Minerals Industries: the cases of Kwinana and Gladstone. *Journal of Industrial Ecology, 11*(1), 55-72.

van Berkel, R., Fujita, T., Hashimoto, S., & Fujii, M. (2009a). Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. *Environmental Science & Technology, 43*(5), 1271-1281.

van Berkel, R., Fujita, T., Hashimoto, S., & Geng, Y. (2009b). Industrial and urban symbiosis in Japan: Analysis of the Eco-Town. *Journal of Environmental Management, 90*, 1544-1556.

van Bree, B., Verbong, G. P. J., & Kramer, G. J. (2010). A multi-level perspective on the introduction of hydrogen and battery-electric vehicles. *Technological Forecasting and Social Change, 77*(4), 529-540.

Vining, J., & Ebreo, A. (1990). What makes a recycler? A comparison of recyclers and nonrecyclers. *Environment and Behavior*(22), 55-73.

Wang, H. T., & Nie, Y. F. (2001). Municipal solid waste characteristics and management in China. *Journal of the Air & Waste Management Association, 51*(2), 250-263.

Yasuda, K. (1998). Towards Larger Designated Areas for Regional Waste Disposal (in Japanese). *Waste Management Research, 9*(7), 462-469.

Yuan, Z., Bi, J., & Moriguichi, Y. (2006). The Circular Economy: A New Development Strategy in China. *Journal of Industrial Ecology, 10*(1/2), 4-8.

Zhao, W., van der Voet, E., Zhang, Y. F., & Huppes, G. (2009). Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: Case study of Tianjin, China. *Science of the Total Environment, 407*(5), 1517-1526.

Chapter 3 Empirical Study on Recycling Activities at Regional Scale

This chapter analyzes the feature of recycling activities in the regional scale based on empirical data. The first section of this chapter presents an empirical study on recycling projects in Japanese eco-towns, aiming to examine the impacts of project scale and recycling boundary on the performances of recycling facilities in eco-towns with regards to different types of wastes recycled. The second section zooms out to the regional/national scale, examining the spatial features of processes of waste recycling and treatment.

3.1 The Matter of Scale, Boundary and Type of Waste to Recycling

3.1.1 Background and Policies of Japanese Eco-Towns

The Eco-Town Program was initiated in 1997 and ended in 2006 with a dual objective of stimulating new industry development and addressing waste management issues in Japan (van Berkel et al., 2009b). It basically adopted the concept of zero emission, which aimed to reduce waste emission to zero by regional waste recycling efforts (GEC, 2006; MoE, 2007). During the ten-year period, Ministry of the Environment (MOE) (Department of Environment under Ministry of Welfare as of 2001) and Ministry of Economy, Trade and Industry (METI) of Japan jointly designated 26 eco-towns (Figure 3.1). Eco-town plans typically consist of two parts: “software projects” (e.g., town planning, community recycling, and outreach activities) and “hardware projects” (i.e., innovative recycling facilities and associated infrastructure) (Fujita, 2006; van Berkel et al., 2009b). The recycling activities in eco-towns do not limit to simple processing of recyclable wastes; they also tightly connect with local industries in terms of utilizing wastes as feedstock or fuel in, for example, iron, cement, and ammonia production (van Berkel et al., 2009a).

The Eco-Town Program has not stood alone but been supported by a comprehensive legislative system. As the fundamental scheme, the Basic Law for Establishing the Recycling Society was enacted in 2001, which requests the government to prepare a Fundamental Plan for Establishing a Sound Material-Cycle Society with specific targets. The Japanese government released the first

Fundamental Plan in 2003 (MoE, 2003) and the second Fundamental Plan in 2008 (MoE, 2008), the latter of which sets the target, by 2015, to improve resource productivity by about 60%, to raise the ratio of recycled material to total material input by about 40-50%, and to decrease the total wastes to landfills by about 60% from the 2000 level (Table 3.1). Under the Basic Law and the Fundamental Plan, the government enacted a series of laws between 2000 and 2003 on promoting recycling of containers and packaging, home appliances, construction materials, food, and end of life vehicles (van Berkel et al., 2009b).

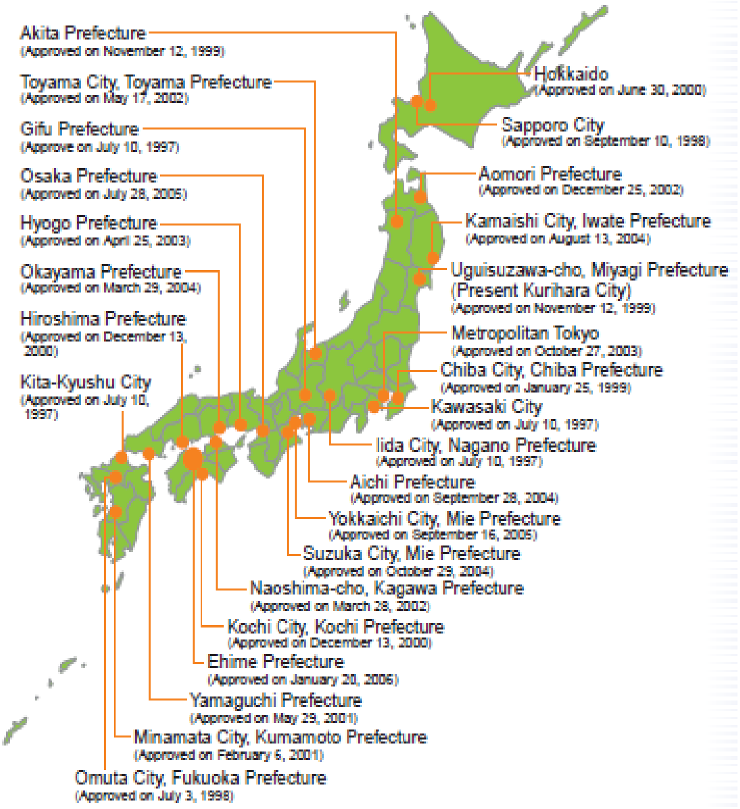


Figure 3.1 Location of Japanese Eco-towns

Source: Fujita, Tsuyoshi. 2006. Eco-Town Projects/Environmental Industries in Progress: The Ministry of Economy, Trade and Industry, Japan.

Eco-towns have played a key role in approaching to the sound material-cycle society and recycling various types of wastes as required by the Basic Law. The national government also provided financial supports for eco-town projects. MOE offered a subsidy to the local authority for the “software projects” of eco-towns, up to 50% of the project costs, typically in the range of 3 to 5 million JPY/year (approximately 24,000 to 40,000 USD/yr) (GEC, 2006; van Berkel et al., 2009b). Meanwhile, METI provided another subsidy to private companies for the “hardware projects”. The total amount of subsidy for the 61 hardware projects was about 60 billion JPY. Each project received subsidy ranged between 14% and 50% of the total investment with an average of 36% (van Berkel et al., 2009b). The national subsidies for software and hardware projects were finished in 2004 and 2005 respectively after the “trinity reform” in Japan, which was a decentralization reform through reducing central government subsidies, transferring national tax sources for eco-towns to general budgets of local governments as one of reformed allocations of taxation (Fujita, 2006). In addition to the national subsidies, several local governments, such as Kawasaki, Minamata, and Kitakyushu, also provided matching subsidies for either software or hardware projects in their municipalities (GEC, 2006).

Table 3.1 Targets of establishing a sound material-cycle society in Japan

Plan	Year of release	Target year	Resource productivity (10000 JPY/t)	Ratio of recycled resource to total resource input (%)	Final disposal (million tons)
Base year	--	--	28	10	57
The 1st fundamental plan for establishing a sound material-cycle society in Japan	2003	2010	39	14	28
The 2nd fundamental plan for establishing a sound material-cycle society in Japan	2008	2015	42	14-15	23

Source: Summarized by authors based on the following two documents:

MOE. 2003. The Fundamental Plan for Establishing a Sound Material-Cycle Socie*ty*. Tokyo: Ministry of the Environment. http://www.env.go.jp/en/recycle/smcs/f_plan.pdf. Accessed May, 2010.

MOE. 2007. *Annual Report on the Environment and the Sound Material-Cycle Society in Japan 2007*. Tokyo: Ministry of the Environment. http://www.env.go.jp/en/wpaper/index.html. Accessed July, 2009.

After the Eco-Town Program completed, the existing eco-towns were expected to evolve gradually to the next generation. In the 2nd Fundamental Plan for Establishing a Sound Material-Cycle Society, eco-towns were regarded as recycling industry clusters with extensive cooperation among companies, which the State would support in order to create a sound material-cycle society at the regional level and to promote sound material-cycle businesses (Government of Japan, 2008).

3.1.2 Methodology

Data collection

Meta data of this study were derived mainly from the survey to all recycling facilities in 26 Japanese eco-towns. One of the author's advisors led a Study Group on evaluating the performances of eco-town projects, which was organized by MOE. The Study Group designed the survey questionnaire and, with supports from MOE, conducted the survey in December 2008 in order to better understand the role that eco-towns are about to play in the creation of regional recycling networks and sound material-cycle society. Before the formal survey questionnaires were distributed, preliminary surveys were sent to the municipalities where the eco-towns located in and nine chosen recycling facilities in Chiba, Tokyo, Kawasaki and Aichi eco-towns. The preliminary surveys aimed to inquire the current states of eco-town projects and to check if the responses were as expected and modifications were necessary. The formal survey questionnaires were then sent to all recycling facilities in operation. The questionnaires inquired in five aspects, including basic information of the facility; amounts, types, sources or destinations of waste treated and products delivered; energy consumption of processing; utilization of by-products and waste heat; and operational performance in terms of profitability, difficulties in operation and expecting supports. A sample of the questionnaire is included in the Appendix. Sharing the survey data, the author conducted the following analyses and discussions.

Research framework

The empirical study aims to examine the relationships of project scale, recycling boundary, and performances of each eco-town and each recycling facility with regards to different types of waste treated. Three influencing factors (project scale, recycling boundary, and type of waste) and two performance indicators (virgin material saving (VMS) and operating rate (OR)) were studied. A simple framework was adopted to organize the analysis of multiple relationships among the influencing factors and performances (Figure 3.2). Two sets of relationships were analyzed: (1) the relationships between factors and performances, respectively at both single facility and eco-town levels; and (2) the relationship among the influencing factors. The former served to examine if any of the influencing factors was correlated with performances, while the latter was expected to explore some self-emerging characteristics of the recycling facilities in terms of correlations among the factors. Data on type of waste and project scale (indicated by the amount of waste treated) were directly derived from the survey results. The indicators of virgin material saving, operating rate, and recycling boundary are defined in the following section.

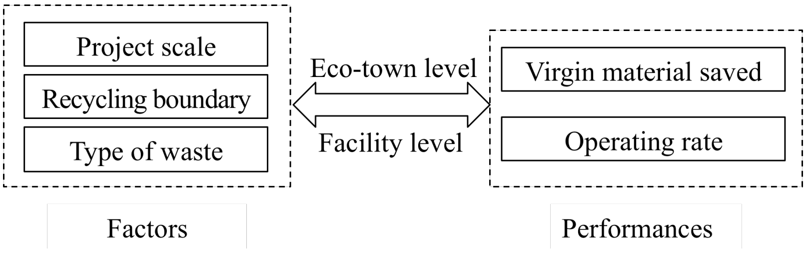


Figure 3.2 Research framework

Indicator

As this empirical study did not aim at developing a delicate indicator system, it employed only two indicators to measure each sample's environmental benefits and operational performances. Virgin material saving (VMS) was chosen for the environmental benefits. The objectives of eco-town projects were not only to treat and safely dispose of wastes, but also to reuse or recycle materials from waste to replace virgin materials. Therefore, saving virgin material was an important aspect of environmental benefits from eco-town projects. VMS is determined according to the following equation:

$$\mathrm{VMS}\ (\mathrm{t/yr}) = \mathrm{VME} - \mathrm{C} \qquad \text{(eq. 3.1)}$$

where VME is the virgin material with equivalent function to the recycled materials or recovered energy, and C is the virgin resource consumed in the recycling process. The recycled materials do not necessarily have the same physical and chemical properties as the saved virgin materials, as long as they can fulfill the same function in production or consumption scenarios. For example, 1 kg of refuse derived fuel (RDF) produced from mixed municipal solid waste can be used to replace, on average, 0.7 kg of coal with the same heat value; and 1 kg of waste plastic can produce reductant applied in blast furnace to substitute pulverized coal and coke (equivalent to 0.73 kg of coal) in producing the same amount of iron (Table 3.2). VME included virgin materials and utilities that are required to produce the substituted products. For example, for ferrous metals that substituted by iron scraps, the iron ore and resources consumed in producing metals are considered as parts of VME. The amount of recycled products and resource consumed in the recycling process (C) were obtained from the survey. The substituted virgin materials are estimated according to conversion factors of recycled products provided by Japanese Ministry of the Environment (MOE, 2010). Table 3.2 lists the references for the conversion factor of each recycled product. Totally three types of fossil fuels, 19 mineral materials, and wood were considered respectively for recycled products. All the references and detailed types of fossil fuels and mineral materials were also shown in Table 3.2. It should be noted that this simple estimation treats all types of saved virgin materials with the same weight and fails to distinguish the difference in resource scarcity and environmental impacts associated with each unit of different virgin materials. However, it can still shed some light on the environmental benefits of eco-town projects.

Operating rate (OR) was chosen as the indicator for the operational performance of each recycling project. OR was calculated as the ratio of the amount of wastes practically treated (W) to the planned amount of treatment (PAT):

$$\mathrm{OR}(\%) = \frac{\mathrm{W}}{\mathrm{PAT}} \qquad \text{(eq. 3.2)}$$

The survey questionnaire did not ask specifically the transportation distance of waste collection and recycled product delivery, but questioned the origin of waste and the destination of recycled products by categories of “within the city”, “within the eco-town plan area”, “within the prefecture”, "outside the prefecture", and "unknown". An approach to represent the recycling boundary is by the rates of waste collection and product delivery within the city, within the prefecture, and outside the prefecture, as the method adopted by Lyons (2007). However, it is helpful to have one indicator for the recycling boundary, rather than rates in categories, so that recycling boundaries of different types of wastes can be compared at a single dimension. In such a case, rate of waste collection and product delivery in a single category, e.g. within the prefecture, would not be able to represent the difference between within the city and outside of the city. Therefore, we roughly estimated the average distances of waste collection and product delivery. Because the geographical boundary of eco-towns varies vastly from an agglomerated site to a whole prefecture, it is difficult to estimate the distance of transportation based on the category of "within the eco-towns". As a result, we estimate the average transportation distance by the other four categories according to the following equation:

$$\text{Average distance (km)} = \rho_{\mathrm{wc}} \cdot 10 + \rho_{\mathrm{wp}} \cdot 30 + \rho_{\mathrm{op}} \cdot 100 + \rho_{\mathrm{un}} \cdot 50 \qquad \text{(eq. 3.3)}$$

where ρ is the ratio of waste collected from or product supplied to a category of region, and the subscripts of *wc, wp, op*, and *un* represent the categories of within city, within prefecture, outside prefecture, and unknown, respectively. The 88 sample projects are located in 48 cities/counties in 21 prefectures, of which the total area is available. If each city or prefecture is considered a single recycling unit in the shape of circles, the average radiuses for cities and prefectures are 12 km and 56 km, respectively. If sources of wastes and destinations of wastes are distributed within the circles with even probability, the average transportation distance would be half of the radius. For the category of outside prefecture, adjacent prefectures are considered the most possible sources of wastes and destinations of recycled products. For the sake of simplicity, we set the transportation distances for the four categories to equal 10, 30, 100, and 50 kilo meters, respectively. The distances were not calculated for each project with regards to its location because the figures of average distances aimed to show the levels of boundaries across different facilities and type of wastes, but the real distances of transportation were not precisely distinguished. For example, a type of waste having an average collection distance of 60 km indicates that it is mostly collected in a wider boundary over the prefecture than another with a figure of 30, which is mostly collected within the prefecture.

Table 3.2 Conversion factors of recycled products to virgin materials

Recycled product	Unit	Conversion factor				
		Fossil fuel[#]	Mineral material[$]	Wood	Total	Ref*
plastic resin	per kg	1.629	0	--	1.629	1
glass cullet	per kg	0.181	1.384	--	1.565	2
metal	per kg	0.627	0.972	--	1.599	3
construction material	per kg	0.001	1.000	--	1.001	4
refuse derived fuel (RDF)	per kg	0.700	0	--	0.700	5
feedstock for paper production	per kg	0.017	0	1	1.017	6
feedstock for iron production	per kg	0.728	0	--	0.728	7
feedstock for cement production	per kg	0.120	1.441	--	1.561	8
electricity	per kWh	0.160	0	--	0.160	9
syngas	per m3	0.422	0	--	0.422	5
steam	per kg	0.069	0	--	0.069	10
formwork board	per kg	0.042	0	2	2.042	6
aluminum	per kg	3.047	5.446	--	8.493	11
copper	per kg	0.307	3.237	--	3.544	12
steel	per kg	0.684	0.966	--	1.650	3
zinc	per kg	0.875	1.673	--	2.548	12
oil	per kg	1.036	0	--	1.036	13
compost N	per kg	1.198	0	--	1.198	14
compost P	per kg	0.395	0	--	0.395	14
compost K	per kg	0.201	0	--	0.201	14
feedings	per kg	0.048	0.129	--	0.177	15
coal	per kg	1.000	0	--	1.000	13
cokes	per kg	1.451	0	--	1.451	13

Source: MOE. 2010. *FY2009 Report on the Project to Survey and Examine Measures to Further Promote Eco Town Programs (in Japanese)*. Tokyo, Japan: Waste Management and Recycling Department, Ministry of the Environment.

#: Fossil fuels include coal, oil, and natural gas as feedstock, utility, and that are embodied in electricity consumed in the production of each virgin materials.

$: Mineral materials include silica sand, soda ash, thenardite, lime, iron ore, bauxite, copper ore, zinc ore, silica rock, fluorite, dolomite, iron slag, copper slag, zinc slag, clay, iron (feedstock for cement production), gypsum, sand and gravel, and halite.

*: Ref refers to References for the conversion factor of each recycled product listed in (MOE, 2010):

1. JLCA-LCA database. 2008. Version 4.
2. Japan Environmental Management Association for Industry (JEMAI). 1998. Introduction to LCA in practice (in Japanese). Tokyo: JEMAI.
3. New Energy and Industrial Technology Development Organization (NEDO) and Japan Environmental Management Association for Industry (JEMAI). 1995. 1994 Working Report: International Survey on Methods for Rational Utilization of Energy (in Japanese).
4. Hashimoto, S., Hiroiki, H., Terashima, Y. 2000. Evaluation of Concrete Waste Recycling From Environmental Aspects (in Japanese). Journal of Environmental Systems and Engineering. 657(VII-16): 75-80.
5. Converted based on lover heat value of RDF and coal
6. Nakazawa, K., Katayama, K., Katsura, T., Sakamura, H., Yasui, I. 2001. Life Cycle Inventory of Wood-Free Paper Containing Non-Wood Pulp or Deinked Pulp (in Japanese). Japan Tappi Journal. 55(6):838-852
7. Japan Containers and Packaging Recycling Association (JCPRA). 2007. The Environmental Impacts of Plastic Containers and Packaging Recycling (in Japanese). Tokyo, Japan: JCPRA.
8. Japan Cement Association. 2007. The General Knowledge of Cement. Tokyo: Japan Cement Association.
9. JEMAI LCA-Pro Version 2.1.2 database.
10. Assumed to be generated by boilers fueled by heavy-fuel-oil-C with heat conversion efficiency of 80%.
11. Japan Aluminum Association. 2005. LCI Data on Raw Aluminum Ore and Recycling Aluminum for Wrought Products. Tokyo: Japan Aluminum Association.
12. JLCA-LCA database. 2009. Version 4.
13. Ministry of the Environment, Japan. 2006. Methods and Emission Factors for Accounting, Reporting and Publicizing. http://www.env.go.jp/earth/ghg-santeikohyo/material/itiran.pdf. Accessed May, 2010.
14. Turhollow, A.F., Perlack, R.D. 1991. Emissions of CO_2 from Energy Crop Production. Biomass and Bioenergy 1(3): 129-135
15. Pimentel, D. Patzek, T.W. 2005. Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower. Natural Resources Research, 14(1):65:76

3.1.3 Results

Data description and screening

As of the end of 2008, totally 205 eco-town projects had been established in 26 eco-towns, of which 170 were recycling and recovery projects in operation (there were other 4 recycling projects closed down) and other 35 were either research projects, wind power projects, or projects in planning or test run stages. Among the 170 ongoing projects, 61 received subsidies and 109 did not. Survey questionnaires were sent to the 170 in-operation recycling facilities inquiring their operational information in 2007, and 93 valid surveys were collected back, with a response rate of 55%. Among the 93 valid samples, five were considered invalid for the reason that will be discussed in the data screening session later and thus been excluded in the following analysis. The remaining 88 samples were from 23 eco-towns (Figure 3.3). Kitakyushu and Hokkaido eco-towns offered large numbers of examples over 10, followed by Hiroshima, Aichi, Sapporo and Omuta eco-towns. Unfortunately, questionnaires from Iida, Suzuka, and Ehime eco-towns were either unreturned or invalid.

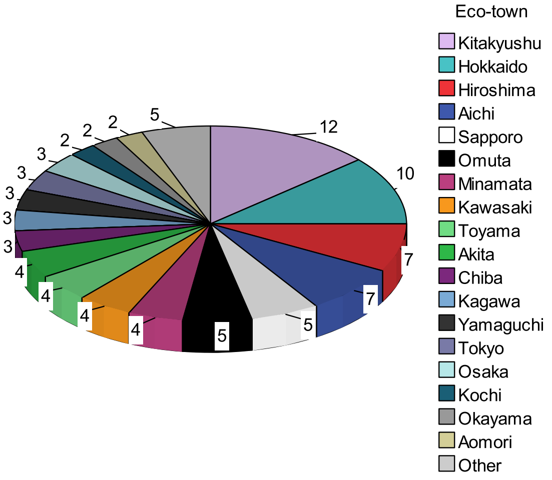


Figure 3.3 The number of sample projects in each eco-town

The sample projects were further categorized into various facility types according to the major types of waste they treat (Figure 3.4). Waste plastic recycling projects appeared to be the largest group, followed by WEEE, wood, ash and food recycling projects. Although this categorization is slightly different from the one given by van Berkel et al. (2009b), the basic pattern of the distribution remained the same.

Following the calculation of VMS and OR for all sample projects, the results were screened to exclude outliers. VMS was divided by the amount of waste treated to obtain the virgin material saving ratio for each project. If there was no unacceptable error in reporting the amount of wastes treated and products yield, this ratio should fall into a reasonable range because recycled products should have a reasonable physical capacity on replacing virgin materials. Samples with virgin material saving ratios deviating far away from the mean value were excluded as outliers. As a result, five outliers were excluded. The distribution of virgin material saving ratios of the remaining 88 samples is illustrated in Figure 3.5. The variation of the virgin material saving ratio could be explained by the differences in such factors as type of waste, level of contamination, type of virgin material replaced, processing efficiency, and errors in bookkeeping and reporting.

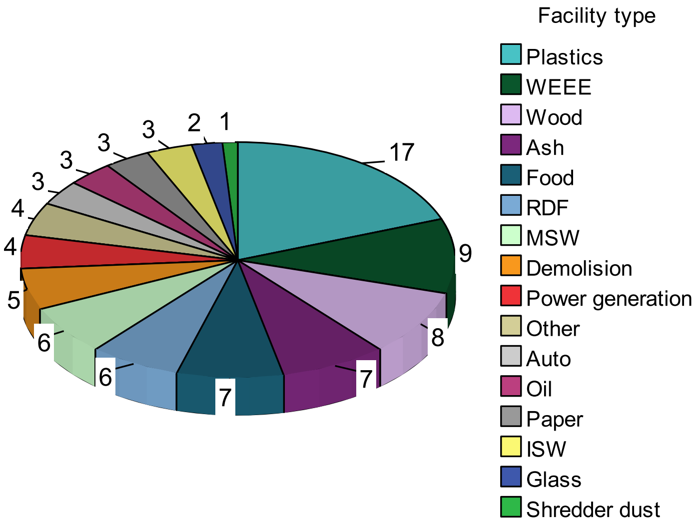


Figure 3.4 The number of samples of each type of facility

Note: WEEE = waste electronic and electrical equipments, RDF = refuse derived fuel, MSW = municipal solid waste, ISW = industrial solid waste.

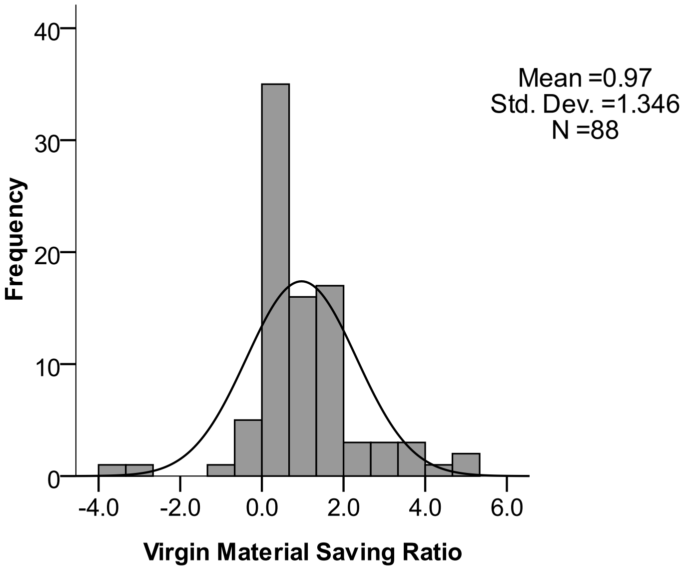


Figure 3.5 Distribution of samples by virgin resource saving ratio

Note: Std. Dev. = standard deviation; N = the total number of samples. The curve represents the normal distribution of samples.

Scale and performances

The relationship between scale and VMS in eco-towns is firstly examined. The total amount of wastes treated in the sample projects in each eco-town varies significantly (Figure 3.6). The largest eco-town, Sapporo, received approximately 250 thousand tons of waste, whereas small ones, such as Yokkaichi, Kamaishi, and Kochi, handled only several hundred tons in 2007. Total VMSs in different eco-towns also vary, with the highest in Sapporo exceeding 250 thousand tons per year and the lowest in Kurihara with a negative value. The total amount of waste treated and VMS are statistically correlated. That is, eco-towns treating more wastes are likely to save more virgin materials.

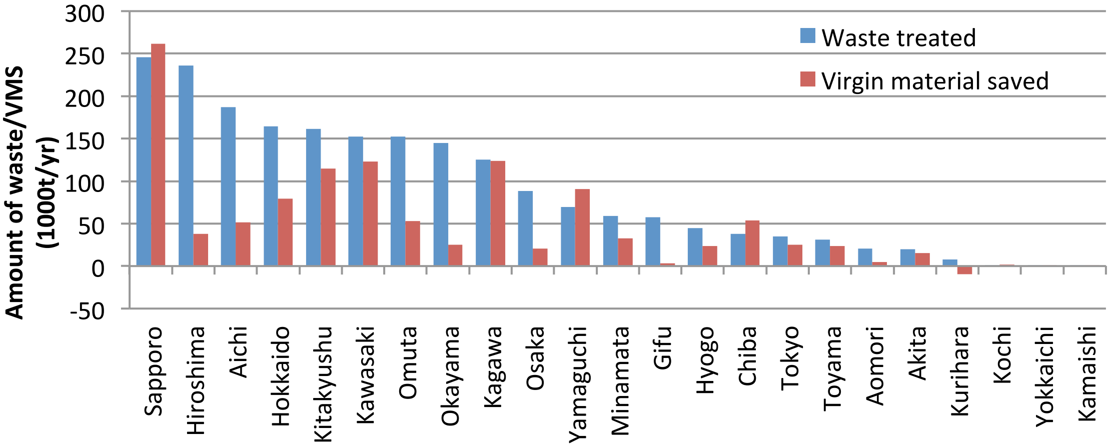


Figure 3.6 Total amount of waste treated and VMS in eco-towns

Following the analysis of eco-towns, the relationship between scale and VMS of each sample project is studied (Figure 3.7). The scales of projects also vary, but most of them have a treatment capacity of less than 100 thousand tons per year. Only four projects treated more than 100 thousand tons of waste in 2007. These projects include a power generation facility, a waste wood treatment facility, an industrial waste treatment facility, and a demolition waste treatment facility. A slight trend towards upper-right can be observed in the plots. A simple linear regression with zero intercept2 shows an R-squared value of 0.39. The result is not surprising because, given relatively comparable

---

[2]: The zero intercept is assumed because technically if there is no waste treated, VMS would equal to zero.

efficiencies, the more inputs (i.e. wastes) eco-town projects take, the more outputs they could produce, and thus the more virgin materials could be saved. On average, for every additional ton of waste recycled in an eco-town project, the recycled material/energy would likely substitute additional 0.5 ton virgin materials.

Scale and OR of eco-towns and sample projects are plotted in Figure 3.8 and Figure 3.9. A slight upper- right trend between scale and average OR of eco-towns can be observed, which indicates that facilities located in large eco-towns on average are likely to maintain higher operating rates. For individual facilities, the correlation between scale and OR is not significant (R2=0.082) and therefore the fit line is omitted. A more worth noting pattern of the plots in Figure 3.9 is that plots on the left-hand side dispersed more widely than the ones on the right. This pattern suggests that as the facility’s scale increases, the operating rate becomes more stable and stays in a relative high range. The stability can be resulted from more diversified waste suppliers; and even with the same fluctuation in the amount of waste treated, large projects would have smaller changes in their operating rates simply because the amount of fluctuation accounts for a smaller proportion of the total amount of waste treated.

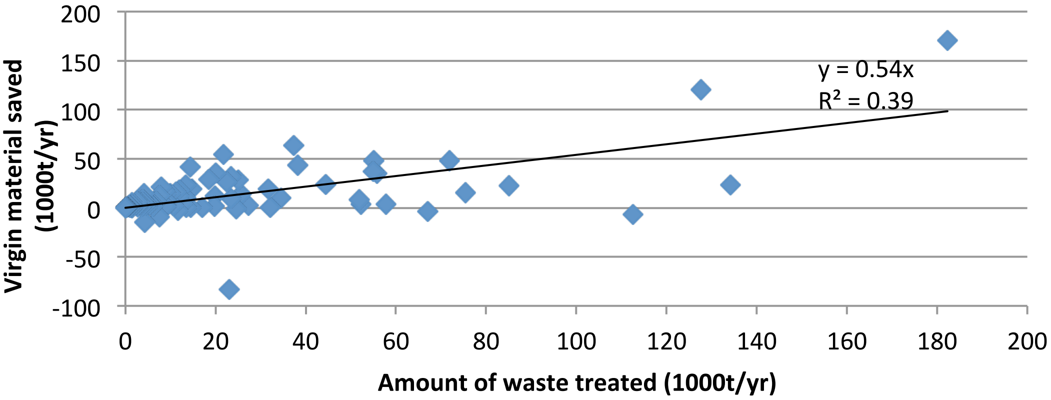


Figure 3.7 Scatter plot of total waste treated and VMS in sample projects

One of the hypotheses for the positive correlation between the scale of eco-towns and operating rates is that facilities in large eco-towns could share infrastructure, information, and services. The recycling facilities in an eco-town, in fact, may not locate in a designated site although all of them are under the same eco-town plan. If no more than one facility is situated outside a designated site, the eco-town is categorized as "agglomerated" eco-town, otherwise as "dispersed" eco-town3 The size of the designated site is considered around 1 km radius. As shown in Figure 3.8 and Figure 3.9, benefits from the proximity of facilities could not be observed in the scatter plots. Independent t-test confirms that there is no significant difference in average OR, as well as VMS between agglomerated and dispersed eco-towns (Table 3.3).

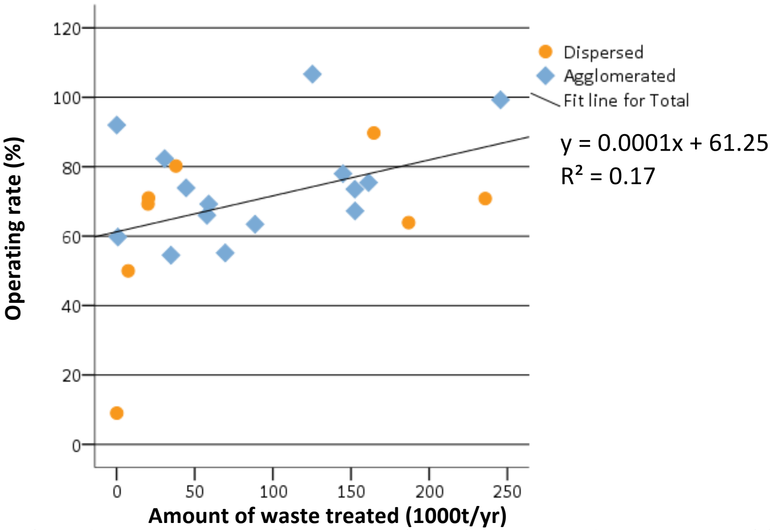


Figure 3.8 Scatter plot of average operating rate and total amount of waste treated in eco-towns

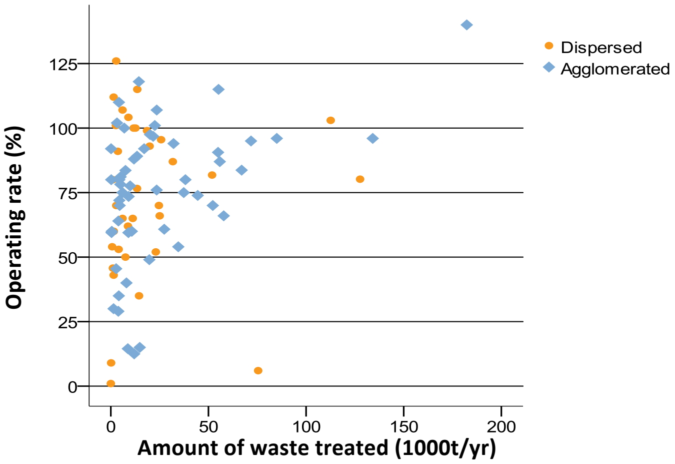


Figure 3.9 Scatter plot of operating rate and amount of waste treated in sample projects

---

[3]: Agglomerated eco-towns include Kitakyushu, Hyogo, Kawasaki, Osaka, Omuta, Tokyo, Kamaishi, Toyama, Okayama, Kochi, Gifu, Yamaguchi, Minamata, Kagawa and Sapporo eco-towns; Dispersed eco-towns include Aichi, Hokkaido, Hiroshima, Kurihara, Chiba, Aomori, Akita, and Yokkaichi eco-towns.

Table 3.3 Independent t-test for the performances between agglomerated and dispersed eco-towns

		Levene's Test for Equality of Variances		t-test for Equality of Means		
		F	Sig.	t	df	Sig. (2-tailed)
Operating rate	Equal variances assumed	.877	.360	1.378	21	.183
	Equal variances not assumed			1.194	9.974	.260
Virgin material saved	Equal variances assumed	3.080	.094	1.225	21	.234
	Equal variances not assumed			1.522	20.570	.143

Recycling boundary and performance

Recycling boundary does not appear to significantly correlate with either VMS and OR at both eco-town and facility levels (Tables 3.4 and 3.5). That is, large scale (cross-prefecture) does not necessarily lead to higher VMS and OR than small scale (city/county). Due to the existence of a number of waste management and recycling laws, wastes are available in most of the cities. For facilities whose inputs of wastes can be provided within short distances, the diversity of suppliers at a larger scale would not provide additional benefits. With the coordination of several super-regional organizations for different types of recyclable wastes, recycling companies can bid for wastes from different sources with reasonable treatment fees and search for proper final users of recycled products. In stead of recycling boundaries, VMS is related more to the properties of the wastes, and OR more to competition among recycling companies. Recycling boundaries do not appear to be an important influencing factor to competition. However, because the smallest recycling boundary analyzed in this Chapter is at the city or county level, it does not test if recycling at the city level and above would result in higher VMS or OR than that at the industrial park level.

Table 3.4 Pearson correlation matrix of operating rate, circulation boundary, scale, and VMS of eco-towns

	Operating rate	Average collection distance	Average delivery distance	Total amount of waste	Total amount of product	Virgin material saved
Operating rate	1					
Average collection distance	-.166	1				
Average delivery distance	-.059	.128	1			
Total amount of waste	.415*	-.086	-.439*	1		
Total amount of product	.367	-.151	-.343	.815**	1	
Virgin material saved	.491*	-.064	-.387	.699**	.833**	1

N=23.
**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 3.5 Pearson correlation matrix of operating rate, circulation boundary, scale, and VMS of sample projects

	Operating rate	Average collection distance	Average delivery distance	Total amount of waste	Total amount of product	Virgin material saved
Operating rate	1					
Average collection distance	-.067	1				
Average delivery distance	-.191	.312**	1			
Total amount of waste	.286**	.020	-.233*	1		
Total amount of product	.286**	-.041	-.122	.773**	1	
Virgin material saved	.310**	.022	-.060	.626**	.845**	1

N=88.
**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Facility type and performances

Although scale has certain power on interpreting the variations of VMS and OR, it is not the only factor that has strong impacts on the performances. Facility type, the major type of waste treated, is also an important factor. Figure 3.10 shows the variance of virgin material saving ratios of different types of facilities. This ratio is dependent not only on the efficiency of processing itself, but also largely on the characteristics of waste in term of its chemical and physical properties, levels of contamination and so forth. The virgin material saving ratio can be decomposed into three independent parts: product yield ratio (η), substitution coefficient (θ) and substituted material's environmental burden (ε) as:

$$\frac{\text{VMS}}{\text{waste}} = \frac{\text{recycled product}}{\text{waste}} \times \frac{\text{substituted material}}{\text{recycled product}} \times \frac{\text{virgin material}}{\text{substitued material}} - \frac{\text{C}}{\text{waste}} \quad \text{(eq. 3.4)}$$

where η = recycled product/waste, θ = substituted material/recycled product, ε = virgin material/substituted material, and C is the consumption of virgin resource during the recycling process. In the right-hand side of the equation, η and θ are influenced by the characteristics of waste. For example, in recycling soft drink plastic bottles (usually made of polyethylene terephthalate or PET) to produce PET palates to substitute virgin PET polymers, the product yield ratio (η) can reach over 90% and is influenced by the contamination level of waste plastic bottles. On the contrary, bottom ash (as feedstock for cement production) and molten slag (as construction material) yield from incinerating MSW can never reach such a ratio. The amount of materials (fibre or PET polymers) that one unit of recycled PET can substitute (θ) is close to 1 and influenced by the quality of waste PET. In contrast, the amount of fossil fuel that one unit of RDF can replace in power generation is around 0.7, which is determined by the heat value (chemical composition) of RDF. High virgin material saving ratio is not correlated with large scale of facilities (Figure 3.10). That is, by the given level of technology, every type of waste has a physical limit of the virgin material saving ratio; the efficiency of processing itself, including the effect of economies of scale, matters only the extent to which such a physical limit is approached.

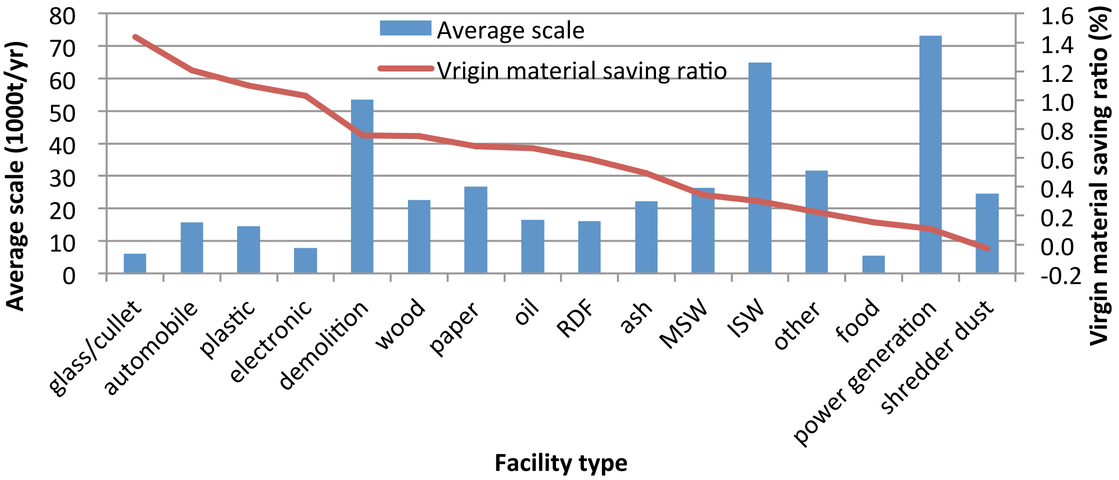


Figure 3.10 Average scale and virgin material saving ratio of different types of facilities

Average OR of various types of facilities also vary (Figure 3.11). The average OR of each type of facilities could reflect the overall supply and demand condition of that waste. However, average ORs shown in Figure 3.11 are less dispersed than the ones of individual facilities illustrated in Figure 3.9. This difference indicates that even the same type of facilities could have very different operating rates. Thus, in addition to the total supply and demand condition, local factors such as scale of facility, technological efficiency, and management level, do have strong impacts on OR.

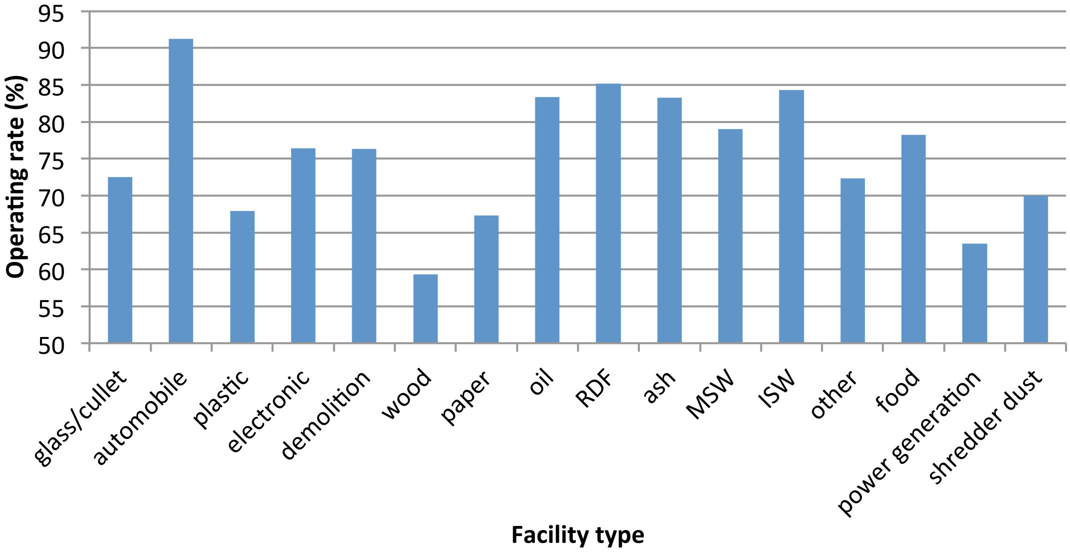


Figure 3.11 Operating rates of different types of facilities

Scale and recycling boundary

Figure 3.12 illustrates the average waste collection and product delivery distances of the 23 sample eco-towns. The same as in Figure 3.6, the total amount of waste treated in the eco-towns, or scale, is in descending order from left to right. The average distances of waste collection and product delivery within different eco-towns fluctuate dramatically from nearly above 10 km (almost collecting all wastes from and delivering all products to the located city) to nearly below 100 km (almost collecting all wastes from and delivering all products to outside the located prefecture). There is no apparent correlation between scale and the waste collection distance (see Table 3.5for detailed statistical results). That is, projects have a large capacity not necessary indicate they collect waste from long distances; it can be a result of they treating wastes that generated in large amounts locally.

However, scale appears to be negatively correlated with product delivery distance at both eco-town and facility levels (Figure 3.12 and Figure 3.13) (Table 3.4 and Table 3.5). That is, small recycling facilities are flexible in delivering products to remote users, whereas large ones are inclined to situate closer to their "customers" who use their recycled materials.

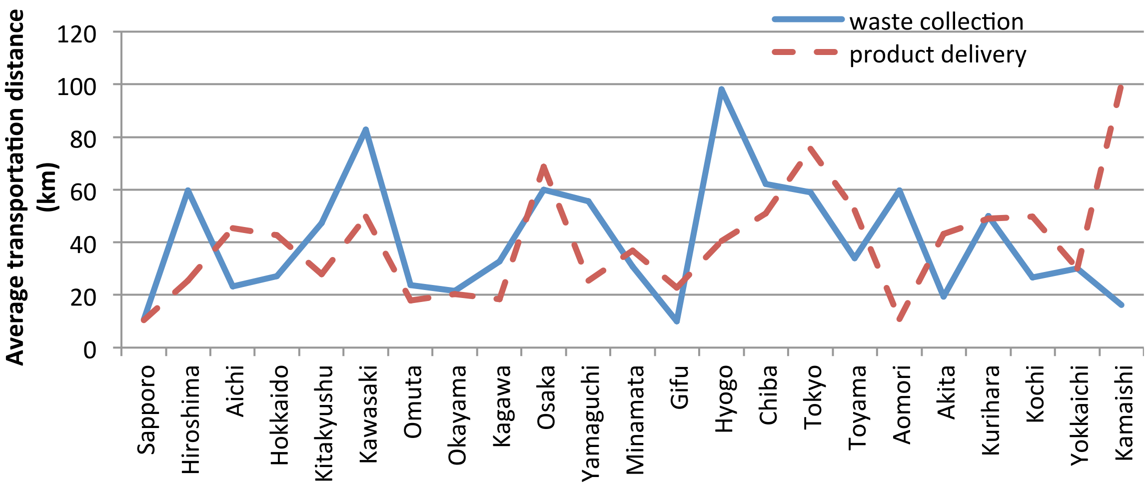
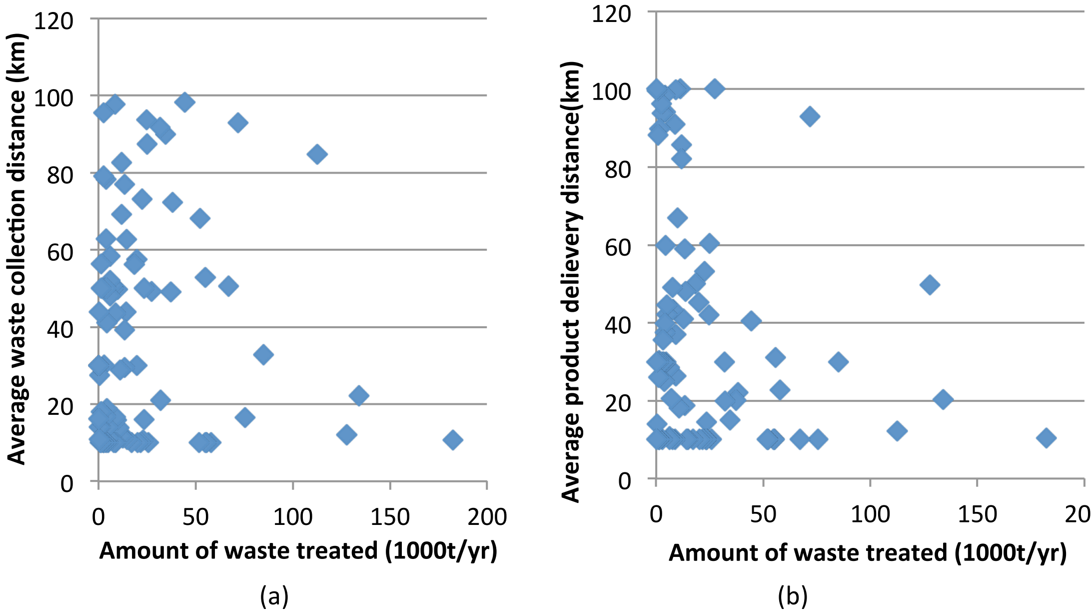


Figure 3.12 Average waste collection and product delivery distances of eco-towns



(a)

(b)

Figure 3.13 (a) Average waste collection distance of sample projects. (b) Average product delivery distance of sample projects

Types of wastes and recycling boundary

Another factor that is relevant to the recycling boundary is the type of waste that determines mostly the suitability, transportation cost and the value of recycled products. Figure 3.14 shows the average collection distances of each type of wastes and the delivery distance of each type of recycled products. Wastes that are costly for transportation and have relatively low market value, such as MSW, debris, wood, and feces, are mostly collected from the city where the recycling facility locates. On the contrary, metal, WEEE, plastics, paper, automobile shredder dust (containing metals), and oil are mostly collected in long distances. The demand side also shows the similar trend. Recycled products that are costly for transportation and low-valued are usually delivered in short distances, whereas high-valued products that are relatively cheap for transportation are delivered in long distances. In addition, in cases where most of the recycled products become inputs for industrial production by particular users (e.g. construction materials and feedstock for iron and cement production), the transportation distances also tend to be short. In such cases, the demand for recycled products is spatially more concentrated than the generation of wastes. Therefore, locating close to the customers is more likely to reduce transportation and transaction costs.

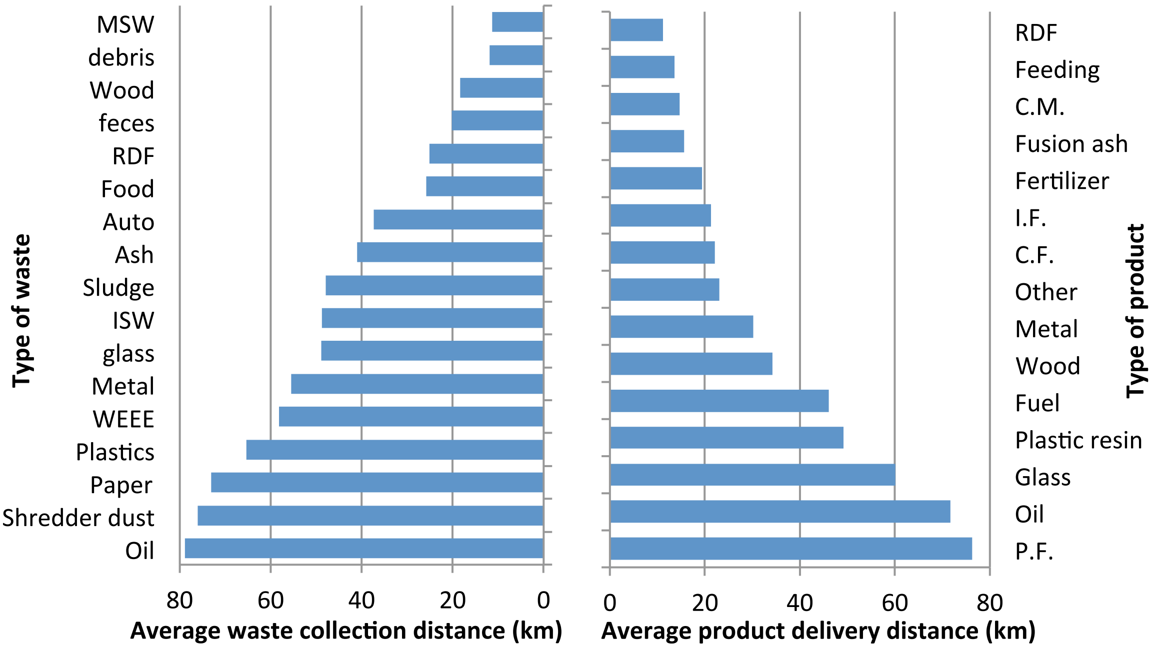


Figure 3.14 Average transportation distance of different types of wastes and products

Note: C.M. = construction material, I.F.= iron production feedstock, C.F.= cement production feedstock, P.F.= paper production feedstock and recycled paper.

In addition to the average transportation distances, the total distances of waste collection and product delivery are also important as they could describe the intensity of transportation of waste and recycled products. Figure 3.15 shows that wastes that are usually collected in long distances, which are also relatively high-valued, are not always in large total transportation distances. Wastes with large total collection distances include waste plastics, ISW, and waste paper. For facilitating information sharing, transaction, and qualification management, there are government affiliated associations in charge of managing these wastes, such as the Japan Containers and Packaging Recycling Association for waste plastics and paper containers and the National Federation of Industrial Waste Management Associations for ISW. The result indicates that in addition to the value and property of wastes, institutional supports also play an important role, especially for long distance transportation of wastes with large volumes.

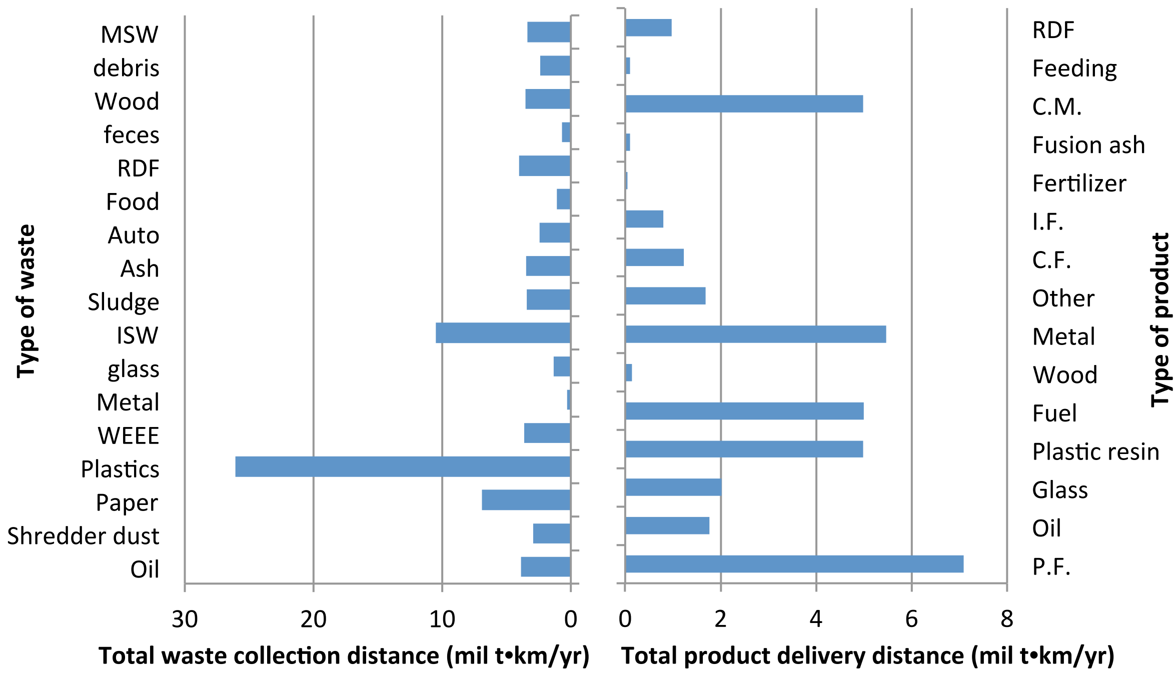


Figure 3.15 Total transportation distance of different types of wastes and products

3.1.4 Discussions

The analysis above has touched upon scale (i.e., amount of waste treated), VMS, OR, and recycling boundary (i.e., waste collection and product delivery distances) of the 23 eco-towns and 88 sample recycling projects. In general, larger scale would lead to more stable operation and more VMS, and appear to be closer to users of the recycled products. As illustrated in Figure 3.9 and Figure 3.13, most of the sample projects are in small scales. Only 14 out of 88 sample projects treated over 50,000 tons of waste in 2007. These projects include, by facility type, power generation (3 projects), MSW (2), demolition (2), ISW (2), RDF (1), wood (1), paper (1), ash (1), and other (1). Except for ISW and paper recycling projects, most of them receive wastes generated in large volumes and collected from the adjacent areas (Figure 3.14). Large projects do not necessarily collect wastes from long distance away for the region generates enough waste for their operation. On the contrary, for projects recycling wastes that are spatially diffuse, such as plastics, paper, and WEEE, the scale is subjected to the amount of available waste because to gather a relatively large amount usually requires long distance transportation and transaction that are more difficult to manage.

The analysis also revealed that agglomerated eco-towns have not shown advantages in their performance to dispersed eco-towns. Considering EIPs as a type of cluster policy, Deutz and Gibbs (2008) summarized three "meta-themes" that contribute to the competitive advantage of EIP projects: external economies of scale, networking, and policy. If one assumes that policies are almost identical to all eco-towns, the drivers that could make agglomerated eco-towns advantageous are the opportunity of better networking (e.g. personal linkage and industrial symbiosis) offered by geographical proximity and external economies of scale (e.g. access to factors for production and supporting institutions). However, such connections among projects in agglomerated eco-towns are not strong. Totally 29 by-products exchanges in 12 eco-towns were found, among which only 16 were in 8 agglomerated eco-towns. No waste exchanges among projects were reported in half of the agglomerated eco-towns. Facilities receiving similar types of wastes are competitive with one another in the market rather than collaborative. The concentration of the same type of facilities in the same eco-town is not uncommon: for example, five food waste recycling plants are located in Hokkaido eco-town, five plastic recycling project in Sapporo and Hiroshima eco-towns respectively, and 4 wood recycling plants in Aichi eco-town. Most of food (5 out of 6), plastic (14 out of 17) and wood (4 out 9) facilities already reported that they found themselves in difficulties to collect enough waste for operation. In theory, the conditions for the diminishing role of location in competition include open global market and faster transportation to acquire enough inputs at low costs for production (M. E. Porter, 1998). As for waste management, in principle, each municipality is responsible for managing their own waste. Cross-region movement of waste would induce additional transaction cost. As eco-town projects work mostly on waste recycling and processing, the competitive advantage of clusters may not be apparent if wastes are not well separated and collected.

The variances of waste collection and product delivery distances indicate that, in general, the recycling boundary is dependent largely on the type of waste and recycled products, in terms of the relative cost of transportation and whether particular users of the recycled products exist. Although our categorization of waste is different from the one given by Lyons (2007), the results of these two studies share some commonalities in the recycling boundaries of several types of wastes (Table 3.6). Plastic and paper could be recycled in large areas, whereas organic wastes might only be suitable for local recycling. The fact that all the listed wastes but organics are collected in larger areas in Japanese eco-towns could be attributed to the existence of national agencies for managing these wastes and facilitating cross-prefecture transaction of waste recycling. Because the Eco-Town program has been a national government-driven program, such institutional support, in addition to policies and regulations, could better facilitate recycling activities.

Table 3.6 Comparison of recycling boundaries between Japanese eco-towns and Texas, USA

Waste	Waste collection boundary		Product delivery boundary	
	Japanese	Texas*	Japanese	Texas*
Plastics	L	L	L, M**	L
Paper	L	S/M	L	L
Metal	M/L	S	M	M
Electronic	M/L	S	M	S/M
Organic	S	S	S	S/M

Note: L = long distance (mainly outside the prefecture or state), M = medium distance (mainly within the prefecture or state), S = short distance (mainly within the city).

*: source: (Lyons, 2007)

**: depending on different type of products. Plastic resin is delivered in relatively long distance, while plastic reducant as feedstock to iron production is delivered in medium distance

To summarize the discussion, the analysis of recycling projects in eco-towns offers three valuable insights. First, large projects are more stable in operation and locate closer to the users of recycled materials than small projects. Second, agglomeration of recycling facilities in eco-towns does not appear to have advantages over dispersed eco-towns. Third, recycling boundaries depend heavily on the type of wastes.

The survey data on recycling facilities in eco-towns allowed us to examine the features of the processing of recyclable wastes. Recycling also involve other processes such as source separation, collection, and pre-treatment. What are the spatial features of recycling activities in these processes? The next section takes waste plastics recycling as an example, to demonstrate the spatial feature of waste being recycled at the regional level.

3.2 Spatial Analysis of Recycling Activities

Municipal governments in most cases are responsible for safe management of wastes generated within the boundary of their administrative areas. Trans-boundary movements of wastes are usually constrained unless permitted by particular local ordinance or delivered to qualified treatment facilities under agreements. From the life cycle perspective, recycling typically includes several stages from waste generation/separation and collection to processing and utilization of recycled materials. While the life cycle thinking has been applied widely on assessment and management of wastes, the spatial analysis of multiple life cycle stages of recycling and waste management is rarely found in literature. This section takes waste plastic recycling in Japan as an example and analyzes the spatial organization of its generation, treatment (incineration together with combustible wastes), separation/collection, and recycling processing.

3.2.1 Current Waste Plastic Recycling System in Japan

In Japan, mix garbage is collected and treated mostly by municipalities or cooperatives of municipalities. In the Tokyo Metropolitan Region, 80 waste management cooperatives (kumiai) have been formed by 225 municipalities. Recyclable wastes are also mostly collected and pre-treated by municipal governments. The only exception is waste paper, a large amount of which is collected and pre-treated by private cooperatives or directly delivered to recyclers for processing (Figure 3.19). Except for waste paper, the amount of recyclable wastes collected is relatively small, so that the scale of municipal recycling centers for pre-treatment is usually small.

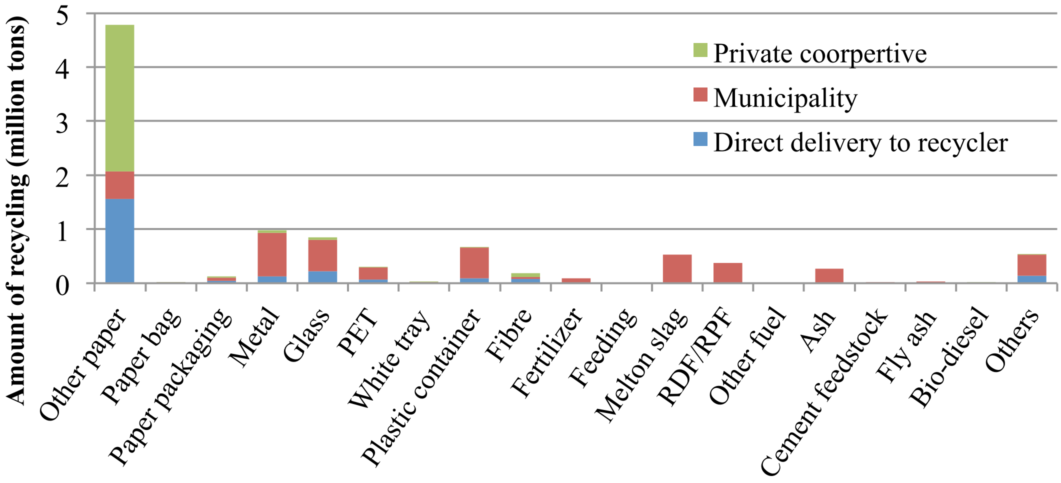


Figure 3.19 Collection and pre-treatment of recyclable wastes from municipalities in Japan

Most waste plastics from municipal sources are plastic containers and packages, including PET bottles and non-PET plastic containers and packaging. These waste plastics are recycled in accordance with the Container and Packaging Recycling Law. This Law was first released in 1995, and revised in 2006. In April 2008, the revised Containers and Packing Recycling Law was enforced completely, and a system was implemented in which extended producer responsibility was employed (MOE, 2010). The Law stipulated the responsibilities of stakeholders for recycling waste plastics. The manufacturers of containers and packaging, and retailers and importers that utilize the containers and packaging are “specified business entities” (Tokutei Jigyousya) who assume the obligation of recycling and thus provide treatment fees to recyclers. Consumers are requested to separate containers and packaging at source according to the collection service schedule offered by municipalities. Municipalities should collect, further select, clean, and properly store separated waste containers and packaging. Recyclers should take the sorted waste containers and packaging from municipalities and process them into recycled materials or products. In order to smoothly promote such recycling scheme, a government-designated organization, the Japan Container and Packaging Recycling Association (JCPRA) was established under the Law. To fulfill their obligations, municipalities can either contract recyclers to treat their waste containers and packaging directly, or pay a commission fee to the JCPRA, who operate an open bidding system for recyclers to bid for recycling waste plastics (Figure 3.16). As of the end of 2009, 1287 out of 1751 cities and counties in Japan separately collected waste non-PET plastic containers and packaging with a total amount over 688 kilo tons, which almost seven timed that in 2000 (Figure 3.17). Among the total amount of non-PET waste plastics collected, 90% was processed by recyclers contacted through JCPRA.

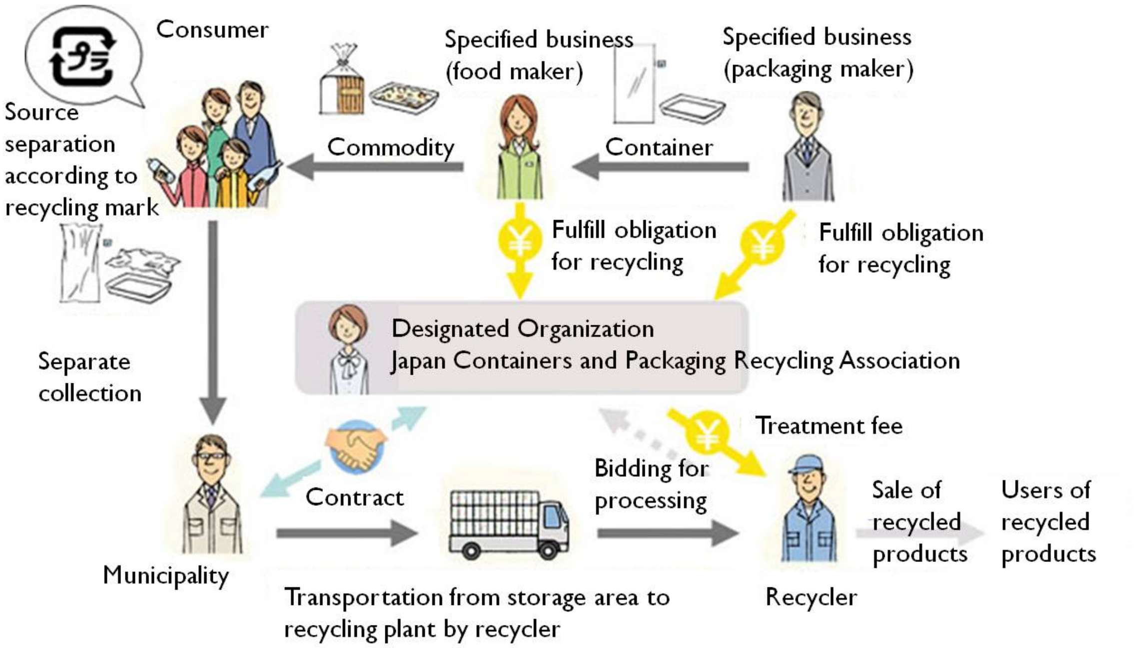


Figure 3.16 Waste plastics recycling in Japan

Source: Japan Container and Packaging Recycling Association (JCPRA). Retrieved in June, 2011 at http://www.jcpra.or.jp/law/what/index.html

3.2.2 Methodology and Data

For analyzing the spatial features of recycling activities, we consider a simple material flow of non-PET waste plastics. A part of waste plastics are separated at sources and then collected by municipalities or designated companies. Waste plastics remaining in the garbage stream are often incinerated with other combustible wastes, and those separated are usually further selected, compressed and packaged in bales in municipal recycling centers and picked by recycling companies for processing. These activities are usually enclosed in the assessment boundary of LCA studies, but geographically may be separated in different places and operated by different agents. To scrutinize the spatial feature of recycling, spatial agglomeration of these processes were tested, and if so, where these centers are.

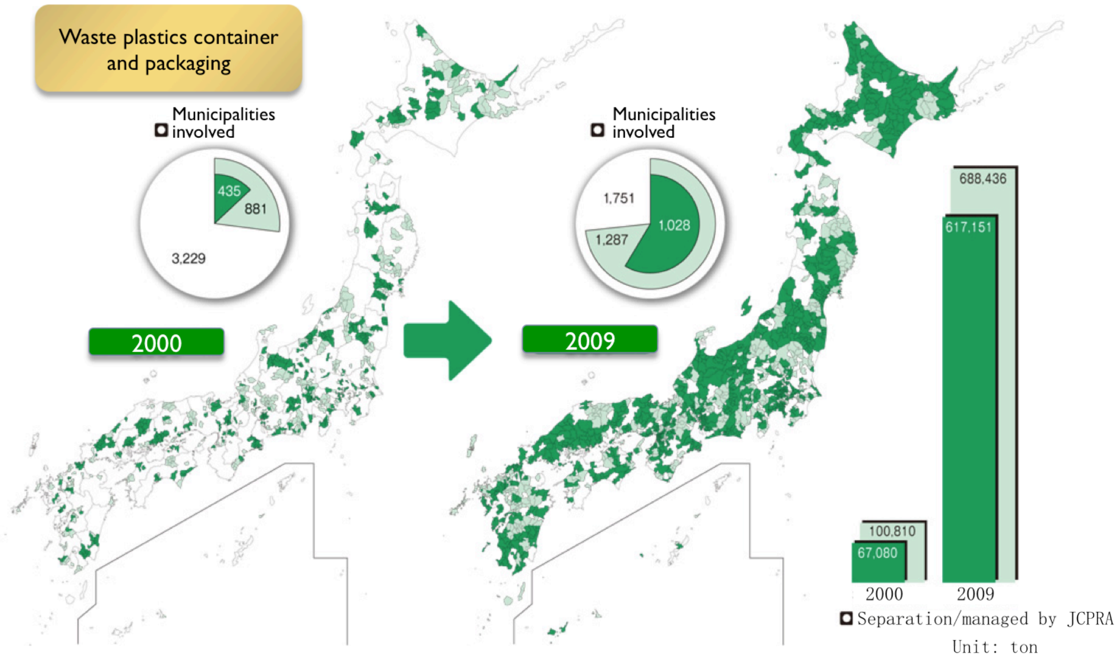


Figure 3.17 Recycling of waste plastics containers and packaging

Source: JCPRA

In order to illustrate the spatial concentration of each of these activities, the concept of location quotient (LQ) in regional economics was employed. In regional economics, LQ was developed and often applied to identify specialization of given region for analyzing its economic base (Chiang, 2009). LQ is determined as the ratio of employees in one industry to the total employees in one city/region to the same ratio in the country. The higher the LQ of an industry in a city/region, the more agglomerated that industry in that city/region. Here, LQ is modified for the purpose to illustrate the relative concentration of recycling activities. The LQs of waste plastic generation, separation/collection, incineration, and processing are defined as:

$$\mathrm{LQ}_{\mathrm{a,i}} = \frac{\mathrm{WP}_{\mathrm{a,i}}/\mathrm{N}_{\mathrm{i}}}{\mathrm{WP}_{\mathrm{a,n}}/\mathrm{N}_{\mathrm{n}}} \qquad \text{(eq. 3.5)}$$

where WP denotes the amount of waste plastics, N denotes population, and subscripts a, i, n denote activity $a \in$ (generation, separation/collection, incineration, recycling processing) or population N in prefecture i or in the whole nation indicated by n. Similar to the economic LQ, LQa,i with a value greater than 1 indicate activity a is relatively concentrated in prefecture i in comparison with the national average; the higher the LQa,i, the more concentrated of activity a in prefecture i.

Data on waste generation, incineration, and total recycling were obtained from Ministry of the Environment (http://www.env.go.jp/recycle/waste_tech/ippan/index.html). Data on population were obtained from e-Stat, a public statistical database managed by the Japanese government (http://www.e-stat.go.jp/SG1/estat/eStatTopPortal.do). Data on waste plastics recycling (PET bottles excluded) were obtained from the Japan Containers and Packaging Recycling Association (JCPRA) (http://www.jcpra.or.jp/archive/index.html). To keep consistency in time, all data were in 2008, at which time the obligated amount of non-PET waste plastic packaging and containers to be recycled, as required by the Container and Packaging Recycling Law, was 772 kilo tons. The amount of waste plastic processing contracted through the JCPRA system was 669 kilo tons, accounting for 87%. That is, the data from JCPRA basically represent the overall condition of waste plastics in Japan. The data from JCPRA were originally categorized by sources and re-categorized by the location of recycling firms so as to show where the recycling processing activities are clustered.

3.2.3 Results and Discussions

The distributions of LQs in different life cycle stages of plastic recycling vary significantly. Along with the direction of waste flow from generation, separation/collection to recycling processing, the variation of LQs across prefectures increases (Figure 3.18). Variation in recycling processes is much larger than the LQ of incineration (Figure 3.18). The distribution of incineration is fairly even over the country, mainly because each municipality is required to properly manage their own wastes.

On the contrary, plastic recycling is clustered in a few places. Large clusters include Hokkaido, Akita-Miyagi, Kanagawa-Chiba, Toyama-Niigata, Fukui-Shiga, Hiroshima-Yamaguchi, and Fukuoka-Oita area. This result implies that waste plastics are transported across prefecture boundaries for processing. It agrees with the results in the previous section that waste plastics were among the types of wastes with large recycling boundaries.

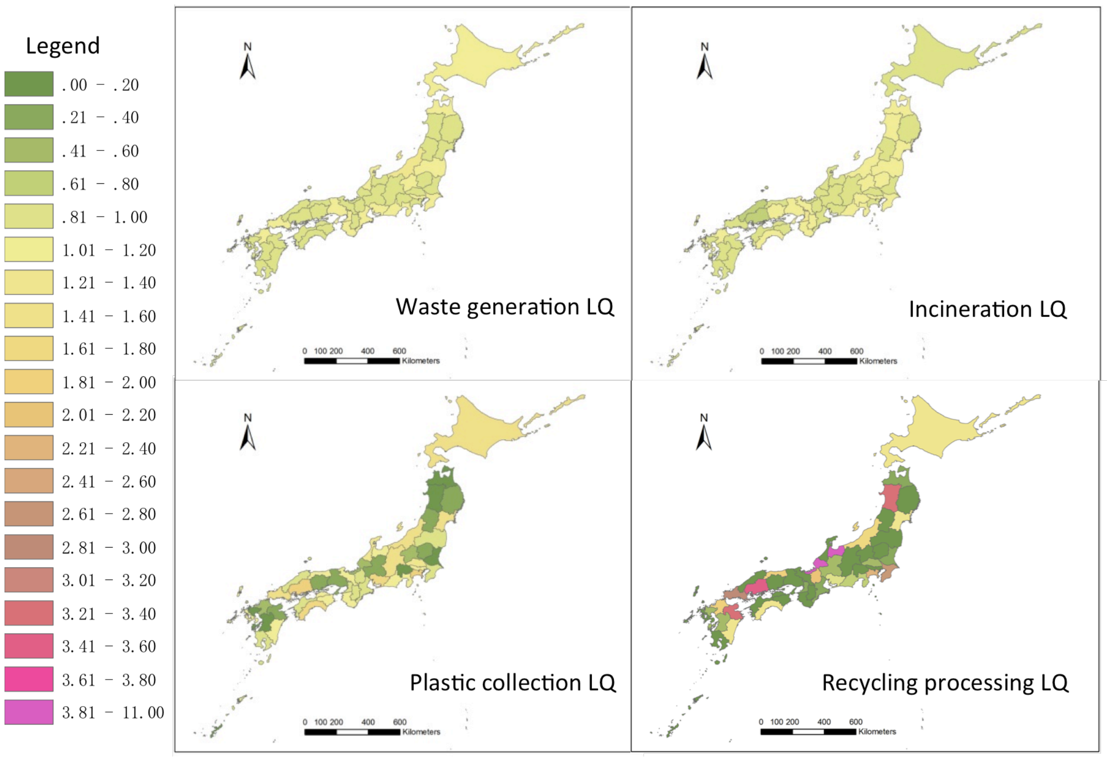


Figure 3.18 The location quotients of waste generation, incineration, plastic collection and packaging and recycling processing.

Most clusters of recycling processing include eco-towns in which advanced recycling technologies have been developed and applied. Seeing the potential of business, a number of entrepreneurs invested in plastic recycling businesses. The treatment capacity has exceeded supply of recyclable waste plastics, resulting in the average operating rate of sampled eco-town facilities being below 70% (Figure 3.11). In order to further promote recycling at the regional level, a system that supports these clusters is needed in terms of efficient collection and pre-treatment.

3.3 Summary

This chapter analyzed spatial features of individual recycling facilities and agglomeration of recycling processing in prefectures. The findings show that large recyclers appear to be more stable in operation. Agglomeration of recycling facilities in eco-towns does not appear to have advantages over dispersed eco-towns. Recycling boundary differs for different types of waste. For processing waste plastics, clusters are present. Although the recycling facilities have different functions than regional recycling centers, they face similar conditions in terms of collecting wastes from spatially diffuse facilities. With facilitations of designated organizations, such as the JCPRA, recycling of several types of wastes are already at the regional level. The findings on recycling facilities and agglomeration of recycling processing could shed lights on analyzing and designing regional recycling networks. Transportation cost is likely to affect the recycling boundaries because wastes that are costly for transportation appear to the recycled locally. This result also implies that the theory on determining recycling boundaries according to the trade-off between economies of scale and transportation costs is valid. Based on this theory, an optimization model is developed and introduced in the context of planning for regional recycling networks.

Reference

Chiang, S. H. (2009). Location quotient and trade. *Annals of Regional Science, 43*(2), 399-414.

Deutz, P., & Gibbs, D. (2008). Industrial Ecology and Regional Development: Eco-Industrial Development as Cluster Policy. *Regional Studies, 42*(10), 1313-1328.

Fujita, T. (2006). *Eco-Town Projects/Environmental Industries in Progress*: The Ministry of Economy, Trade and Industry, Japan.

GEC. (2006). *Legal and Other Support Systems for Eco-Towns in Japan*. Osaka: Global Environment Center Foundation.

Government of Japan. (2008). *The Second Fundamental Plan for Establishing a Sound Material-Cycle Society (Draft in Japanese)*. Tokyo.

Lyons, D. I. (2007). A spatial analysis of loop closing among recycling, remanufacturing, and waste treatment firms in Texas. *Journal of Industrial Ecology, 11*(1), 43-54.

MoE. (2003). *The Fundamental Plan for Establishing a Sound Material-Cycle Society*. Tokyo: Ministry of the Environment.

MoE. (2007). *Annual Report on the Environment and the Sound Material-Cycle Society in Japan 2007*. Tokyo: Ministry of the Environment.

MoE. (2008). *The 2nd Fundamental Plan for Establishing a Sound Material-Cycle Society*. Tokyo: Ministry of the Environment.

MOE. (2010). *Establishing a sound material-cycle society: Milestone toward a sound material-cycle society through changes in business and life style*. Tokyo, Japan: Ministry of the Environment.

Porter, M. E. (1998). Clusters and the New Economics of Competition. *Harvard Business Review*(Nov.-Dec.), 77-90.

Porter, R. C. (2002). *The Economics of Waste*. Washington, DC: Resources for the Future.

van Berkel, R., Fujita, T., Hashimoto, S., & Fujii, M. (2009a). Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. *Environmental Science & Technology, 43*(5), 1271-1281.

van Berkel, R., Fujita, T., Hashimoto, S., & Geng, Y. (2009b). Industrial and urban symbiosis in Japan: Analysis of the Eco-Town. *Journal of Environmental Management, 90*, 1544-1556.

Chapter 4 Methodology for Planning and Evaluation of Regional Recycling System

This chapter introduces the models for optimizing the number, capacity, and locations of regional recycling centers (RRCs) and allocation of their service areas in the case study region, as well as the life cycle analysis (LCA) model for assessing the associated environmental impacts. In practice, these works should be involved in the planning process for regional recycling. This chapter begins with an introduction of a planning framework to show the roles these models would play before elaborating details of the models.

4.1 An Planning Framework for Regional Recycling Networks

With reference to the planning models reviewed in Chapter 2, a framework of planning for RRCs is shown in Figure 4.1. It follows the basic structure of rational comprehensive models (RCM), and integrates with adaptive models for solving optimizing number, capacity and location of RRCs and participatory models for consultation with stakeholders (e.g. government, experts, professionals, NGOs, and residents). In case studies on local waste management systems, Chen et al. (2010b) found that common understanding and collaboration among these stakeholders are important for efficient management. Therefore, they should be involved in early stages of planning. The planning process starts from defining goals and objectives. Then, relevant data required in the following processes need to be collected and managed. Given possible recycling technologies and demands for recycled materials, including opportunities for utilizing wastes in industrial facilities, need to be identified. In this step, the corresponding function of the RRCs needs to be determined for providing separated wastes that meet the requirement of recycling technologies. Uncertainties and alternative operational options should be considered in the next step, in which various scenarios are to be designed to test the impacts of uncertainties and operational options. Next, the optimal number, capacity, and location of RRCs need to be determined, and corresponding environmental impacts are to be assessed. Due to practical reasons (e.g. land use, public opposition), the real implementation may not be the optimal result as modeled. Such a decision need to be made through consultation with stakeholders to reach consensus. Policies and measures need to be proposed for implementation in the next step. After the operation of RRC starts, regular monitoring and assessment need to be conducted. Feedbacks can be helpful to modify the working process for revising the plan in the future and for preparing similar plans in other regions.

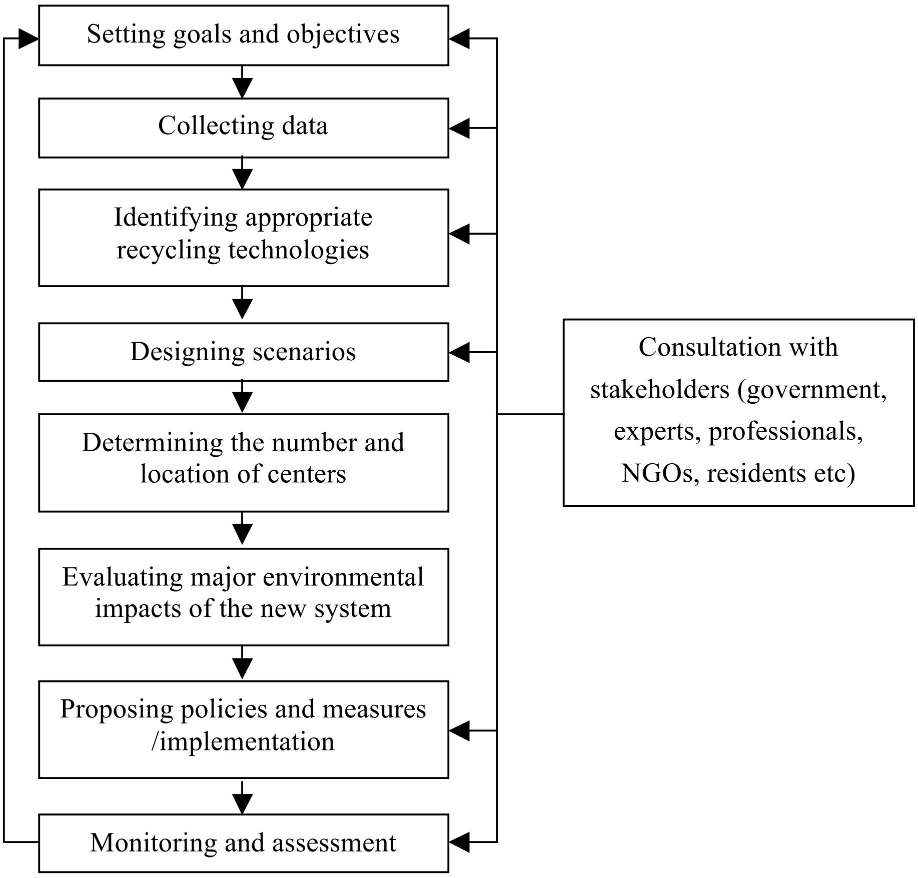


Figure 4.1 Planning framework for regional recycling network and RRCs

As a part of the author's doctoral study, this research can not demonstrate all the processes for a real planning project. This dissertation rather focuses on developing models for siting RRCs, evaluating environmental impacts, and proposing policies. In the following chapter, models are applied in a case study on waste plastics recycling in the Tokyo Metropolitan Region of Japan, and results can be implied to planning for other types of wastes. The outcomes of this research would contribute to the development of "recycling blocks" policies in Japan.

4.2 Recycling Technologies and Function of Regional Recycling Centers

For planning RRCs, it is important to identify suitable recycling facilities and industrial facilities as the destinations of the waste treated in RRCs. Their demands also determine the type of waste to be separated and the degree of separation. Unlike landfill and incineration, for which most countries already issued technical standards, recycling involves a number of different technologies. For example, waste plastics can be recycled by various mechanical recycling, chemical recycling, or energy recovery technologies (Al-Salem et al., 2009); sewage sludge can be treated by agricultural landspreading, incineration, wet oxidation, pyrolysis, incineration in cement kilns, and anaerobic digestion (Houillon & Jolliet, 2005; Wong et al., 2008); food waste can be treated by composting, anaerobic digestion, and wet or dry feeding (Kim & Kim, 2010; Levis et al., 2010). Choosing different technologies could result in differences in initial investment and operational costs. Figure 4.2 shows the difference in the initial investments for a unit treatment capacity of recycling facilities in Japanese eco-towns. Unit investments on facilities for recycling of plastics, PET bottles, paper, and wood are vastly different, illustrating variations in technologies and scales. In contrast, unit investments on WEEE, rubber, MSW, RDF, metal and organics are similar. Different technologies co-exist for a mixture of economic and environmental benefits. However, no single technology appears to dominate in practice yet, and research efforts are made on evaluating these technologies from different perspectives.

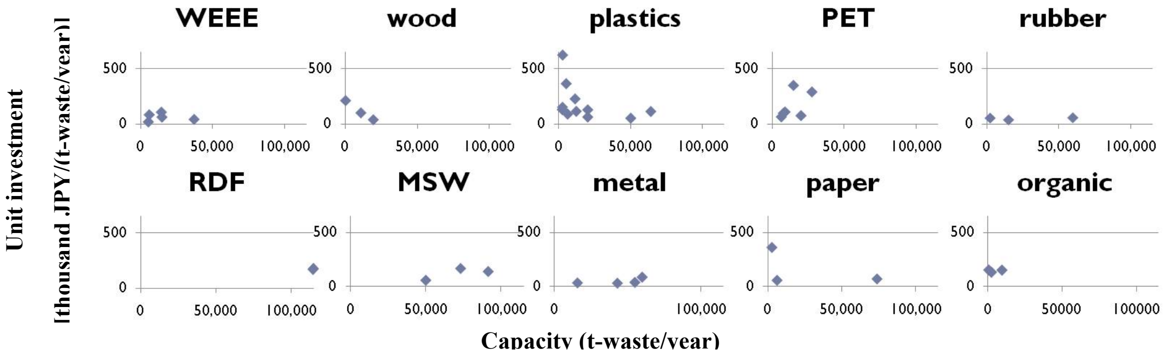


Figure 4.2 Variation in unit investment on recycling facilities

Source: processed by author and data from van Berkel et al. (2009).

Note: WEEE = waste electronic and electrical equipment; RDF = refuse derived fuel, MSW = municipal solid waste; PET = polyethylene terephthalate.

As shown in Figure 4.2, plastic recycling has the largest variation in technologies. Which technologies have high eco-efficiencies depends heavily on local conditions. First, the environmental benefits that recycling can gain are affected by the baseline against which the benefits are assessed. The "with-and-without" principle is commonly used in assessing the environmental benefits of recycling, and thus the baseline is usually the current common practice without application of the recycling technologies under study. Since the common practices in different countries and regions may be different, even for the same technology, the benefits could differ (Chen et al., 2011a). For example, substituting wood products with recycled plastics would lead to less reduction in GHG emissions in Japan than in China because in the baseline in Japan, incinerating plastics would generate anthropogenic CO_2 emissions and incinerating wood is considered carbon neutral; on the contrary, as the baseline in China, landfilling wood would generate methane and plastics in landfills become carbon sink (Chen et al., 2011b; JCPRA, 2007). Therefore, substituting materials that have heavy environmental loading in their life cycles would lead to significant benefits.

Second, recycled products and recovered energy should fit local demands. Management of the demand side is important for realizing the potential benefits as expected. In LCA studies on recycling, a 100% substitution rate is commonly assumed. If recycled products can not be effectively utilized, the expected environmental benefits could not be fully realized (Chen et al., 2011b; JCPRA, 2007). When considering recycling through industrial symbiosis, industries that locate *in the region* and are *in large scale* should be considered in priority. Local demands are preferred due to savings in transportation and convenience in communication and transaction. Users in large scales are preferred because the supply of wastes may fluctuate and large users can bare such relatively small fluctuations without compromising their production.

Third, aiming at high efficiency requires taking advantage of the value of wastes to the fullest. Separated recyclable wastes can be of various qualities in terms of contamination level, chemical composition and properties, and so forth. Especially for recycling waste plastics, high quality plastics, such as polyethylene (PE) and polypropylene (PP) with low level of contaminations, should favor mechanical recycling because they can substitute virgin materials and remain the possibility to be recycled for energy recovery. Low quality plastics can be recycled through chemical recycling or energy recovery with high efficiency, such as fuel or feedstock to industrial facilities. Taking energy recovery from waste plastics as an example, cement plant can utilize waste plastics as fuel in a much higher efficiency than incinerators (Fujii et al., 2010).

4.3 Scenario Setting

Scenarios were set for testing impacts of uncertainties and operational factors that may influence the total cost of recycling networks. For modeling and decision making, researchers and decision makers often face the lack of required information. The decision environment can be categorized according to the level of certainty. The decision environment can be (1) certain where all parameters are deterministic and known; (2) risk where uncertain parameters whose values are governed by probability distributions that are known; and (3) uncertain where parameters are uncertain and no information about the probabilities is known (Owen & Daskin, 1998; Snyder, 2006). Waste management and planning can be highly uncertain. Operational factors are often changeable to adapt to uncertain conditions, such as quantity and quality of separated wastes that can hardly be predicted precisely.

One approach to tackle the uncertainties is to determine the probabilities and reduce the problem to a risk decision environment. Probability of risks can be provided empirically to reflect accidents and impacts on population (Ahluwalia & Nema, 2006). Probabilities of parameters can also be determined by models internally and the objective function can be optimized, such as the hybrid interval-parameter possibilistic programming (IPP) approach (Zhang et al., 2010).

Another approach to deal with uncertainties is to design various scenarios to describe possible conditions and outcomes. This approach is widely applied on studies on waste management and planning related issues, particularly when using the consequential LCA approach to assess their environmental impacts (e.g. Calabrò, 2009; Ekvall & Weidema, 2004; Geng et al., 2010; Mastellone et al., 2009). Scenarios are also employed in urban and environmental planning, where planners offer different scenarios of plans and stakeholders participating in the planning process can determine which scenario is preferred. Höjer et al. (2008) distinguished three types of scenarios in research: predictive, explorative, and normative scenarios. Predictive scenarios try to predict what is going to happen. Some predictive scenarios provide predictions presented with one reference result, often the "most likely" result, while others focus on analyzing how the development depends on certain well-specified external events and internal decisions. Explorative scenarios aim to explore the future from a variety of perspectives, responding to the question "what can happen". Finally, normative scenarios take the starting point in one or several well-defined targets, responding to the question "how can a specific target be reached".

This research takes the scenario approach because the major influencing factors are mostly external to the model and can not be predicted precisely. The scenarios designed in this dissertation aim to examine the impacts of uncertain and operational factors on the optimal solution of the location-allocation problem for RRCs and the corresponding environmental impacts, and to extract key determinants for recycling boundary by comparing the results from scenarios.

The first factor considered in this research is population. Waste is generated from human activities. Population is proved to be a major factor correlated with the amount of waste generation (Chen et al., 2010a; Shan, 2010). Recently, decreasing and aging population in Japan has drawn great attention in the society. According to the projection by National Institute of Population and Social Security Research (NIPSSR), the total population would decrease, on a 2005 basis, to 96.1% and 86.1% in 2020 and 2035, respectively. Moreover, more people are expected to move to several metropolitan areas, such as Tokyo, Nagoya, and Osaka. Some rural areas would lose up to 40% of their population by 2035 (Figure 4.3). Given a region under study, both the number and distribution of population would influence the result of RRCs' locations and allocations of service areas. According to the data on population projection by municipalities from NIPSSR, predictive scenarios are set to examine the impacts of population.

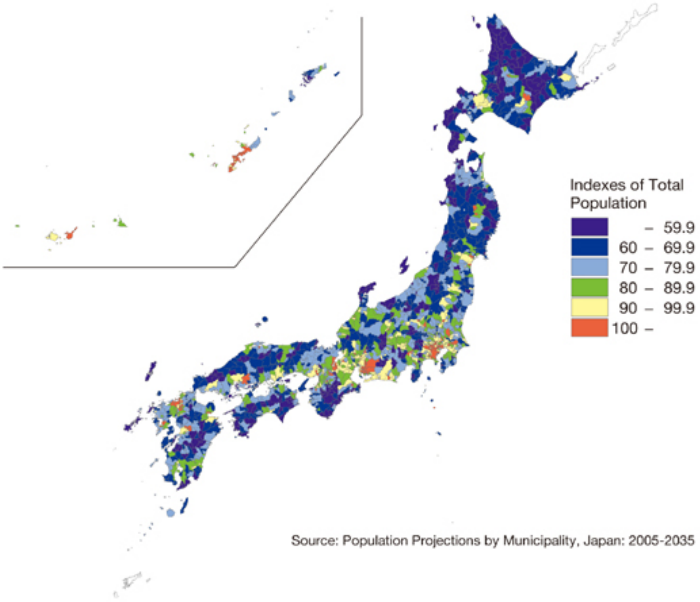


Figure 4.3 Index of Total Population in 2035 (indexes equal to 100.0 in 2005)

Source: National Institute of Population and Social Security Research. 2010 Projection of Population in Japanese by Municipalities. Retrieved in June 2010 at http://www.ipss.go.jp/pr-ad/e/eng/04.html.

The second factor that affects waste generation is per capita waste generation. Per capita waste generation in Japan had increased from the mid-80s to the end of 20th century, and continued decreasing afterwards (Figure 4.4). There are numerous factors can influence per capita waste generation, such as age, income, economic disincentives and so forth (Miranda & Aldy, 1998; Shan, 2010). Since a detail discussion about these factors is beyond the scope of this study, explorative scenarios are designed to test a decreasing trend.

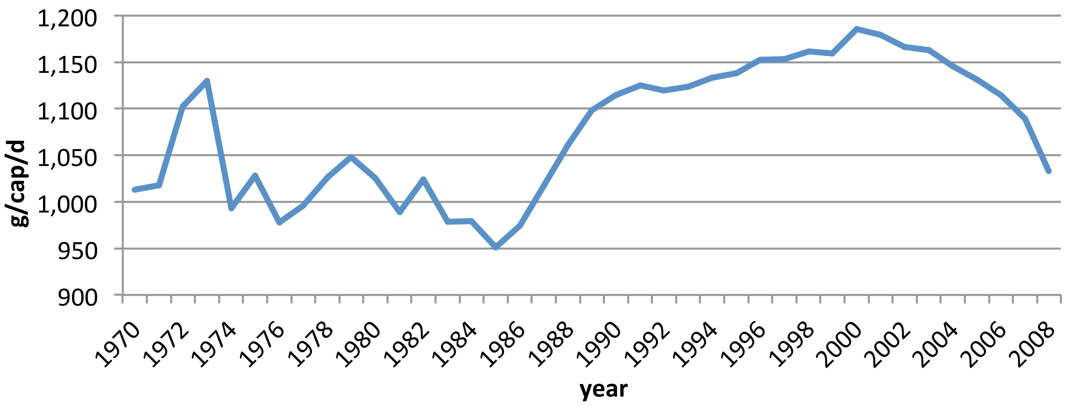


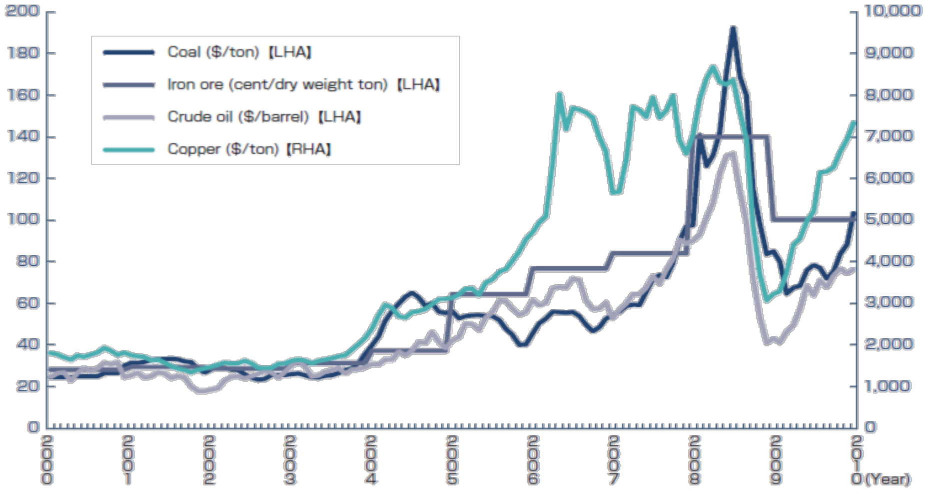
Figure 4.4 MSW generation per capita per day in Japan

Source: Ministry of the Environment. Environmental Statistical Book 2011. Retrieved in June 2011 at http://www.env.go.jp/doc/toukei/contents/index.html

Third, impacts of the recycling rate of plastics are tested. Recycling rate here refers to the ratio of weight of separated collection for recycling to weight of waste plastic generation. As discussed in the preceding chapter, the overall recycling rates have increased since 2000 but vary in different areas in Japan (Figures 3.17 and 3.18). Because current policies and regulations continue promoting recycling, it is rather safe to assume that the recycling rate in each municipality would not decrease. However, how much they can be increased is uncertain.

Forth, two factors related to the cost of transportation are taken into account: price of fuel and fuel efficiency of vehicles. In a long term, if demands do not decrease, resource prices incline to increase due to depleting reserves. However, prediction of resource prices in a short and middle terms is difficult. In the last five years, the price of crude oil, together with other natural resources, has experienced dramatic fluctuations (Figure 4.5). Therefore, scenarios are designed to examine impacts of fluctuations in fuel prices. Another factor related to transportation is the fuel efficiency of vehicles. From 2000 to 2009, the number of high-efficiency and low emission gasoline/diesel vehicles and hybrid vehicles has increased 34 and 20 times, respectively. This research does not provide extrapolation of fuel efficiencies of trucks that will be used for collecting wastes, but sets scenarios to test the trend of increasing fuel efficiencies.

Finally, three operational factors are considered: loading capacity of trucks for transporting waste plastics from municipalities to RRCs, unit construction cost, and unit labor cost. These factors are examined because not only could they reflect the impacts of estimated costs of waste plastic recycling in the case study, but also they could imply to the recycling of different types of wastes. For, example, separating waste plastics and mixed paper involves manual works and have relatively high labor costs, whereas separating steel and aluminum cans are usually processed by machines and has relatively high construction costs.



Source: Prepared by the Ministry of the Environment based on IMF, "Primary Commodity Prices"

Figure 4.5 Trends of resource prices

Source: Ministry of the Environment, Japan. Annual Report on the Environment, the Sound Material-Cycle Society and the Biodiversity in Japan 2010. Retrieved in June 2011 at http://www.env.go.jp/en/wpaper/

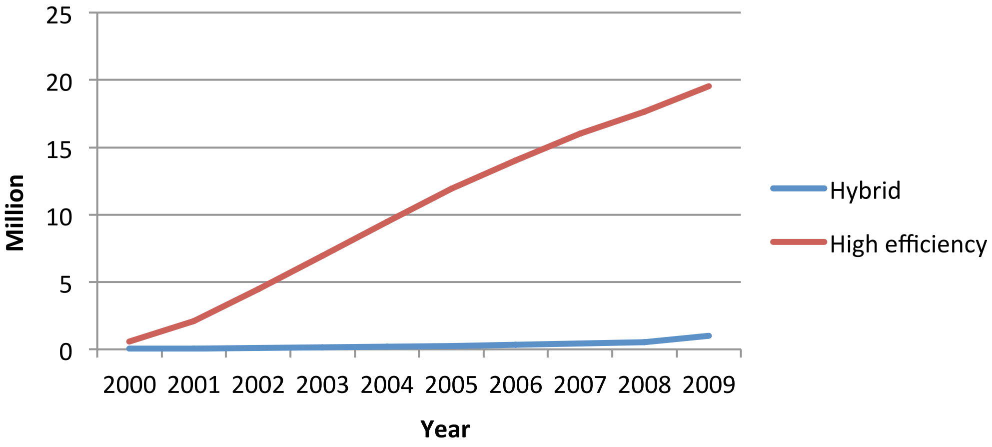


Figure 4.6 Hybrid and high efficiency vehicles in Japan

Source: Source: Ministry of the Environment. Environmental Statistical Book 2011. Retrieved in June 2011 at http://www.env.go.jp/doc/toukei/contents/index.html

To wrap up, this research designs nine sets of scenarios testing eight factors. In order to facilitate comparison, one scenario is set as the *standard scenario.* Impacts of each of the aforementioned factors are examined one set of scenarios against the standard scenario (Table 4.1). Optimization of the number, capacity, and location of RRCs and environmental impacts are calculated under each scenario. Formation and solution of the optimization problem are discussed in the next section. Values of the factors under all scenarios of the case study are presented in the next chapter.

Table 4.1 Summary of scenarios

Scenario	Factor tested
0	Standard scenario
1	Population
2	Per capita generation of waste plastics
3	Lower limit of recycling rate
4	Cost of diesel
5	Fuel efficiency of trucks
6	Loading capacity of trucks
7	Unit construction cost
8	Unit labor cost

4.4 The Location-Allocation Problem for RRCs

A number of studies in the literature have focused on siting waste management facilities. In general, determining the optimal number, capacity, and location of facilities, and allocation of their customers (or service areas) are often referred to as *location-allocation problems*, which was first defined by Cooper (1963). Studies on optimal locations of facilities are a topic of *location analysis*, which refers to “the modeling, formulation, and solution of a class of problems that can best be described as siting facilities in some given space (ReVelle & Eiselt, 2005, p. 1)”. For site waste management facilities, Spengler et al. (1997) developed a mixed-integer linear programming model for recycling of industrial byproducts and applied in German steel industry. Steel companies need to decide the recycling processes, capacity of recycling plants and their locations. The model is a modification of multi-level capacitated warehouse location problem specifically for recycling. Barros et al. (1998) applied a multi-level capacitated warehouse location model to analyze two types of facilities, regional depots and specialized treatment facilities, for the recycling of sand from construction waste in the Netherlands. Farhan and Murray (2006) developed a general model to address distance decay, coverage range, and partial regional service. One of the two cases in their study was locating recycling facilities, as undesirable facilities, in Ohio, USA. Due to the complexity of decision making on waste management, recent studies following multi-criteria methods to optimize the location of waste treatment facilities as a compromise of economic and social objectives. For example, Banias et al. (2010) employed a multi-criteria decision making technique, ELECTRE III, to optimize the locations of construction and demolition waste treatment facilities. Queiruga et al. (2008) applied another multi-criteria decision method, Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), on studying on the location of waste electrical and electronic equipment (WEEE) recycling plants. Although these models analyzed various waste treatment facilities, none of them was designed particularly for locating facilities that connect diffuse sources with a limited number of industrial facilities. Moreover, no model was found to take into accounts difference in average construction and operation costs of facilities in different scales and no model was applied for a theoretical exploration of determinants for recycling boundaries.

As for the location-allocation problem in this research, the objective is to determine the number, capacities, and locations of RRCs in a given region so that all municipalities are serviced and the total cost, including transportation, construction, and operation costs, is minimized. Intuitively, as the service area of a RRC expands, the average transportation cost increases; meanwhile, the scale of the RRC also increases so that the average construction and operation costs decrease. Therefore, there is likely to be an optimal number of RRCs to be established with specified scale, locations and allocation of service areas to each RRC in a given region.

Several key factors need to be defined when forming a problem of location analysis. First, the space in which facilities to be located can be a d-dimensional continues space, a discrete space, or a network. As most separated waste plastics are transported by trucks, the road network is used in this research to determine transportation distance and time among municipalities, RRCs, and recycling facilities. The optimization problem is thus on a network.

Second, the distance between any two points in the space needs to be defined. For example, in a two-dimensional continue space, the distance between i and j can be defined as:

$$d_{ij}^{p} = [\left|a_i - a_j\right|^{p} + \left|b_i - b_j\right|^{p}]^{1/p} \qquad \text{(eq. 4.1)}$$

where a and b are the coordinates in the space. When p equals to 1, it becomes Manhattan distance; when p equals to 2, it is Euclidean distance; and when p approaches infinite, the distance becomes Chebyshev distance (ReVelle & Eiselt, 2005). This research employs the Euclidean distance on the network, namely the real transportation distance.

Third, the objective should be defined. Desired facilities are sited for the pull objective, i.e., to minimize costs or to maximize a firm's benefit. On the contrary, undesired facilities are located for the push objective, which is often coupled with pull objectives to meet explicit or implicit requirements given the tradeoffs of the objectives involved. Some public facilities are sited for the equity objective, for which facilities are located so that consumer-facility distances are as similar to all consumers as possible (Owen & Daskin, 1998; ReVelle & Eiselt, 2005). Although recycling centers are not as desired as warehouses, they are currently present in most large cities. It is reasonable to assume that large cities are able to host regional recycling centers. At the regional level, regional recycling centers are sited for pull objectives to minimize the cost for alleviating the fiscal burden of the public sector.

Finally, some location models require that the number of facilities to be located is pre-determined, while the others internalize the number of facilities (ReVelle & Eiselt, 2005). In this research, the optimal number of p is not solved directly by the model because non-linear functions are considered. The model is solved in two-steps where a series of pre-determined ps are tested to find the optimal solution.

In a particular scenario, identifying the optimal locations of RRCs, namely the *hosting cities* of RRCs, can be seen as an uncapacitated facility location (UFL) problem on networks. Capacity constraints can be applied on individual recycling centers. A hosting city can have multiple RRCs if the amount of waste plastics it receives exceeds the capacity limit of a single RRC. Municipalities can be taken as nodes that are connected by transportation networks. Among n municipalities in total, m are taken as candidates for p hosting cities ($n \geqslant m \geqslant p$). For any given p, the problem is reduced to a p-median problem on network (Berman & Drezner, 2008; Mladenovic et al., 2007). However, the location problem in this study differs from typical UFL problems. In a typical UFL problem, the construction and operation costs for a given node are fixed so that the endogenous p and the location-allocation problem can be solved simultaneously (Maric, 2010; Tohyama et al., 2011). In this study, the construction and operation costs of a RRC are functions of the capacity of that center. Therefore, the problem is formed in two steps as follows: (1) to locate a pre-determined number (p) of hosting cities in $j \in J$ (j = 1, 2 … m, $J \in I$) to service 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 the all waste plastics in the study region is minimized. Such a two-step solution is rational in practice. Different from locating warehouses in which case the owner company could decide service areas for each warehouse at its will, RRCs receive waste plastics collected by municipalities. It is the municipalities' decision that to which RRC their waste plastics are to be delivered. Given the plan of RRCs in the region, it is rational that each municipality would choose the closest RRC, which leads to the minimization of transportation cost for any given p RRCs. The problem can be written as:

$$\min_{p} Total\ cost = \min_{\mathrm{i,j}}[\sum_{i,j} TRS_{ij}^{ce} x_{ij} + \sum_{j} (TRS_{j}^{rf} + TRS_{j}^{if})] + \sum_{j}(COS_j + OPR_j) + INCI \quad \text{(eq. 4.2.0)}$$

Subject to

$$TRS_{ij}^{ce} = w_i d_{ij} \mu^{ce} + \frac{(t_{ij}^{ce} + t^l) w_i}{Cap^{ce} \cdot T} \cdot \omega^{ce} \quad \text{(eq.4.2.1)}$$

$$w_j = \sum_i w_i x_{ij} \quad \text{(eq.4.2.2)}$$

$$TRS_{j}^{rf} = \beta^{rf} w_j d_j^{rf} \mu^{rf} + \frac{(t_j^{rf} + t^l) \beta^{rf} w_j}{Cap^{rf} \cdot T} \cdot \omega^{rf} \quad \text{(eq.4.2.3)}$$

$$TRS_{j}^{if} = \beta^{if} w_j d_j^{if} \mu^{if} + \frac{(t_j^{if} + t^l) \beta^{if} w_j}{Cap^{if} \cdot T} \cdot \omega^{if} \quad \text{(eq.4.2.4)}$$

$$COS_j = f_{cos}(w_j) \quad \text{(eq.4.2.5)}$$

$$OPR_j = f_{opr}(w_j) \quad \text{(eq.4.2.6)}$$

$$\sum_j x_{ij} = 1,\ \forall i, \quad \text{(eq.4.2.7)}$$

$$x_{ij} \leq y_{j,} \qquad \forall i, j, \tag{eq.4.2.8}$$

$$\sum_j y_j = p \ \in \{1, 2 \ldots m\}, \tag{eq.4.2.9}$$

$$x_{ij}, y_j \in \{0, 1\} \tag{eq.4.2.10}$$

$$INCI = \sum_i INCI_i \tag{eq.4.2.11}$$

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*;

d_{ij}= transportation distance between i and j via network; superscript *rf* and *if* to d_j denote distance between center in *j* to the closest mechanical recycling facility and industrial facility, respectively;

w_i = waste generated from municipal *i*;

w_j= waste treated in center in *j*;

μ = cost of gas for transporting one unit weight of waste for one unit distance; superscripts *ce*, *rf*, and if denote unit costs of the transportation mode to RRC, to the closest mechanical recycling facility, and to the closest industrial facility, respectively;

t_{ij}= transportation time between city *i* and center *j*; superscripts *ce* denotes the traveling via road network to centers and *l* denotes loading times;

t_j = transportation time between center j and recycling/industrial facilities via road network; superscript *rf* and *if* denote time between center in j to the closest mechanical recycling facility and industrial facility, respectively;

Cap = loading capacity of trucks; superscripts *ce*, *rf*, and *if* denote capacity of trucks to RRC, to the closest mechanical recycling facility, and to the closest industrial facility, respectively;

T = pre-determined total annual working time;

ω = fixed costs for one truck per year including depreciation, maintenance, and salary of the driver;

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

$INCI$ = cost of incinerating the plastics that are not separated for recycling, which is not related to the number and location of RRCs in a given scenario.

The objective function eq. 4.2.0 consists of three sums: the costs of transportation, the costs of construction and operation of the RRCs, and the costs of incinerating unseparated waste plastics. Transportation costs (eq. 4.2.1 to 4.2.4) take into account the costs of gas, depreciation and maintenance of trucks, and salary of drivers. Construction and operation costs are functions of capacity of RRCs. These functions and parameters will be specified in the next chapter for the case study Eq. 4.2.7 to 4.2.10 provide the constraints to be met for p-median problems, including every municipality is serviced by and only by one RRC and the total number of hosting cities equals to p. Finally, eq. 4.2.11 ensures that the functional unit of assessment remains the same under all scenarios as the total amount of waste plastics generated from the region under study. Unseparated waste plastics are incinerated with other combustible wastes.

The P-median problem in the first step has been proved to be NP-hard (Hansen & Mladenovic, 1997; Mladenovic et al., 2007). In operational research, many problems are classified as NP-hard For solving such NP-hard problems, “no algorithm with a number of steps polynomial in the size of the instance is known, and that finding one for any such problem would entail obtaining one for any and all of them. Moreover, in some cases where a problem admits a polynomial algorithm, the power of this polynomial may be so large that instances of realistic size cannot be solved in reasonable time in the worst case, and sometimes also in the average case or most of the time (Mladenovic et al., 2007, p. 928).” Instead of exact algorithms, p-median problems are often solved by heuristic algorithms that can quickly find a solution that is near to being optimal. Mladenovic et al. (2007) recently reviewed 19 heuristics in four types (i.e. constructive heuristics, local search, mathematical programming and meta heuristics) for solving p-median problems and concluded that the use of meta heuristics has led to substantial improvements in solution quality on large scale instances within reasonably short computing time, but there is no dominant meta heuristic method over others. In this research, the variable neighborhood search, one of the meta heuristics, was employed to solve the p-median problem (Hansen & Mladenovic, 1997). The algorithm was programmed by R® (version 2.11.1) (R Development Core Team, 2011).

Solving the p-median problem for each pre-determined p under a particular scenario, the program also determines the capacity and locations of RRCs and the allocation of their service areas, so that the construction and operation costs can be calculated on a case-specific basis. The equations to calculation construction and operation costs of RRCs and incineration costs for the case study are introduced in Appendix II.

4.5 Evaluation of Environmental Benefits of Regional Recycling through Industrial Symbiosis

Among various methods for evaluating environmental impacts of waste management, Life Cycle Analysis (LCA) is widely used. For example, LCA was used to assess and compare the potential impacts of various treatments and disposal methods on the waste hierarchy (Banar et al., 2009; Finnveden et al., 2005; Liamsanguan & Gheewala, 2008); to evaluate the applications of one method or of one type of facility on different scales (Habara et al., 2002; Lundie & Peters, 2005; Wanichpongpan & Gheewala, 2007); and to assess various treatment methods for a particular type of waste (Al-Salem et al., 2009; Cadena et al., 2009; Lundie & Peters, 2005). In most of these studies, the LCA methodology was used to assess the possible consequences of certain decisions (e.g., applying different treatment methods or establishing facilities in different locations or at different scales) by setting up multiple scenarios that represent the various options. Such an approach is often referred to as change-oriented or consequential LCA, and it describes how environmentally relevant physical flows might change in response to possible decisions (Ekvall & Weidema, 2004; Finnveden et al., 2009).

The consequential LCA method also fits the purpose of this research: to identify the environmental benefits of recycling waste plastics in the regional scale through industrial symbiosis.

The functional unit is the estimated total amount of waste generated in 2025 in the region under study, namely under the standard scenario. Since most waste plastics processed in RRCs are delivered to industrial facilities for recycling, the technologies considered in this research are *symbiotic technologies*, namely, converting waste plastics into feedstock to replace virgin materials in producing the same product as produced exclusively from virgin materials. In such a case, part of the recycling process involves production processes with modified technologies and updated facilities. The focus was on assessing the change in the inputs and outputs of the production process, as well as the yields of byproducts arising from the utilization of waste plastics. As the final products are the same, the disposal of these products is excluded from the system boundary (Chen et al., 2011b). For the unseparated plastics remaining in the garbage steam, the emissions from incineration are counted (Figure 4.7). In responding to the multiple environmental pressures, particularly on global warming and resource depletion, the impact category in this research includes CO_2 emissions (global warming potential) and fossil fuel saving (preventing resource depletion). The emission factors of process for the case study are introduced in Appendix II.

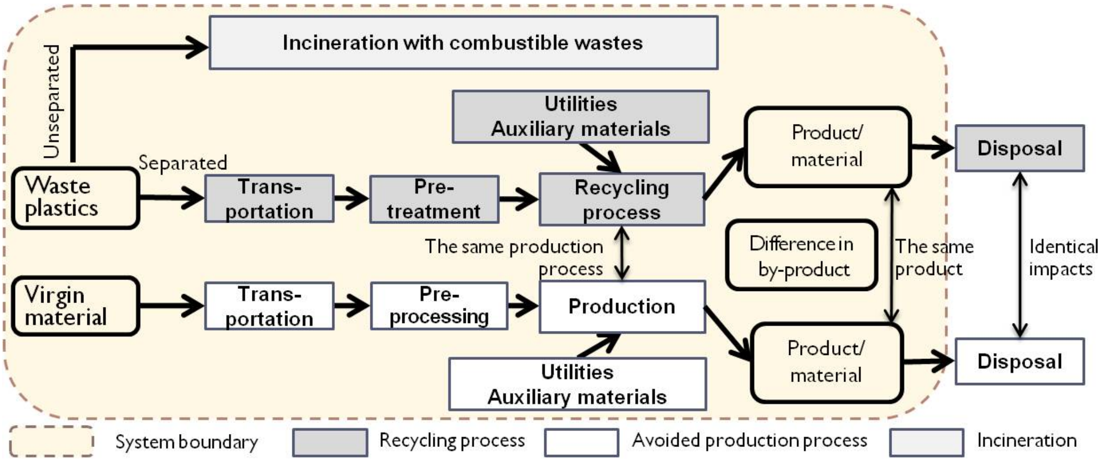


Figure 4.7 System boundary of life cycle assessment

4.6 Future Development of Models

Although the models were carefully selected and modified to fit the objectives of this research, they are not free of shortcomings. First, the models are applied on a case study area with a confined boundary. In some cases, waste plastics are transported across the boundary before being recycled. For example, an industrial facility in Kawasaki received waste plastics generated from Nagoya as feedstock in its production[4]. In order to deal with such open boundary issues, the current models need to be modified in terms of estimating, for example, the material flows crossing the boundaries and average distances to sources and destinations, and determining the principles for allocating the environmental impacts associated with the cross-boundary material flows. These tasks require a large amount of data. To some extent, the boundary conditions are ultimately set based on some assumptions or estimations. The case study in this research covers a large urban and rural area with different population densities, which could demonstrate meaningful findings. Due to limitation of resource and time, this research applied the models on such a case study with a confined boundary.

Second, due to limitation in data, the model takes account only for road transportation. Railway and waterway transportation modes could also be used for transporting waste and recycled products at lower costs. This limitation would result in an overestimation of the transportation cost and environmental impacts. Third, also because of limitation in data and information, this research does not consider the possibility of update existing municipal recycling centers to RRCs. All RRCs in the discussion are assumed to be new constructions. This assumption would result in an overestimation of construction costs and environmental impacts. Finally, progress in technology is not accounted in the models. All the inventory data on treatment and industrial technologies are acquired from surveys on current technologies or literature. As technology develops, the resource efficiency is expected to increase. However, the impact of cost is rather uncertain.

4.7 Summary

This chapter positions the models employed in this research in the context of planning for regional recycling network. It provides a practical justification to the case study on which the models

---

[4] Based on personal contact with the manager of that company during the Eco-Tech Fair 2011 held in Kawasaki.

are applied in the following chapter. In such a context, selection of recycling technologies, scenario designs are discussed. The scenarios aim to test impacts of uncertainties and operational factors that may influence the total cost of regional recycling system. The modification of a location optimization model is then introduced, taking account economies of scale in construction and operation of RRCs and in incinerating unseparated plastics. Finally, an LCA-based model is introduced for assessing the reduction in GHG emissions and saving of fossil fuels. Applying these models, the case study on waste plastics recycling in Tokyo Metropolitan Region is elaborated in the next chapter.

Reference

Ahluwalia, P. K., & Nema, A. K. (2006). Multi-Objective Reverse Logistics Model for Integrated Computer Waste Management. *Waste Management & Research, 24*(6), 514-527.

Al-Salem, S. M., Lettieri, P., & Baeyens, J. (2009). Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Management, 29*(10), 2625-2643.

Banias, G., Achillas, C., Vlachokostas, C., Moussiopoulos, N., & Tarsenis, S. (2010). Assessing multiple criteria for the optimal location of a construction and demolition waste management facility. *Building and Environment, 45*(10), 2317-2326.

Barros, A. I., Dekker, R., & Scholten, V. (1998). A two-level network for recycling sand: A case study. *European Journal of Operational Research, 110*(2), 199-214.

Berman, O., & Drezner, Z. (2008). The p-median problem under uncertainty. *European Journal of Operational Research, 189*(1), 19-30.

Calabrò, P., S. (2009). Greenhouse gases emission from municipal waste management: The role of separate collection. *Waste Management, 29*(7), 2178-2187.

Chen, X., Fujita, T., Geng, Y., & Xi, F. (2011a). Exploring and Assessing Innovative Approaches to Utilizing Waste as a Resource: toward Co-Benefits. In *Waste Management* (pp. 83-96): InTech.

Chen, X., Geng, Y., & Fujita, T. (2010a). An Overview of Municipal Solid Waste Management in China. *Waste Management, 30*, 716-724.

Chen, X., Haight, M. E., Geng, Y., & Fujita, T. (2010b). Managing municipal solid waste from a system perspective: A comparative study of Dalian, China and Waterloo, Canada. *Sustainable Development, 18*(5), 282-294.

Chen, X., Xi, F., Geng, Y., & Fujita, T. (2011b). The potential environmental gains from recycling waste plastics: Simulation of transferring recycling and recovery technologies to Shenyang, China. *Waste Management, 31*, 168-179.

Cooper, L. (1963). Location-Allocation Problems. *Operations Research, 11*(3), 331-343.

Ekvall, T., & Weidema, B. P. (2004). System boundaries and input data in consequential life cycle inventory analysis. *International Journal of Life Cycle Assessment, 9*(3), 161-171.

Farhan, B., & Murray, A. T. (2006). Distance decay and coverage in facility location planning. *Annals of Regional Science, 40*(2), 279-295.

Fujii, M., Fujita, T., Chen, X., Ohnishi, S., & Yamaguchi, Y. (2010). *Efficient use of organic municipal solid waste in a sound material-cycle society.* Paper presented at the ISIE Asia-Pacific Meeting & ISIE MFA-ConAccount Meeting, Tokyo, Japan.

Geng, Y., Fujita, T., & Chen, X. (2010). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production, 18*(10-11), 993-1000.

Höjer, M., Ahlroth, S., Dreborg, K. H., Ekvall, T., Finnveden, G., Hjelm, O., et al. (2008). Scenarios in selected tools for environmental systems analysis. *Journal of Cleaner Production, 16*(18), 1958-1970.

Hansen, P., & Mladenovic, N. (1997). Variable neighborhood search fro the p-median. *Location Science, 5*(4), 207-226.

Houillon, G., & Jolliet, O. (2005). Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. *Journal of Cleaner Production, 13*(3), 287-299.

JCPRA (The Japan Containers and Packaging Recycling Association). (2007). *The Environmental Impacts of Plastic Containers and Packaging Recycling (in Japanese)*. Tokyo, Japan: JCPRA.

Kim, M. H., & Kim, J. W. (2010). Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. *Science of the Total Environment, 408*(19), 3998-4006.

Levis, J. W., Barlaz, M. A., Themelis, N. J., & Ulloa, P. (2010). Assessment of the state of food waste treatment in the United States and Canada. *Waste Management, 30*(8-9), 1486-1494.

Maric, M. (2010). AN EFFICIENT GENETIC ALGORITHM FOR SOLVING THE MULTI-LEVEL UNCAPACITATED FACILITY LOCATION PROBLEM. *Computing and Informatics, 29*(2), 183-201.

Mastellone, M. L., Brunner, P. H., & Arena, U. (2009). Scenarios of Waste Management for a Waste Emergency Area. *Journal of Industrial Ecology, 13*(5), 735-757.

Miranda, M. L., & Aldy, J. E. (1998). Unit pricing of residential municipal solid waste: lessons from nine case study communities. *Journal of Environmental Management, 52*(1), 79-93.

Mladenovic, N., Brimberg, J., Hansen, P., & Moreno-Perez, J. A. (2007). The p-median problem: A survey of metaheuristic approaches. *European Journal of Operational Research, 179*(3), 927-939.

Owen, S. H., & Daskin, M. S. (1998). Strategic facility location: A review. *European Journal of Operational Research, 111*(3), 423-447.

Queiruga, D., Walther, G., Gonzalez-Benito, J., & Spengler, T. (2008). Evaluation of sites for the location of WEEE recycling plants in Spain. *Waste Management, 28*(1), 181-190.

R Development Core Team. (2011). R: A Language and Environment for Statistical Computing [Electronic Version], from http://www.R-project.org

ReVelle, C. S., & Eiselt, H. A. (2005). Location analysis: A synthesis and survey - Invited review. *European Journal of Operational Research, 165*(1), 1-19.

Shan, C. S. (2010). Projecting municipal solid waste: The case of Hong Kong SAR. *Resources Conservation and Recycling, 54*(11), 759-768.

Snyder, L. V. (2006). Facility location under uncertainty: a review. *Iie Transactions, 38*(7), 537-554.

Spengler, T., Penhert, H., Penkuhn, T., & Rentz, O. (1997). Environmental integrated production and recycling management. *European Journal of Operational Research, 97*(2), 308-326.

Tohyama, H., Ida, K., & Matsueda, J. (2011). A Genetic Algorithm for the Uncapacitated Facility Location Problem. *Electronics and Communications in Japan, 94*(5), 47-54.

Van Berkel, R., Fujita, T., Hashimoto, S., & Geng, Y. (2009). Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997-2006. *Journal of Environmental Management, 90*(3),

1544-1556.

Wong, L. F., Fujita, T., & Xu, K. Q. (2008). Evaluation of regional bioenergy recovery by local methane fermentation thermal recycling systems. *Waste Management, 28*(11), 2259-2270.

Zhang, X. D., Huang, G. H., Nie, X. H., Chen, Y. M., & Lin, Q. G. (2010). Planning of municipal solid waste management under dual uncertainties. *Waste Management & Research, 28*(8), 673-684.

Chapter 5 Case Study on Waste Plastic Recycling in the Tokyo Metropolitan Region of Japan

5.1 Background

The case study taken in this research is non-PET waste plastics recycling in the Tokyo Metropolitan Region (TMR) of Japan, also referred to as the Greater Tokyo Area or *Syutoken* in Japanese. The TMR was defined by the Tokyo Metropolitan Region Planning Act (*Syutoken Seibi-Hou*) of 1956, which aimed to build and develop a TMR as the center of politics, economy, and culture in Japan through comprehensive planning and its implementation. According to the Tokyo Metropolitan Region Planning Act, the TMR consists of eight prefectures, namely Ibaraki, Tochigi, Gunma, Saitaba, Chiba, Tokyo, Kanagawa, and Yamanashi. Except for Yamanashi Prefecture, the other seven are also known as the Kanto Region. In the recent National Spatial Plan (*Kokudo Keisei Keikaku*) released in 2008, the TMR was also planned as one of the eight "blocks" in the nation. These blocks were decided based on (1) scale and accumulation of industries, economic bases and talents for autonomous development and international competition; (2) cooperation within blocks for safe lives and rich natural environments; (3) tight relationships within blocks in the nature of the environment, economy, society and culture; and (4) necessity for the integration of national spatial planning. Therefore, the TMR is an integrated region with tight relationships in politics, economy, and culture and has been acknowledged by laws and national plans. Note that small islands that belong to Tokyo Prefecture were excluded from the study area (Figure 5.1).

The TMR is a proper area for this research because, firstly, it is the most populous region and important economic center in Japan. Table 5.1 tabulates some basic data about the TMR. The TMR has about one third of the nation's population, creates over one third of the total gross domestic product (GDP), and generates about one third of the total municipal solid waste (MSW) in Japan. The distribution of population, as well as waste generation, is rather uneven, with a densely populated core area around the Tokyo Bay and a sparsely populated periphery (Figure 5.1). The variation in population density allows us to test the location of RRCs and their respective service areas with different population densities. In addition, the TMR also holds a large heavy-industrial base in the Tokyo Bay area and several sites in the periphery. Seven cement plants are located in this region with a total annual production capacity close to 9 million tons, and four iron/steel plants with a total volume of blast furnaces close to 25 thousand m^3 (Cement Yearbook, 2009; Iron and Steel Yearbook, 2009). These industries in the TMR consume a large amount of coal and coal products (e.g. cokes), as much as 23% and 31% of the national total, respectively (Table 5.1). These energy intensive industries also foster a large potential to recycle waste plastics. In fact, recycling facilities that process waste plastics into fuel or feedstock for these industrial plants are already present at each cement plant's site and two iron/steel plant's sites[5]. Because their large scales and high efficiencies, these energy intensive industries become proper recipients of waste plastics for chemical recycling or energy recovery with sufficient capacity.

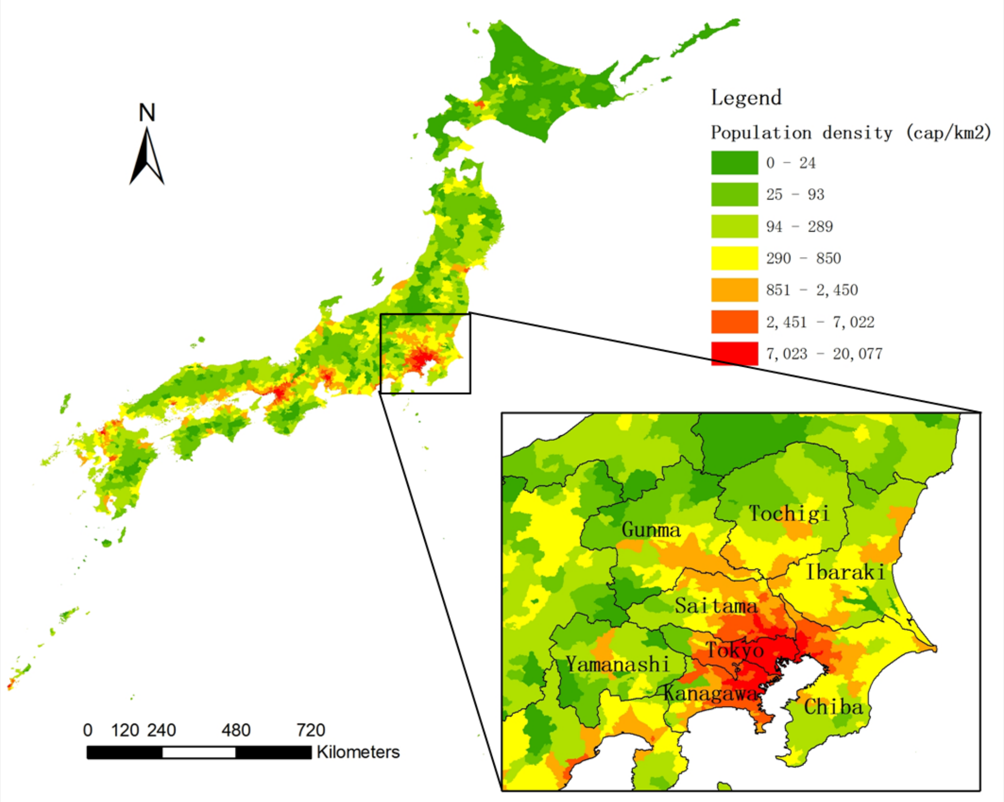


Figure 5.1 Study area and population density in Japan

---

[5] Refer to Sound Material-Cycle Society and Waste Research Center, National Institute for Environmental Studies, Japan, retrieved in June 2011 at http://www-cycle.nies.go.jp/precycle/material/map.html .

Table 5.1 Basic data of the National Region of Japan

Prefecture	Pop[1]	Projected pop (2025) [2]	GDP[3]	MSW[4]	Waste Plastics[4]	Coal[5]	Coal product[5]
Unit	1000	1000	10^9JPY	kt	kt	kt	kt
Ibaraki	2985	2690	11578	1060	1.4	1027	3840
Tochigi	2071	1879	8268	730	4.7	156	34
Gunma	2034	1845	7498	829	4.5	10	39
Saitama	7098	6752	21108	2558	45.0	434	17
Chiba	6112	5879	19651	2313	31.3	1323	6216
Tokyo	12564	13025	92300	4916	63.1	142	33
Kanagawa	8956	8896	31960	3209	87.4	376	2006
Yamanashi	871	802	3236	324	1.0	8	1
Subtotal in the TMR	42691	41768	195599	15939	238.5	3475	12185
Japan	127530	125,430	520249	48106	661.2	15187	39227

NOTE: 1. Population in 2008. Source: e-Stat (http://www.e-stat.go.jp)

2. Population in 202. Source: National Institute of Population and Social Security Research. 2010 Projection of Population in Japanese by Municipalities. Retrieved in June 2010 at http://www.ipss.go.jp/pr-ad/e/eng/04.html.

3. Latest data available in 2007. Source: e-Stat (http://www.e-stat.go.jp)

4. Data in 2008. MOEJ (http://www.env.go.jp/recycle/waste_tech/ippan/h20/index.html)

5. Data in 2008. METI (http://www.rieti.go.jp/users/kainou-kazunari/energy/index.html)

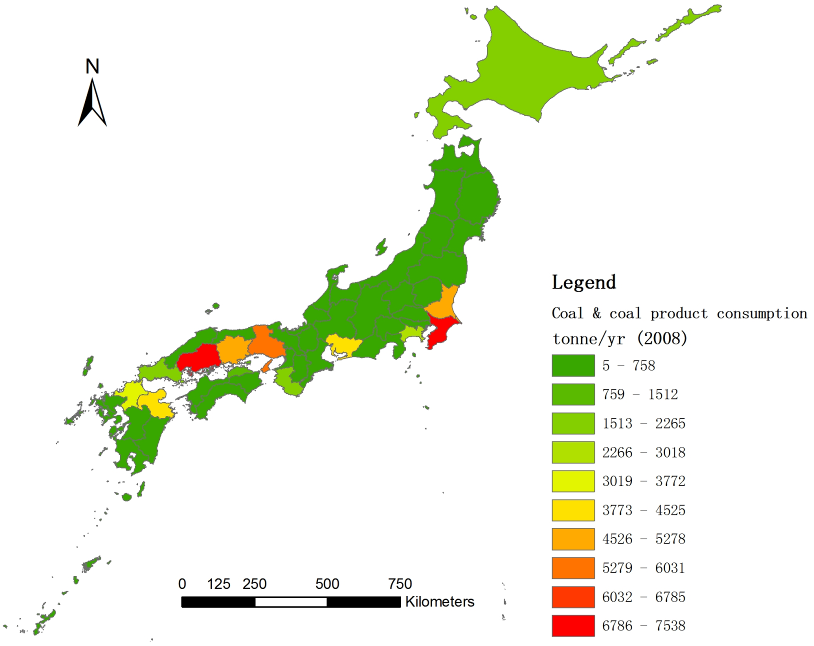


Figure 5.2 Coal and coal product consumption in Japan by prefecture

In summary, the TMR is chosen as a case study for the following reasons. First, it is an integrated, important region in Japan in terms of politics, economy, and culture. Second, in the TMR, there is a mix of different population densities and multiple energy-intensive industrial facilities (Figure 5.1 and Figure 5.2). Such a study area would reflect the spatial mismatch of diffuse sources of waste plastic generation and a limited number of industrial facilities that can recycle the plastics. Moreover, the results can demonstrate how population density influences the number, location and scale of RRCs.

5.2 Function of Regional Recycling Centers

Regional recycling centers (RRCs) are designed to replace small transfer and pre-treatment centers that are currently operated at the municipality level (i.e. municipal recycling centers (MRCs)). RRCs would have the same function as MRCs but will serve for multiple municipalities within respective service areas. According to the discussions in section 4.2, high-quality waste plastics should be recycled through mechanical processes and low-quality plastics should be recycled through industrial symbiosis. The RRCs are to be designed to meet local demands for the recycled products. According to the current recycling practice of waste plastic containers and packaging (JCPRA, 2007), in this case study 15% was assumed to be of high-quality and thus mechanically recycled, while 75% was assumed to be of low-quality and recycled as fuel or reductant at cement or iron plants to substitute coal and coke. For a particular RRC, the closest material recycling facility among those registered to the JCPRA in 2008 is taken as the destination of high-quality plastics. The closest cement or iron/steel plant, more specifically the recycling facility on the site of the industrial facility, was considered the destination of low-quality plastics. The remaining 10% was assumed to be material loss during the recycling process (Astrup, Fruergaard, & Christensen, 2009). In other words, a RRC receives separated non-PET waste plastics collected from municipalities in its service area. These waste plastics are then further selected, compressed, and bailed for transportation, 15% of which goes to the closest material recycling facility and 75% to the closest industrial facility. The treatment process at a RRC is shown in Figure 5.3. Capacity limit is rather an operational issue. To test the impact of capacity limit, RRCs were assumed to have a limit of 100 kilo tons per year. If a hosting city received waste plastics more than this limit, two or more RRCs with identical capacities below the limit were assumed to be built. Recycling facilities were assumed to be able to adjust their capacities to receive separated waste plastics from RRCs. Waste plastics that were not separated remained in the garbage and were assumed to be incinerated together with other combustible wastes with a power generation efficiency of 10% (JCPRA, 2007).

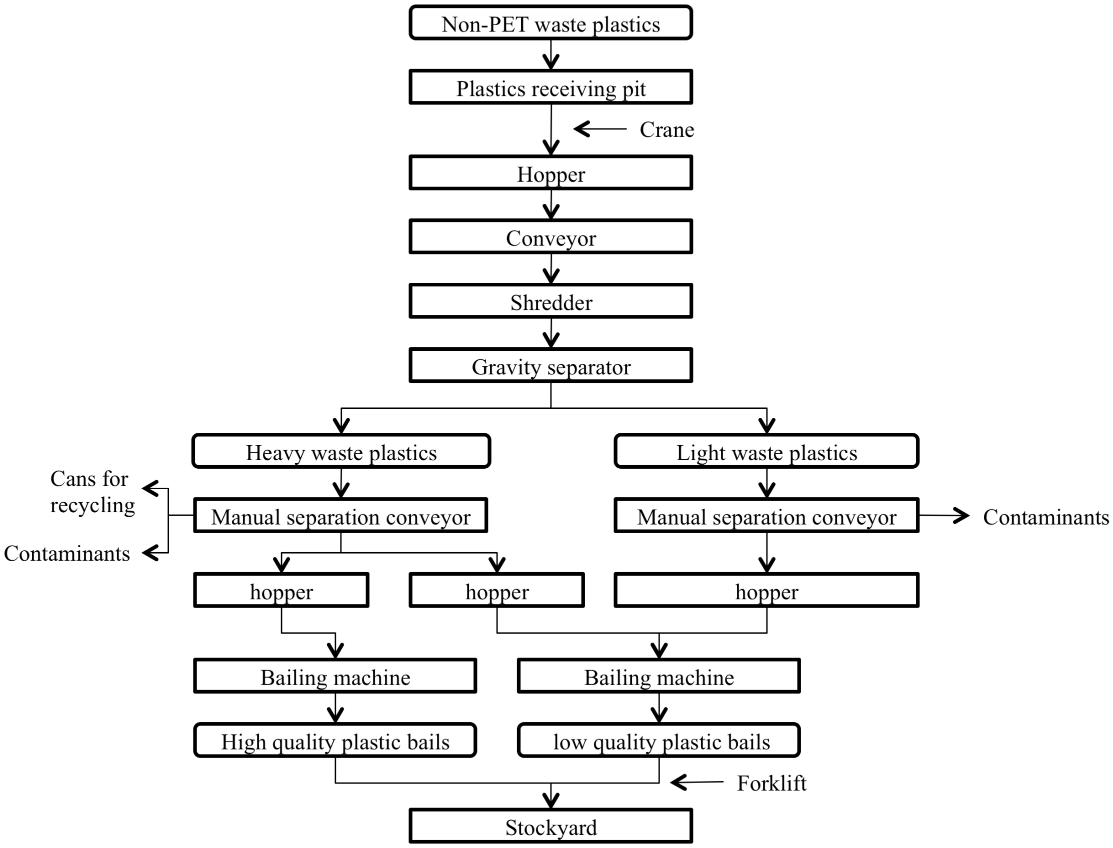


Figure 5.3 Treatment process in the RRCs

Source: revised based on Basic Plan on Waste Treatment Facility in Kofu-Kyoto Region, retrieved on July, 2011 at http://www.kofu-kyotojimukumiai.jp/modules/contract/index.php?content_id=7.

5.3 Database and Model Parameters

5.3.1 GIS-Based Database for Location Optimization Modeling

According to the location optimization model and the LCA model for assessing environmental benefits, required data were collected. A GIS based database was constructed for managing spatial data used in the models. Major data sources, categories of data are summarized in Figure 5.4. Most data were in 2008. For those that data in 2008 were not available, such as digital data on the road network and base map, data in 2005 were used. Some examples of data managed in the GIS database are illustrated in Figure 5.5 and Figure 5.6.

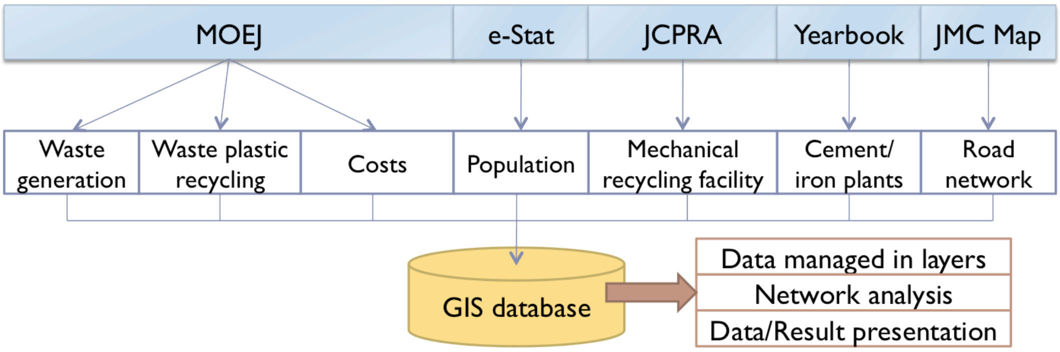


Figure 5.4 Structure of GIS-based database

MOEJ = Ministry of the Environment, Japan; e-Stat: portal site of official statistics of Japan (http://www.e-stat.go.jp); JCPRA = Japan Container and Packaging Recycling Association; JMC = Japan Map Center

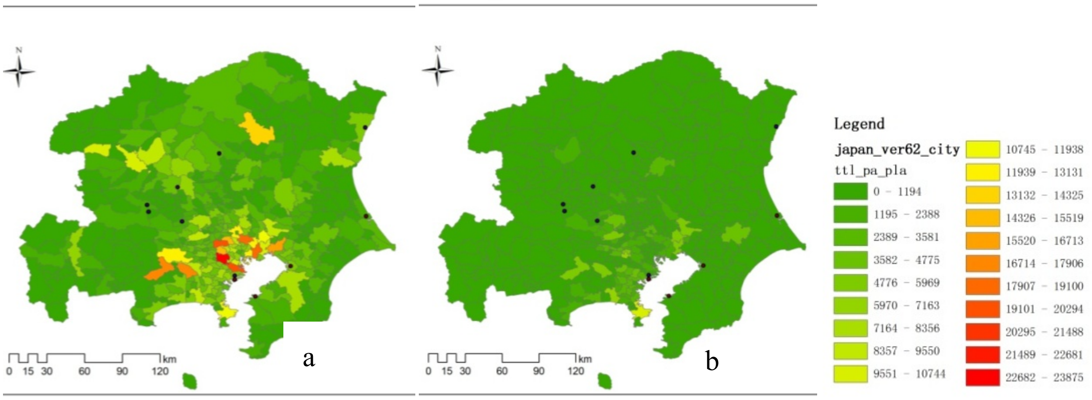


Figure 5.5 Estimated waste plastic generation (a) and recycled waste plastics (b) by municipality in the study area

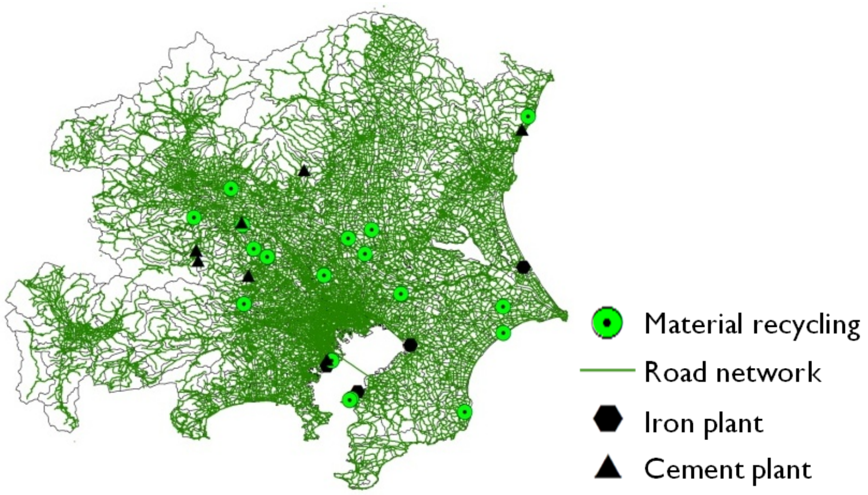


Figure 5.6 Road network and locations of mechanical recycling industrial facilities in the study area

5.3.2 Waste Plastic Generation and Recycling Rates

Data on the generation of municipal solid waste from households in each municipality in the NRC came from the statistical data. The composition of household wastes was referenced to the average sampling result of six cities in Japan, conducted by MOEJ in FY 2008 (Figure 5.7). Of waste plastics (11.6%), 7.5% of the total household waste was categorized as non-PET plastic packaging and containers, which according to the Waste Packaging and Container Recycling Law should be recycled. This 7.5% becomes the target composition in this research. Except for special notes, waste plastics in this dissertation refer to this non-PET plastic packaging and containers. The composition was assumed identical in all municipalities. The estimated generation of waste plastics packaging and containers are show in Figure 5.5 (a).

The amount of waste plastics recycled from each municipality in 2008 is illustrated in Figure 5.5 (b). The total recycling rate was 20%. For the planning in future scenarios, a lower limit of recycling rate was set. All municipalities were assumed to at least meat this limit. For example, in case of a lower limit of 50%, municipalities that had a recycling rate in 2008 greater than 50% would remain the recycling rate, while those that had a recycling rate lower than 50% were assumed to improve to 50%.

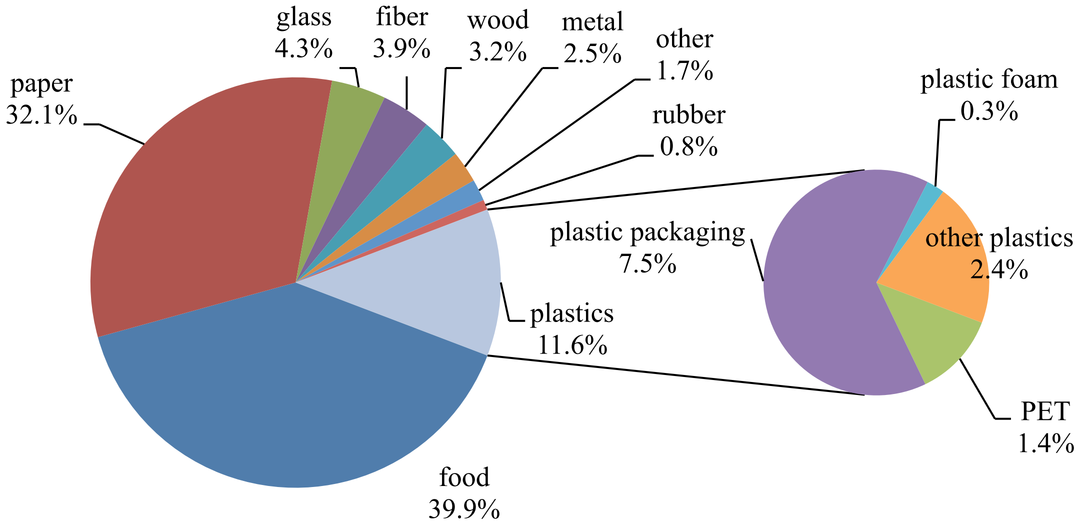


Figure 5.7 Composition (weight in a wet base) of household waste in Japan sampled in 2008
Source: Ministry of the Environment of Japan,
http://www.env.go.jp/recycle/yoki/c_2_research/research_03.html

5.3.3 Parameters in Scenarios

As argued in section 4.3, this case study is for the planning of RRCs in the future. Most scenarios were explorative and parameters with high uncertainties were assumed in a reasonable range by the author with consultations to experienced researchers and engineers. The values of the eight key uncertain and operational parameters under the *standard scenario* are listed in Table 5.2. Eight sets of scenarios were analyzed. Each set aims to test the impacts of one of the eight parameters. The values of these parameters tested in each set of scenarios are summarized in Table 5.3.

Table 5.2 Parameter value in the target scenario

Parameter	Value/description
Population and distribution	Estimated in 2025
Per capita generation of waste plastics	Per capita waste at the 2008 level (7.5% of the MSW)
Lower limit of 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 from center to recycling/industrial facilities
Loading capacity of trucks	2 t (loading factor: 0.5) for collection trucks; 10 t (loading factor: 0.79) 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

Table 5.3 Values of parameters to be tested in scenarios

Scenario	Value of parameter deviating from the standard scenario
1	Population in 2008, 2015, 2025, and 2035
2	Per capita generation of waste plastics at 100%, 95%, 90%, 85%, and 80% of the target scenario
3	Lower limit of recycling rate of 30%, 40%, 50%, 60, and 70%
4	Cost of diesel at 80%, 100%, 120%, 150%, and 200% of the standard scenario
5	Fuel efficiency of trucks at 100%, 120%, 150%, and 200% of the standard scenario
6	Transportation of waste plastics from municipalities to RRCs by collection trucks (1 t/trip), 4t container trucks (2 t/trip) and 10t container trucks (4 t/trip)
7	Unit construction cost at 100%, 150%, and 200% of the target scenario
8	Unit labor cost 60%, 80%, and 100% of the target scenario

5.4 Costs and Number, Location, and Capacity of RRCs

5.4.1 Model Outputs under the Standard Scenario

Under each and every scenario, the number of hosting cities of RRCs to be located, *p*, was given from 6 to 20, which covered the optimal numbers of hosting cities under all scenarios. For each value of *p* under a particular scenario, the cost of transportation was minimized in the first step. At the same time, the optimal number, capacity, and location of RRCs could be obtained. The costs of construction, operation, and incineration were then calculated by the optimization model. The total costs for different *p'*s can then be compared to determine the optimal number of hosting cities of RRCs. For example, under the standard scenario, the total costs at different *p'*s formed a U-shaped curve and reached its minimum point at 22.1 billion JPY/year when 13 hosting cities were planned (Figure 5.8). Due to the constraint on treatment capacity, the total cost decreases rapidly until facility scales meet the constraint. It then gradually reaches the optimal point and gradually increases as the number of hosting cities increases. At an extreme condition where each municipality were to have a local center for the pre-treatment of waste plastics, the total construction costs would be close to 37 billion JPY, 67% more expensive than the optimal solution.

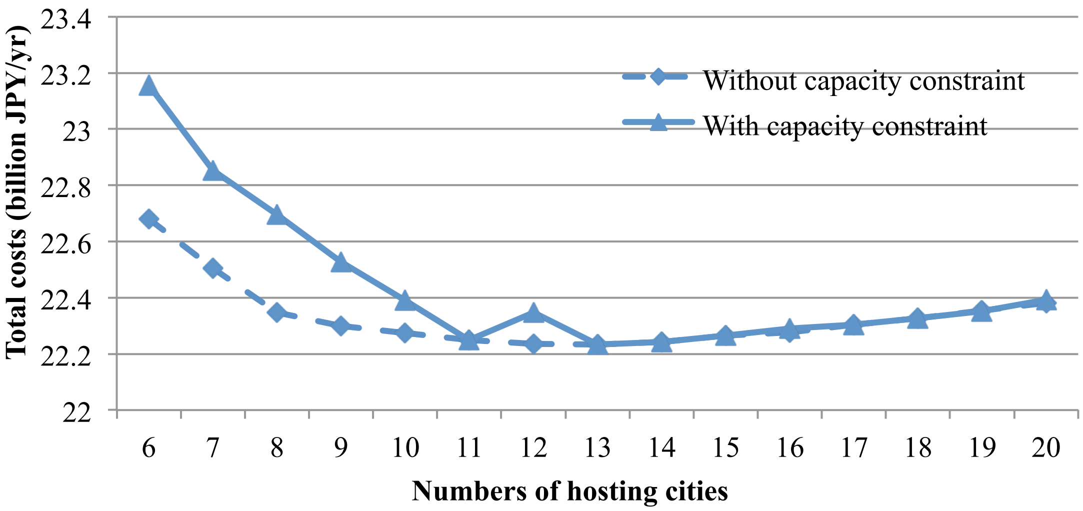


Figure 5.8 Total costs under the target scenario for various numbers of hosting cities

Under the standard scenario, costs of transportation, operation of RRCs, and incineration of the unseparated waste plastics each accounts roughly one third of the total cost, whereas annual construction costs accounts for only 4% (Figure 5.9). A major reason for this pattern is that costs of personnel are relatively expensive in Japan compared with construction and utilities. The treatment process in RRCs involves manual selections of waste plastics and thus is relatively labor-intensive.

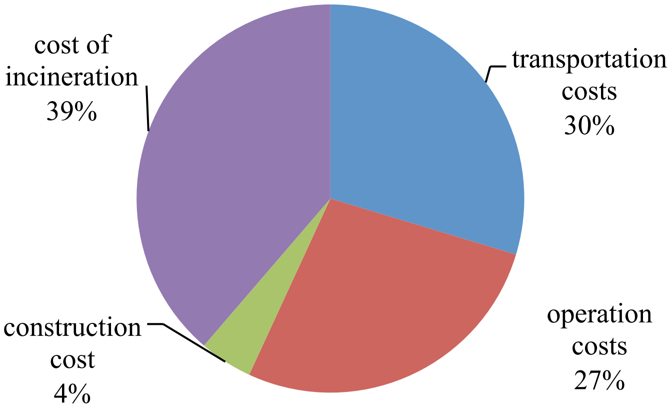


Figure 5.9 Breakdown of the minimum cost under the target scenario

The capacity and location of RRCs and the allocation of their service areas are illustrated in Figure 5.10. The RRCs located in relatively populous areas around the Tokyo Bay have larger capacities and smaller service areas than those located in less populous areas in the periphery. This is because the amount of waste plastics collected from a few municipalities in the populous region is large enough for a RRC. The additional cost of transportation due to expanding the service area exceeds the benefit gained due to economies of scale. On the contrary, in less populous areas, a RRC receiving waste plastics in a relatively long distance can still benefit from the increasing scale. This result implies that wastes generated in large (small) amounts in each municipality, due to high (low) population density or a large (small) proportion of municipal solid waste (MSW), tend to be treated locally (regionally).

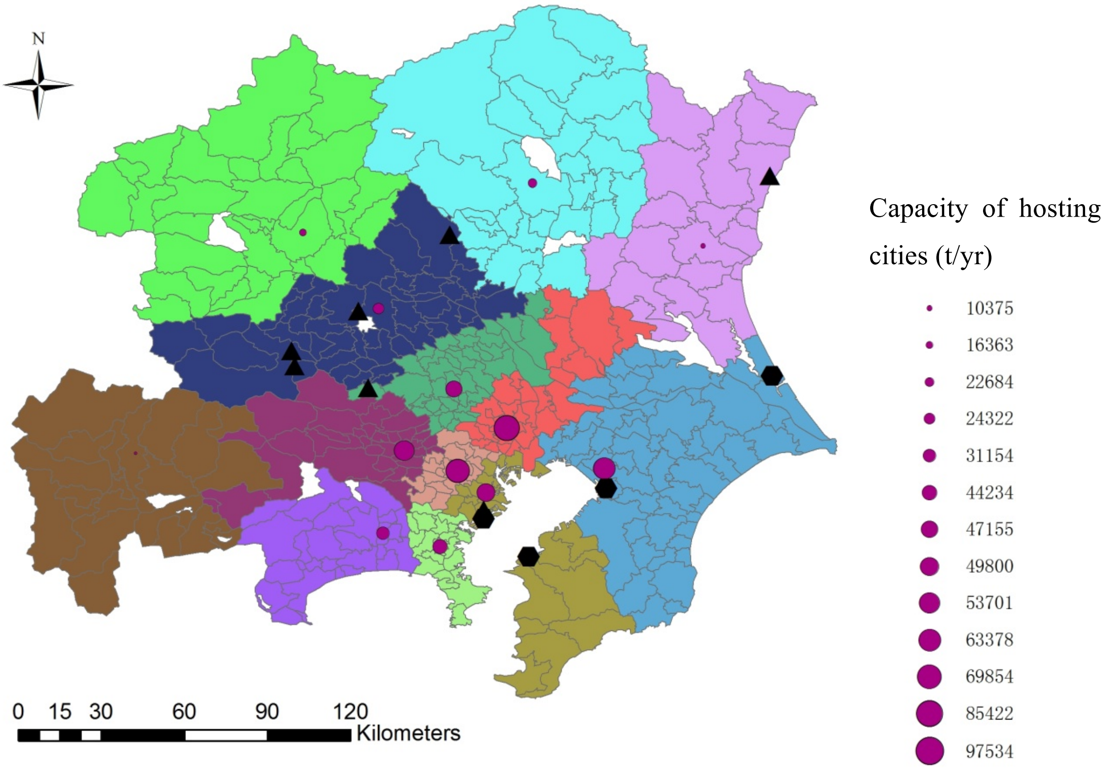


Figure 5.10 Location-allocation of the optimal number of RRCs under the standard scenario

5.4.2 Total Costs and Numbers of Hosting Cities under Various Scenarios

The impacts of various factors on the optimal total costs and numbers of hosting cities were examined by repeating the solutions under different scenarios, each of which aims to test the impact of one factor, respectively. The detailed results of the total costs and breakdowns under all scenarios are presented in the Annex III of this dissertation. Figure 5.11 summarizes the results of the minimum total cost under all scenarios. Given the factors tested in this research, the total cost of managing non-PET waste plastics in the TMR varies from 18 billion to 23 million JPY per year. Waste generation rates have the heaviest impact on the total cost. When the total generation of waste plastics decreases by 20%, the total cost could reduce by 18% due to savings from both recycling and incineration. This result confirms that waste reduction is a preferred approach of waste management. Other factors that heavily influence the total cost include unit labor cost, recycling rate, and loading capacity of trucks. Of these three factors, the first two have positive correlations with the total cost, whereas the last one has a negative correlation. Changes in diesel price and fuel efficiency exert very low impacts on the total cost.

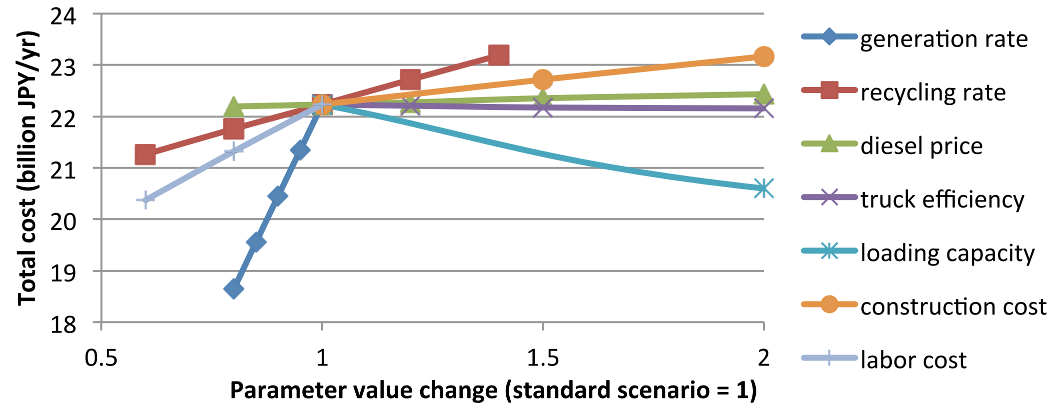


Figure 5.11 Impact of parameters on the total cost

The optimal numbers of hosting cities under various scenarios also differ dramatically from 9 to 16 (Figure 5.12). This result implies significant differences in the service area of RRCs. The allocation of service areas of 9 and 16 hosting cities are shown in Figure 5.13. Among all the factors, recycling rate, loading capacity of trucks, and unit labor cost have heavy impacts on the optimal number of hosting cities and the service areas of RRCs. While recycling rate has a positive correlation with the number of hosting cities (thus a negative correlation with service areas of RRCs), loading capacity of trucks and unit labor cost have negative correlations with the number of hosting cities (negative correlation with service areas). Waste generation rate, unit construction cost, and fuel efficiency of trucks have low impacts, while diesel price almost has no impact on the optimal number of hosting cities.

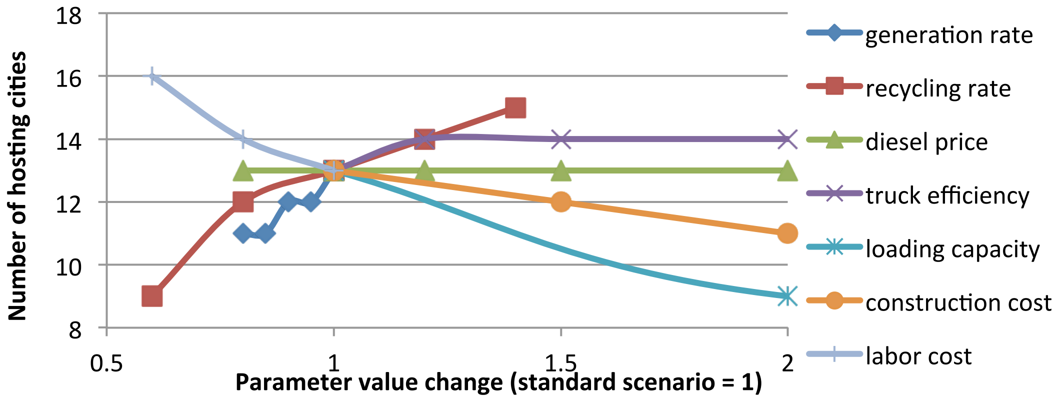


Figure 5.12 Impact of parameters on the optimal number of RRCs

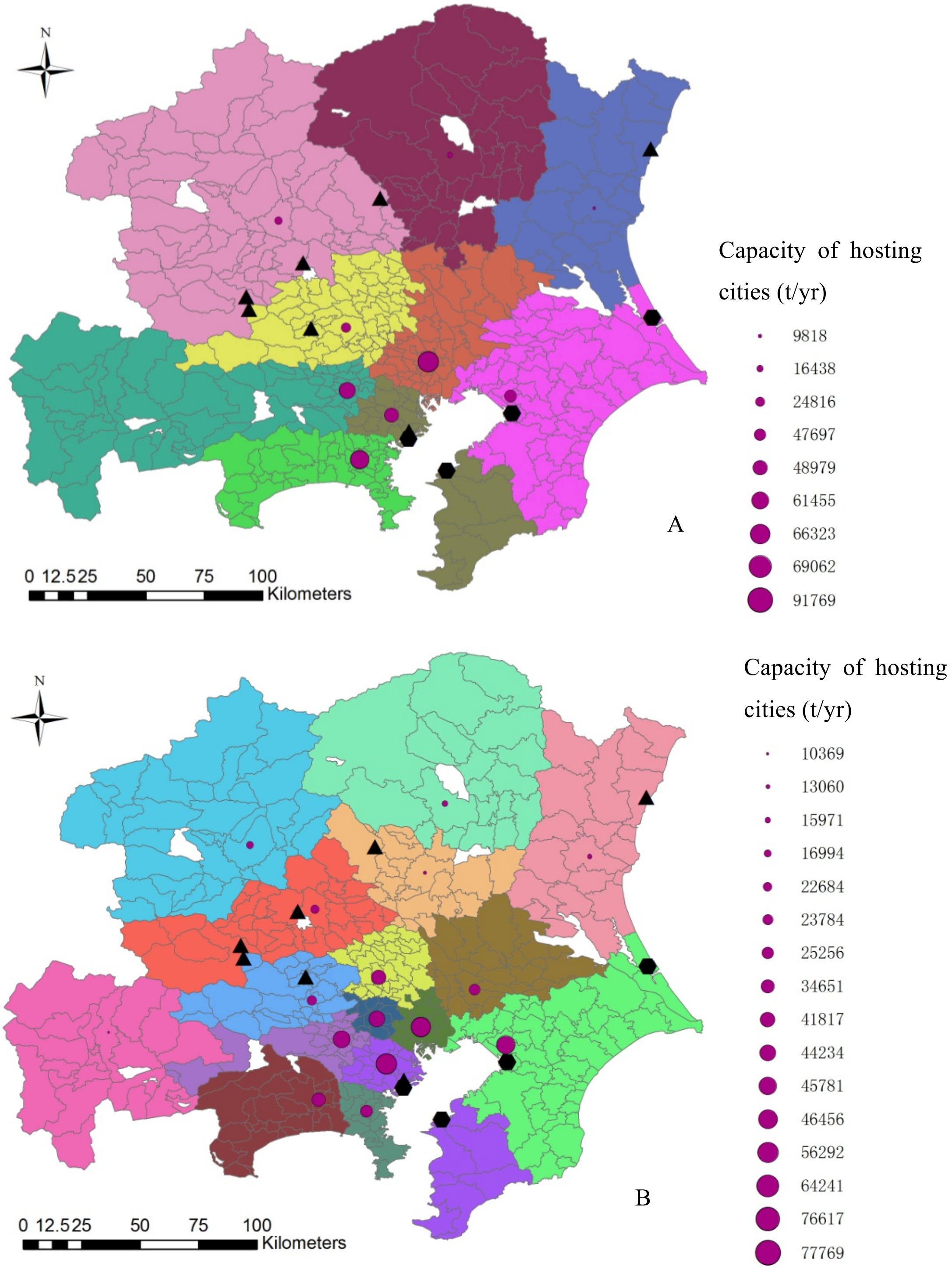


Figure 5.13 Location of allocation of RRCs under scenarios of (A) the limit of recycling rate of 30% and (B) labor costs decreasing to 60% of the standard scenario.

5.5 Environmental Benefits of the Regional Recycling System

5.5.1 GHG Emissions

Together with costs and the location-allocation of hosting cities of RRCs, the models also produce the life cycle impacts of managing the waste plastics in both recycling and incineration processes. Figure 5.14 summarizes the impacts of parameters on the reduction of CO_2 emissions. The detailed results under each scenario can be found in the Annex. The average reduction of CO_2 emissions under various scenarios is between 1.45 and 2.36 million tons per year, which are about 34 to 57 kg per capita per year. If Japan attains the goal of reducing 20% GHG emissions by 2025 on a 1990 basis, the reduction of waste plastics recycling would result in additional 0.4 to 0.7% reduction in GHG emissions on a per capita basis. The major reduction is attributed to the substitutive effects, namely using waste plastics as feedstock or fuel to substitute cokes and coal. Transportation, operation, and construction processes contribute very limited to the total greenhouse gas emissions. Therefore, regardless to the location of RRCs, the reduction of CO_2 emissions is only sensitive to the amount of waste plastics being recycled. Recycling rate exerts the heaviest impacts on the reduction of CO_2 emissions. The impacts of generation rate is not as significant as recycling rate because when the generation decreases, the reduction due to substitutive effect decreases, but the reduction of incineration (i.e. the reduction effect) contributes to the reduction of CO_2 emissions.

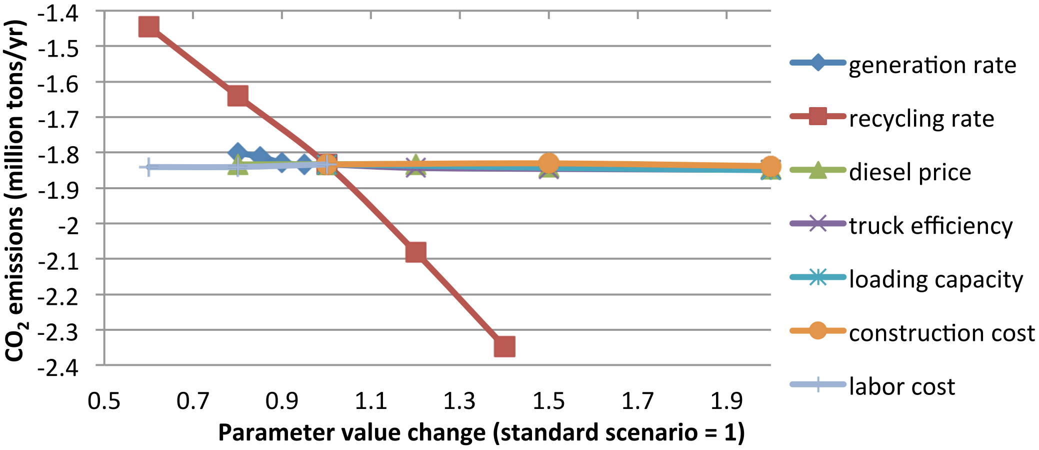


Figure 5.14 Impact of parameters on the reduction of CO_2 emissions

5.5.2 Fossil Fuel Savings

In addition to reduction in CO_2 emissions, another environmental benefit examined is fossil fuel saving. As designed in the technology selection process, the major benefit is saving of coals, in terms of substituting cokes (a coal product) and fuel coals. About 0.45 to 0.78 million tons of coal can be saved, which account for 3 to 5% of the current coal and coal products consumption in the TMR. Similar to the reduction in CO_2 emissions, saving of fossil fuel is only sensitive to the amount of waste plastics being recycled. Hence, recycling rate and waste generation rate have heavy impacts on the saving of coals, whereas other factors exert very low impacts (Figure 5.15).

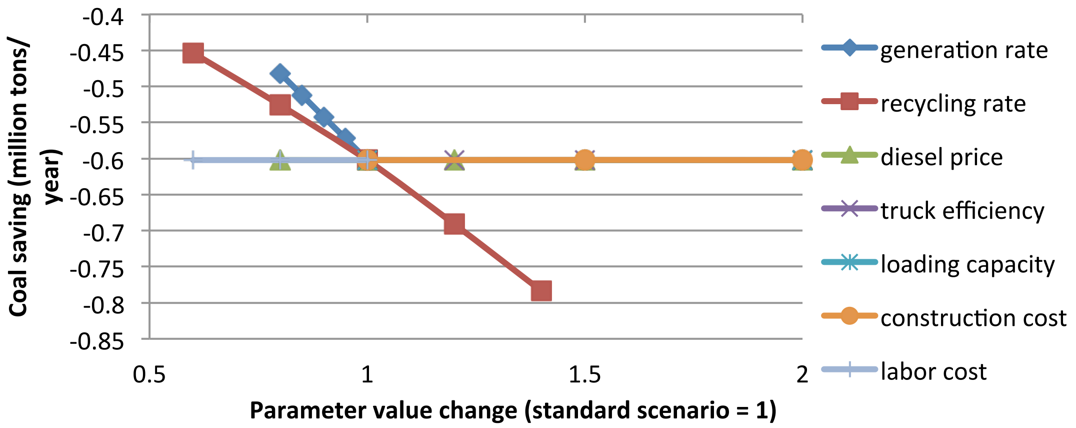


Figure 5.15 Impact of factors on coal saving

5.6 Result Summary and Discussions

5.6.1 Impacts on Eco-Efficiency

In 2025, the total cost of the public sector for managing non-PET waste plastics in the TMR by regional recycling through industrial symbiosis and incineration is expected to be approximately 22 billion RMB per year. The establishment of regional recycling system with RRCs can lower the total cost in comparison with the present recycling system in which each municipality holds its MRC for separation and pre-treatment. In comparison with incineration, recycling of waste plastics in most scenarios can reduce over 1.8 million tons of CO_2 emissions and save 0.6 million tons of coal every year.

To combine the results of cost minimization and environmental assessment, the eco-efficiencies, namely costs for reducing 1 ton of CO_2 emissions, are summarized in Figure 5.16. Waste generation rate and recycling rate have heavy impacts on the eco-efficiency. Waste reduction and promotion of recycling appears to be an efficient way of reducing CO_2 emissions. In most of the scenarios considered, the costs to reduce one ton CO_2 emissions exceed 10 thousand JPY, which is higher than the carbon credit in the international market. However, the benefit of recycling does not limit to the market value of CO_2 emissions. For every ton of CO_2 emissions reduction, 0.32 ton of coal can be saved. Table 5.4 summarizes the economic benefits of CO_2 emission reduction and coal saving. Although the market value of carbon credits and coal saving is lower than the cost of recycling, the external social benefits of CO_2 emissions reduction and coal saving are comparable to the cost of recycling. Moreover, recycling waste plastics can also stimulate energy intensive industries by lowering the cost of feedstock and encouraging green innovations.

Table 5.4 Economic value of Environmental Benefits

Benefits	Category	Value	Unit	Reference
CO_2 emission reduction	Market	933	JPY/t-CO2	JVETS[1]
		6963	JPY/t-CO2	J-VER[2]
		1010	JPY/t-CO2	CER[3]
	External	2770	JPY/t-CO2	LIME-2[4]
Coal saving	Market	10500	JPY/t-coal	IMF[5]
	External	22900	JPY/t-coal	LIME-2[4]

Note: 1: Average of bid and ask prices in 2011. Retrieved from JVETS-NET MAGAZINE at http://www.jvets.jp/jnm/magazines/view/34
2: Average of bid and ask prices from Sep. 2010 to June 2011. Retrieved from http://www.j-cof.org/jver/markettrend.html
3: Weighted average of 1694 transactions of CER (Carbon Emission Reduction) in the EU market. Retrieved from BlueNext at http://www.bluenext.eu/statistics/downloads.php. (1 EUR=100 JPY)
4. Japan Environmental Management Association for Industry (JEMAI). 2010 LIME (Life-cycle Impact assessment Method based on Endpoint modeling)-2: Environmental Impact Assessment Method for Decision Making. Tokyo: Nippon Publicity. The value is the sum of monetary value of preventing impacts on human health, social capital, biodiversity, and net primary product. The monetary value was investigated by conjoint analysis of interview results to 1000 individuals in Japan.
5. Average of international coal prices from Jan. to Nov. 2011. Retrieved from IMF at http://www.imf.org/external/np/res/commod/index.aspx. (1 US$ = 80 JPY)

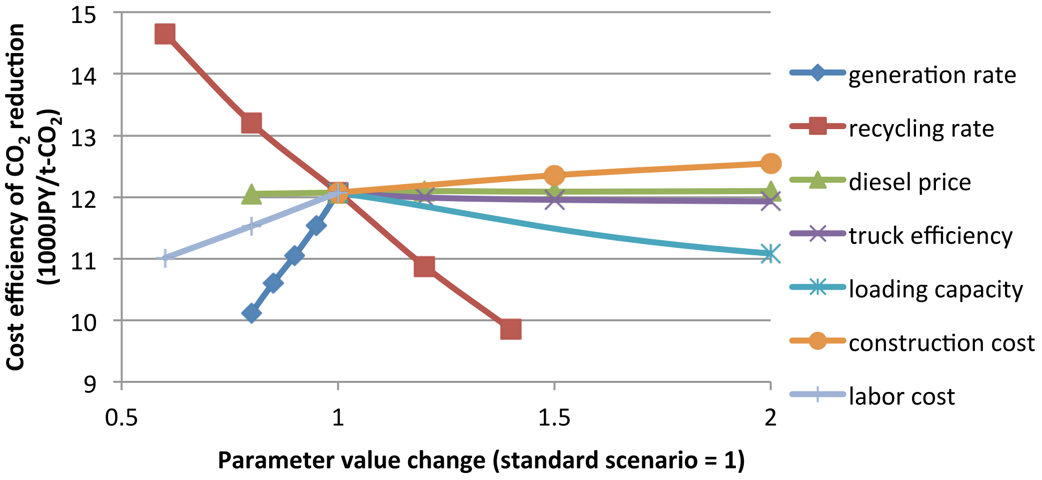


Figure 5.16 Impact of factors on the efficiency of reducing CO_2 emissions

5.6.2 Major Factors and Mechanism Determining Recycling Boundary

Based on the modeling results presented in section 5.5, factors that significantly influence on service area, total cost, and environmental benefits are summarized in Table 5.5. A particular attention is paid on the influencing factors on the service area here because this research aims to explore the factors and mechanism that determines appropriate recycling boundaries. The results from various scenarios imply that service areas of RRCs are determined mainly by two relatively independent factors. The first one, related to population density, waste generation rate and waste plastics recycling rate, is the density of separated waste. As illustrated in Figure 5.10, the service area in densely populated areas around the Tokyo Bay is much smaller than the less populated areas in the periphery.

The other factor that determines the service area is the ratio of unit transportation cost to unit treatment cost (i.e. the sum of unit operation cost and construction cost). When unit transportation cost increases (e.g. loading capacity of trucks decreases), the service area tends to become smaller for reducing transportation costs. On the contrary, when unit treatment cost increases (e.g. increase in construction costs or operation costs per unit waste), the service area tends to become larger for more benefits yielded by a larger scale, which in practice is under the constraints of land availability, transportation accessibility, and so forth.

Table 5.5 Impacts of factors on service area, total cost, and CO_2 emission reduction

Factors	Service area	Cost	CO_2 emissions
Generation rate (or population)	- M	+ VH	- L
Recycling rate	- VH	+ M	- VH
Loading capacity of trucks	+ H	- H	- VL
Construction costs	+ M	+ M	- VL
Labor costs	+ H	+ H	+ VL
Diesel price	- VL	+ L	- VL
Fuel efficiency of trucks	- L	- VL	- VL

Note: 5-level impact scale: very low (VL), low (L), medium (M), high (H), very high (VH).
+ (-): an increase in the factor results in an increase (decrease) in cost or service areas.

In Chapter 2, a theory was reviewed, which interpreted the determinants of recycling boundary for *a single facility*, arguing that the boundary was determined by balancing the gain of economies of scale and costs of transportation due to increasing scale (Ueda, 2000). The case study presents a slightly different problem, which aims to establish *multiple RRCs* that provide services to the whole region at minimum costs. Such a case mirrors the reality more closely because RRCs are public facilities. Rather than minimizing the cost for a single facility, it is important that the region as a whole be able to receive services at minimum costs.

For optimizing the number, location, and capacity of RRCs in a given region, the mechanism is different from minimizing costs for a single facility although the two problems may share the same basic theory. A simple model is built to demonstrate the mechanism according to which the two factors found above influence recycling boundaries. First, we relax the constraint on facility capacity. Using the results under the standard scenario as an example, when the number of hosting cities increase in a given region (i.e. the recycling boundary on average decreases), the transportation cost decreases with decreasing pace whereas the sum of construction and operation costs increase in a linear fashion (Figure 5.17). Here for each and every number of hosting cities, the transportation cost is minimized. If we consider transportation cost and construction + operation costs are continuous function 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.

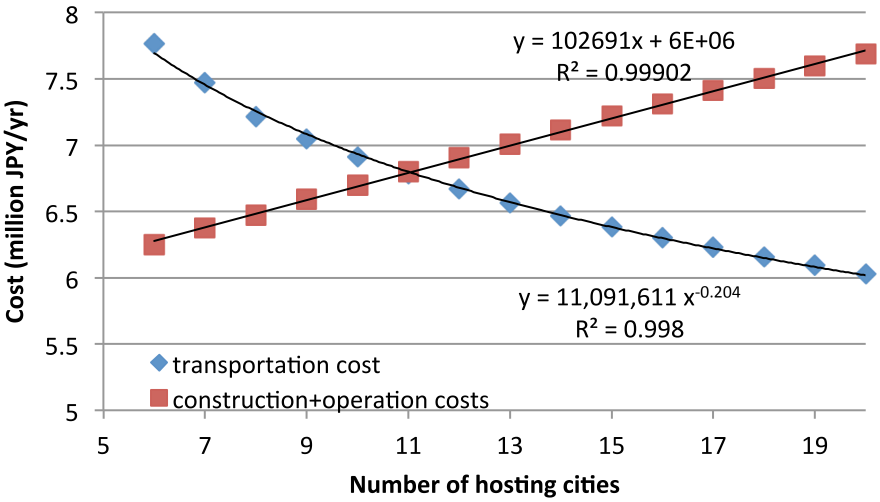


Figure 5.17 Transportation cost and construction + operation costs under the standard scenario

We now examine the influence of transportation costs on the number of hosting cities. We use the results from the case study when loading capacity of collection trucks increases from 1 t/trip to 2 t/trip (Figure 5.19). By plotting *minus* MCT and MCCO in the figure, the intersection 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 the same. The optimal number of hosting cities thus decreases. Under another scenario when construction cost doubles, the MCCO line moves up, while the -MCT curve remains in the same position, and the optimal number of hosting cities also decreases (Figure 5.19). If the transportation costs and construction + operation costs at any given number of hosting cities change the same times, say, a factor of x, the MCT and MCCO would also change x times. Therefore, the ratio of unit transportation cost to unit construction + operation costs is a major influencing factor for recycling boundary.

Density of separated waste exerts more complex influences on both MCT and MCCO. For example, when the lower limit of recycling rate of waste plastics in the cases increases from 30% to 70%, both -MCT and MCCO curves move up. The influence on -MCT is more significant than that on

MCCO because an increase in the number of hosting cities in high density of separated waste would result in more waste plastics reducing transportation distances than that in the case with a low density of separated waste plastics, resulting a large shift of the -MCT curve. On the other hand, the impact on MCCO is weaker because the increase of waste density is shared by all hosting cities so that the capacity of an additional hosting city in the high recycling rate case would not be so significantly larger than the one in the case of low recycling rate case.

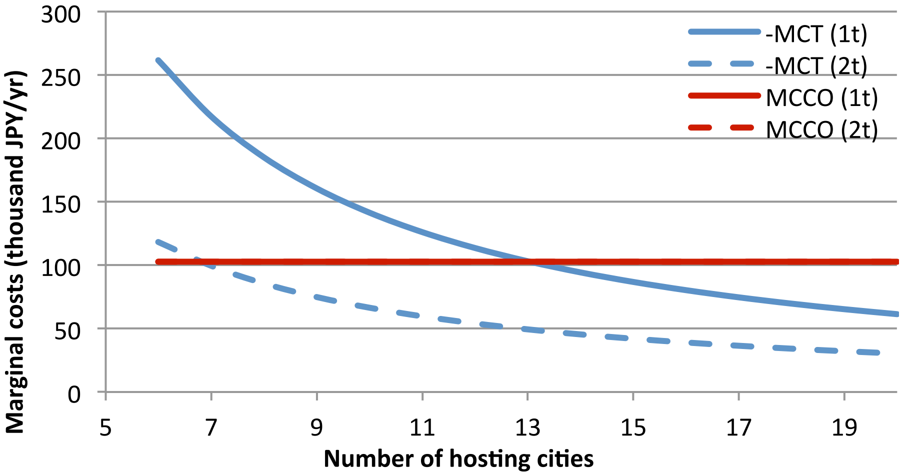


Figure 5.18 Impacts of unit transportation cost on marginal costs and the optimal number of hosting cities

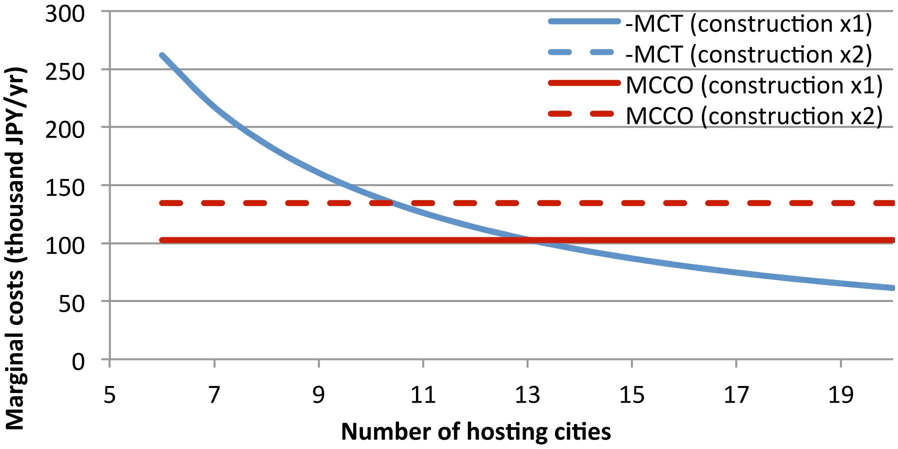


Figure 5.19 Impacts of unit construction cost on marginal costs and the optimal number of hosting cities

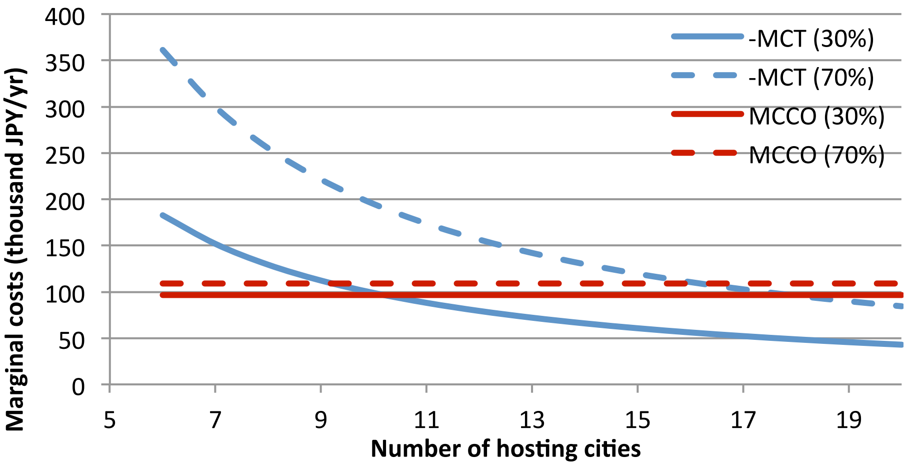


Figure 5.20 Impacts of density of separated waste plastics on marginal costs and the optimal number of hosting cities

When constraints do exist on treatment capacity of RRCs, the MCCO would become a piecewise function, of which in the left-hand side, the function needs to be specified contingent on the scale of hosting cities and the level of constraint. If a decrease of one hosting city results in an RRC exceeding the capacity limit and thus being divided into two RRCs, the MCCO would be close to zero at that point because the total number of RRCs actually remains the same. If it results in two or more RRCs exceeding the capacity limit, the MCCO would become less than zero at that point. The larger the density of separated waste plastics, the larger the number of hosting cities at which the “tipping point” of MCCO shifting to zero or less would appear. Under the scenario to test recycling rates, the “tipping point” appeared at 8 hosting cities when the recycling rate was 30% and 14 when the recycling rate was 70%.

Reference

Astrup, T., Fruergaard, T., & Christensen, T. H. (2009). Recycling of plastic: accounting of greenhouse gases and global warming contributions. *Waste Management & Research, 27*(8), 763-772.

Berthouex, P. M. (1972). Evaluating Economy of Scale. *Journal of Water Pollution Control Federation, 44*(11), 2111-2119.

Cement Yearbook. (2009). Tokyo: *Semento Shibunsya*.

Geng, Y., Fujita, T., & Chen, X. (2010). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production, 18*(10-11), 993-1000.

Iron and Steel Yearbook. (2009). Tokyo: *Tekkou Shinbunsya*.

JCPRA (The Japan Containers and Packaging Recycling Association). (2007). *The Environmental Impacts of Plastic Containers and Packaging Recycling (in Japanese)*. Tokyo, Japan: JCPRA.

Matsutou, T. (2005). *Analysis, Planning, and Assessment of Urban Waste Treatment Systems: Material Flow and LCA Programs*. Tokyo, Japan: Gihoto Shuppan.

MOE. (2006). Procedures for bidding and contracts of constructing waste treatment facilities. Retrieved from http://www.env.go.jp/hourei/syousai.php?id=11000360

Ueda, K. (2000). Public Policy for Sound Material-Cycle Society (in Japanese). *Policy Science, 7*(3), 77-88.

Chapter 6 Discussions and Policy Implications

This chapter has two purposes. The first one is to generalize the findings from the case study to different types of wastes so as to propose a regional recycling system with high cost-efficiency. These issues are discussed in section 6.1. The second purpose is to provide policy recommendations for promoting the proposed regional recycling system. The general policies are discussed in section 6.2.

6.1 Multi-Layer Regional Recycling Network

Results from modeling indicated two factors, (1) the ratio of unit transportation costs to unit treatment costs and (2) density of separated waste, are of great importance in determining the proper boundary of recycling. In the case study, the impacts of the two factors on recycling a particular type of waste, waste plastics, were modeled. In a wider scope, values of the two determinants are different for different types of wastes due to their properties and characteristics of recycling. Unit transportation cost is mainly influenced by loadings per truck for transportation, whereas the price of fuel (i.e. diesel) and fuel efficiency of trucks exert little impacts. Wastes that are bulky, of low density, requiring frequent maintenance of trucks, and unsuitable for storage, often have low loadings of trucks and thus high unit transportation costs, such as food wastes, PET bottles and bulky wastes (e.g. furniture). Unit treatment cost is affected heavily by the needs of manual works due to the relatively high costs of labors in Japan. The density of separated waste is determined by several relatively independent factors. It can be estimated by:

$$\text{density of separated waste } j = D_i \times G_{i,cap} \times C_j \times R_j \qquad \text{(eq. 6.1)}$$

where D_i denotes population density in municipality i, $G_{i,cap}$ denotes per capita waste generation in municipality i, C_j denotes the composition of waste j, and R_j denotes the recycling rate (or ratio of treatment) of waste j. Because $G_{i,cap}$ dose not vary largely in municipalities in a given region, wastes that are generated from populous areas, account for a large proportion in municipal solid waste, and have a high recycling rate are of high density.

Under typical circumstances in Japan, the ratio of unit transportation cost to unit treatment cost and density of different types of separated wastes are summarized in Table 6.1. Here, the *type* of separated waste is rather an operational definition, which is defined as the waste(s) demanded for by the users. These types can vary from one region to another according to the particular local demands. For example, for producing refuse plastic and paper fuel to substitute fossil fuels, mixed plastics and paper can be taken as one type; while for producing RDF, mixed combustible wastes becomes one type. Properties of different types of wastes would determine the proper recycling boundaries for them by plotting them in a quadrant with the two axes of the aforementioned two factors (Figure 6.1). Wastes that are close to the top-right corner are cost-efficient to be recycled at the local level, whereas those close to the bottom-left corner are at the regional level. As a result, mixed combustible wastes for producing RDF and food waste are proper to be pre-treated at the municipality level. On the contrary, metal (e.g. cans and metal craps) and glass are proper to be pre-treated in the regional level.

Table 6.1 Unit transportation cost and density of separated different types of waste from municipal sources

Type of waste	(A) Unit transportation cost	(B) Treatment cost	A/B	Density of available waste*
Food	H	L	VH	H
Paper	L	M	L	H
Non-PET plastics	M	H	L	M
PET	H	H	M	L
Glass	L	M	L	L
Metal	L	M	L	L
Bulky waste (e.g. furniture)	H	M	H	M
RDF (mixed combustible wastes)	H	L	VH	VH
Mixed plastics and paper	M	H	L	H

Note: * Density of available waste is estimated in the case of average population density and expected recycling rates in the future.

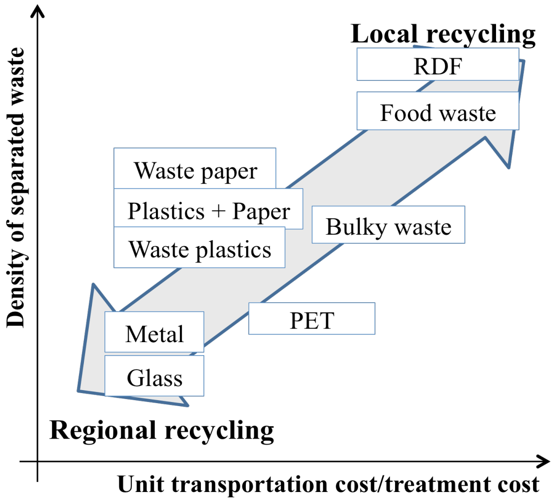
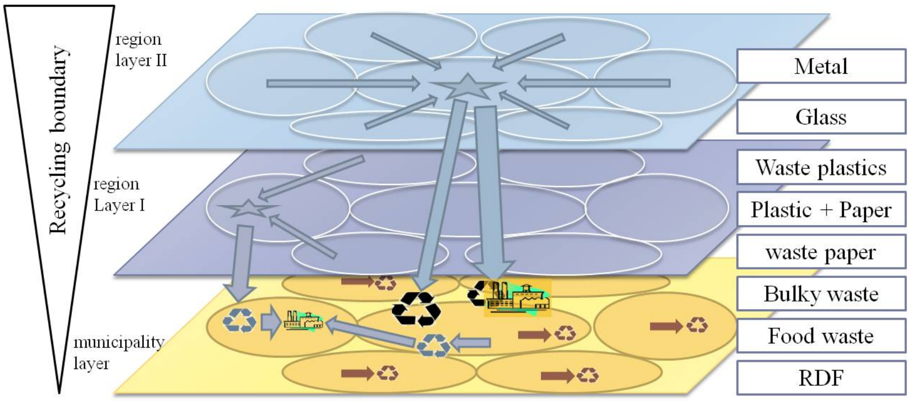


Figure 6.1 Recycling boundary for different types of wastes

This result is consistent with the findings in the literature, such as (Habara et al., 2002), who found that bulky waste treatment, composting, and RDF production at the regional level would cost more than those at the municipality level. This finding also helps explain the findings in the empirical study on recycling projects in eco-towns in Chapter 3, where the finding indicates that different types of wastes have different recycling boundaries (Figure 3.14). In the empirical study, most of wastes from municipal sources were pre-treated by municipalities. The sources of these wastes were still spatially dispersed. Recycling facilities collected wastes directly from municipalities. Their conditions were similar to the RRCs. The basic pattern of the modeling results are proved by the empirical study, where RDF and food wastes had small recycling boundaries whereas metal and glass had relatively large recycling boundaries. Results for some types of wastes require further explanation. For example, waste plastics had a large recycling boundary in the empirical study because the recycling rate was lower than the one set in the models. In addition, the empirical study examined waste plastics after pre-treatment, so that the unit transportation costs would decrease. The empirical result concerning waste plastics should move towards the bottom-left side in Figure 6.1, i.e. having a lager recycling boundary than the modeling results. The modeling result of waste paper is not proved by the empirical data. Waste paper in the empirical study was mostly collected and pre-treated by private cooperatives, which provided services already beyond the municipal boundaries. For recycling facilities, the source of waste paper is not completely dispersed. The empirical studies showed that paper recycling facilities in eco-towns were not located closely to the private cooperatives.

The aforementioned general finding offers an important insight for designing regional recycling networks. At the regional level, recycling networks should have multiple layers with RRCs and MRCs for pre-treating different types of wastes. Meanwhile, regional recycling network should be localized, involving existing industrial facilities in the region, which offer opportunities to utilize wastes, such as low quality waste plastics and paper, in a more efficient way than waste treatment facilities (e.g. energy recovery through incineration). A simple image of regional recycling network is illustrated in Figure 6.2. Here *region layers* refer to the layers in which RRCs provide services for multiple municipalities, some for a large number and some for a small number depending mainly on proper recycling boundaries of different types of wastes. The *municipality layer* includes MRCs that provide service mainly for the municipality where it is located. In the strategic planning stage, the number, capacity, and location of RRCs for a particular type of waste, as well as the service area of each center, should be determined for high cost-efficiencies.



★: RRC : ♻: recycling facility 🏭: industrial facility

: flow of waste

Figure 6.2 A simple image of regional recycling networks

Figure 6.2 illustrates only a simple image of a regional recycling network. In a particular case of planning for regional recycling networks, closer scrutiny on the local conditions and intensive consultation with stakeholders are needed. First, the integrated management of different types of wastes may create opportunities for sharing infrastructures, such as storage areas at the municipal level, taking advantage of obsolete incineration sites, and sharing information platforms. Due to the difference in the properties of different types of wastes, one principle for the planning of regional recycling networks is to design specialized RRCs for different types of waste. At the same time, existing infrastructures should be carefully reviewed when planning for new RRCs.

Second, at the operational level, the RRCs should be able to separate wastes in different levels of quality to meet the demands respectively by industrial symbiosis and conventional open-loop recycling. The coexistence of different recycling methods is important for realizing the potential value of wastes to the fullest because they could treat wastes in different qualities in terms of contamination level. In the case of waste plastics recycling, high-quality waste plastics are separated for material recycling into resins (open-loop recycling) while low-quality waste plastics are treated for industrial symbiosis. The planning of regional recycling networks should take into account the availability and potential of different recycling methods.

Third, regional recycling networks require a regional administrative body to be responsible for waste recycling in the region. This regime involves not only new “hardware” projects, such RRCs, but also tremendous changes in the institutional structure and routine works for waste collection and pre-treatment. Waste management system is complex, which involves a number of closely related actors, such as governments, residents, the private sector (e.g. recyclers) and professionals (e.g. planners) (Chen et al., 2010). Policies promoting regional recycling through IS are even more complex because it involves industries in managing wastes and shift the responsibility from municipality level to the regional level. Regarding the complexity, policies in different aspects, for different actors, should be considered simultaneously. The next section discusses the design of policies in details.

6.2 Policies on Promoting Regional Recycling through IS

Because of the complexity of policy design for promoting regional recycling, research on socio-technical transition was referenced to establish a framework. In Chapter 2, we briefly reviewed a multi-level perspective on studying socio-technical transitions. According to this model, socio-technical transitions are a result of interactions between "landscape pressures", current regime, and niche innovations. The purpose of policy design is to intervene in the interactions and to orient the transition towards a desired goal. Such interventions could be organized in two realms: *articulating pressures* and *coordinating resources to adapt to these pressures* (Smith et al., 2005). Pressure articulation refers to the processes that identify the extent to which pressures are oriented coherently in a particular direction and that translate pressures into a format that prompts and enables responses by the regime. Resource coordination contributes to the adaptive capacity of a regime, the capacity to respond to the pressures bearing on the regime (Smith et al., 2005). A framework for design policies on promoting regional recycling through IS is illustrated in Figure 6.3.

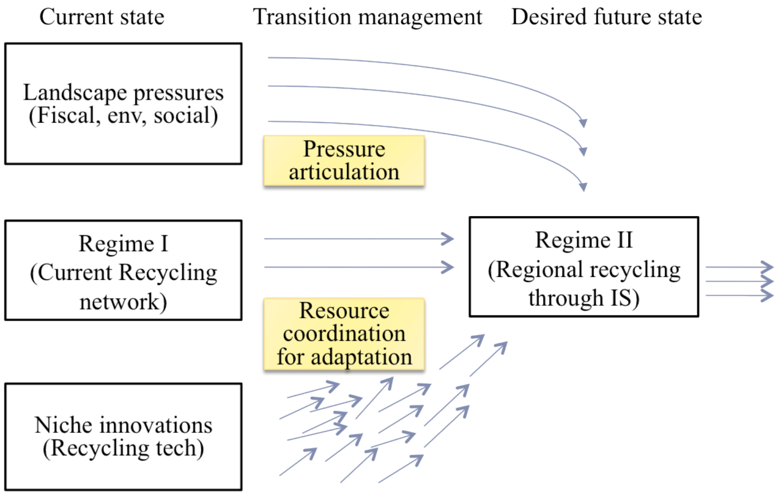


Figure 6.3 A framework for policy design based on socio-technical transition governance

As the starting point of designing policies for regional recycling through IS, the current state of landscape pressures and niche innovations is summarized. One way to identify the landscape pressures on the society is by looking at the issues that are mostly concerned by the public. On an internet survey conducted by Intage Inc., an information service company, between 23th February and 1st March, 2010, 1021 people ranked the top domestic social issues of their concerns in Japan. As a result, the top five issues included domestic economy and prosperity, annuity and social security, domestic politics, aging society and declining birthrate, and environmental issues (Figure 6.4). Among these social issues, the first two pertain to fiscal constraints of the public sector. Domestic politics can be related to a number of different issues contingent on the political will of parties. Of environmental issues, the hottest one under attention is global warming, partially due to international and political pressures. Another one is resource depletion, such as fossil fuels and rare metals. These environmental impacts are commonly analyzed in recent studies on waste management and recycling (Cleary, 2009). In addition, there are specific administrative pressures on the waste management system in Japan, such as the national fundamental plans for establishing a sound material-cycle society.

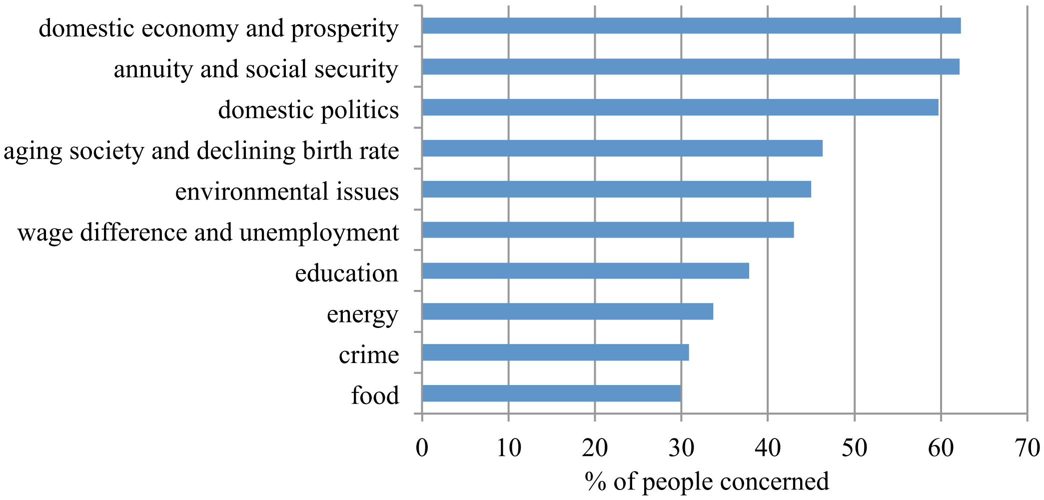


Figure 6.4 Top social issues of concern in Japan

Source: Intage Inc. Retrieved in Sep. 2011 from http://www.intage.co.jp/chikara/02_topics/596/

At the niche level, as discussed in section 4.2, there are no dominant technologies for recycling of many types of wastes. Industries usually purchase recycled products and materials that fulfill the quality requirement of their production. In some cases, industries are involved directly in the recycling process, developing special technologies to accept wastes as feedstock or fuels in their production, as shown in the example of waste plastic recycling in the case study in this research. If more recyclable wastes are properly separated and pre-treated, industries have a large potential to receive them in various forms.

With regards to the current state, policies should first identify the coherent pressures and translate them into a form that the recycling system can respond to, namely, pressure articulation. Table 6.2

tabulates some articulations of the pressures for recycling. These articulations can be reflected in the guideline for regional recycling planning and explanations of the policy direction. For example, response to the aging and concentrating population, waste collection services should be designed respectively for areas with high and low population density. This requires a transformation of the current system in terms of differentiated functioning of areas and locating treatment facilities in large cities where infrastructure and labors suffice. Response to global warming mitigation, recycling options should be encouraged to reduce GHG emissions by diverting fossil fuel-based waste (e.g. plastics) from incineration; efficiently utilizing bio-mass, waste paper, food waste, sludge and other “carbon-neutral” waste to reduce consumption of fossil fuels; and recycling energy intensive materials (e.g. steel, aluminum, rare metals

Table 6.2 Articulation of landscape pressure for recycling

Pressure	Articulation for recycling
Fiscal pressure	・Operating recycling collection and pre-treatment at high cost-efficiency by considering proper scales that balance economies of scale and transportation costs
Aging and concentrating population	・Waste collection services designed respectively for areas with high and low population density ・Pre-treatment and processing facilities locate in populous areas – differentiated functioning of areas
Global warming	・Reducing GHG emissions by diverting fossil fuel-based waste (e.g. plastics) from incineration ・Recycling and efficiently utilizing bio-mass, waste paper, food waste, sludge and other “carbon-neutral” waste to reduce consumption of fossil fuels ・Recycling energy intensive materials (e.g. steel, aluminum, rare metals)
Resource depletion	・Recycling wastes to substitute fossil fuels and other virgin materials ・Recycling wastes that require large amounts of raw materials in production (e.g. copper, aluminum, rare metals)
Establishing a sound material-cycle society	・Increasing total amount of recycling ・Promoting recycling at the regional level

Meanwhile, policies should direct resources to stakeholders to enhance the adaptive capacity of the regime. Smith et al. (2005) summarized five functions that contributed to the adaptive capacity of a regime: creation of new knowledge, influence over the direction of search processes among users and suppliers of technology, supply of resources, creation of positive external economies, and formation of markets. "Resources" refer to not only financial resources, but also information, infrastructure, political support, and technical supports. Because a regional recycling system requires coherent actions of multiple municipalities and industries, policies should be discussed at the national or prefecture level. Some of the policies to direct resources for each of these adaptive capability functions are listed in Table 6.3. For example, to create new knowledge, research on regional recycling should be encouraged from different perspectives, which would gradually form a common understanding among stakeholders to make collaborative efforts. To form a market for recycled materials, policy should promote green-purchase by industries and residents and green-procurement by government, of both intermediate and final products throughout the production chain. For a transformation of the recycling regime, these functions may take effect chronologically in sequence. However, policies for all of these functions need to be issued simultaneously so as to create an expectation of transformation among stakeholders.

6.3 Summary

The findings from the modeling on the case study the preceding chapter can be generalized to estimate proper boundaries of different types of recyclable wastes that are currently pre-treated in municipalities. By deducing the density and the ratio of unit transportation cost to unit treatment cost for each type of recyclable MSW, wastes that are suitable for local and regional recycling are revealed. The results are then verified by comparing with the empirical results in Chapter 3. The comparison shows highly consistent results. The results imply that a regional recycling network should have multiple layers fit the recycling boundaries of different types of wastes.

Table 6.3 Policies providing resources for adaptive capacity of regime

Adaptive capacity function	Policy and management instrument for promoting regional recycling through IS
Creation of new knowledge	・Supporting research on planning and evaluating potential costs and environmental benefits of regional recycling and industrial symbiosis ・Supporting research and development of technologies that uses wastes in industrial production with high efficiency ・Supporting research on analyzing and managing risks of regional recycling and industrial symbiosis
Influence over the direction of search processes among users and suppliers of technology	・Lobbying to decision makers ・Enhancing recycling programs to increase recycling rates ・Demonstrating and assessing the benefits of regional recycling through IS by pilot projects ・Creating incentives for municipalities to host RRCs ・Monitoring and managing the amount, reliability and quality of waste supply
Supply of resources	・Providing subsidies to compensate some initial capital investment and/or operation costs ・Offering taxation reduction for industries that accept wastes ・Managing and distributing updated information to stakeholders ・Summarizing best practices for stakeholders' reference ・Supporting the establishment administrative bodies for regional recycling
Creating positive external economies	・Issuing guidelines for regional recycling planning ・Issuing standards for pre-treated wastes to be accepted as fuel or feedstock in industrial production ・Evaluating the enforcement of recycling laws to ensure municipalities' participation in source separation
Formation of markets	・Promoting green-purchase and green-procurement of intermediate and final products throughout the production chain

Because the design regional recycling networks involves shifts of responsibility from municipalities to regional administrative bodies and a wide range of cooperation among municipalities and industries, comprehensive policies are discussed in two aspects. First, policies identify the extent to which pressures are oriented coherently in a particular direction and translate pressures into a form that prompts and enables responses by the regime. Particularly, implications of fiscal pressure, aging and concentrating population, global warming, resource depletion, and establishing a sound material-cycle society should be articulated for regional recycling. Second, policies contribute to the adaptive capacity of a regime, the capacity and resources to respond to the pressures bearing it. Five functions contributed to the adaptive capacity should be considered in policy making: creation of new knowledge, influence over the direction of search processes among user and suppliers of technology, supply of resources, creating positive external economies, and formation of markets.

Reference

Chen, X., Geng, Y., & Fujita, T. (2010). An Overview of Municipal Solid Waste Management in China. *Waste Management, 30*, 716-724.

Cleary, J. (2009). Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environment International, 35*(8), 1256-1266.

Habara, H., Matsuto, T., Tanaka, N., & Inoue, M. (2002). Comparative Study on Regional Solid Waste Management System in Terms of Cost and Energy Consumption (in Japanese). *Environmental Systems Research, 30*, 323-332.

Smith, A., Stirling, A., & Berkhout, F. (2005). The governance of sustainable socio-technical transitions. *Research Policy, 34*(10), 1491-1510.

Chapter 7 Conclusions

7.1 Main Findings

Recycling through IS contributes to closing the loop of material flows in urban systems. It concerns systematic works including, for example, source separation, collection, pre-treatment, recycling processing, and utilization of recycled materials. Drawbacks in any of these steps would impede further promotion of recycling. In Japan, the pre-treatment of recyclable wastes in municipal recycling centers is one of the steps that are relatively inefficient in the system. An approach to improve the efficiency of pre-treatment is to enlarge the scale of recycling centers and to expand the boundary of recycling to the regional level. This research aims to quantitatively explore the mechanism and factors that determine the proper boundary of regional recycling through IS by both empirical studies and a case study on recycling of waste plastics in the Tokyo Metropolitan Region (TMR) in Japan.

In the case study on waste plastic recycling in the TMR of Japan, the modeling results reveal two key factors that determined the proper boundary of recycling spatially diffused waste, density of recyclable wastes, and the ratio of unit transportation costs to unit treatment costs. In a given region where all municipalities are serviced, considering cost as a function of the number of hosting cities, i.e. the recycling boundary, the optimal solution is determined when the sum of marginal cost of transportation (MCT) and the marginal costs of construction + operation (MCCO) equals to zero. The first factor, density of separated wastes, influences both MCT and MCCO. If the density of separated wastes is so high that even when the number of hosting cities is close to the total number of cities in the region, the absolute value of MCT is larger than MCCO, then expansion to the regional scale is not preferred. The second factor, the ratio of unit transportation cost to treatment cost, influences the relative position of -MCT and MCCO curves and determines the intercept of the two curves.

These two factors reflect properties of different types of wastes as well as economic conditions in the region of concern, such as labor costs and transportation costs. The findings would help interpret the empirical findings, as well as plan for regional recycling networks with multiple layers for different types of wastes. Such a concept resulted in several changes in the present waste management system. First, it partially shifts the responsibility of recycling from municipal to regional level. Second, together with the concept of IS, it demands for localized recycling technologies and separation programs to meet the demand for recycled materials by local industries. Third, it requires specialization in the pre-treatment stage of recycling, seeking for economies of scale rather than economies of scope.

In addition to the aforementioned findings to attain the goal of this research, each chapter presents some other main findings. In Chapter 2, a review of the history of waste management and relevant literature indicate:

- Comprehensive environmental and economic problems require recycling to seek multiple benefits by utilizing wastes in efficient ways; and
- Recycling technologies evolves with the society's attitude towards waste, indicating an integration of the waste management system with the society.

Chapter 3 presents empirical studies on recycling facilities in Japanese eco-towns and recycling of waste plastics in Japan with a focus on spatial features. The empirical studies reveal:

- Large eco-town projects are more stable in operation and locate closer to the users of recycled materials than small ones;
- Geographical agglomeration of recycling facilities in eco-towns does not appear to have advantages over dispersed eco-towns;
- Recycling boundaries of different types of wastes differ from one another;
- Recycling processing centers for waste plastics already exist in Japan, most of which have eco-towns facilities where advanced recycling technologies are cultivated and applied; and

Chapters 4 and 5 introduce the methodology and results of a case study on waste plastics recycling in the Tokyo Metropolitan Region of Japan. In addition to the findings discussed above, the case study also shows:

- The results confirm that waste reduction is an effective approach to reduce the total cost of waste management;
- Environmental benefits of recycling depend heavily on the utilization of waste to substitute raw materials regardless of how wastes are collected. However, how wastes are collected affects the cost of recycling and in turn influences amount of waste to be recycled; and
- If properly managed, the eco-efficiency of recycling would increases as the recycling rate increases.

Chapter 6 discusses the design of multi-layer regional recycling networks based on the generation of modeling results and policies on promoting regional recycling. Main findings in this chapter include:

- Regional recycling networks should have multiple layers for different types of wastes according to their density and the ratio of unit transportation costs to unit treatment costs; and
- Policies on promoting regional recycling should encourage innovation in the management system to alleviate pressing pressures on the society and provide stakeholders with resource to enhance their capacity to adapt to new regimes.

7.2 Research Contributions

This research is interdisciplinary in its nature. The system thinking mode, the perspective from material flows in urban systems, and the concept of IS are adopted from a burgeoning research field of IE, which itself is a highly interdisciplinary filed. The models employed in this research included a revised indicator of location quotient (LQ) for recycling, a modified optimization model solving location-allocation problems and a life cycle assessment (LCA) model assessing the environmental benefits of regional recycling. These models were adopted from regional economics, economic geography, and IE. Combining interdisciplinary knowledge, this research conducted original works in the following aspects:

- The empirical study on recycling facilities in eco-towns, with the first-hand data, showed the relationships between scale, recycling, and waste type, as well as their impacts on performances of recycling projects;
- This research modified the optimization model to taken into account economies of scale in solving the location-allocation problem for regional recycling centers;
- This research found by quantitative approaches the mechanism and factors that determines the appropriate recycling boundaries for different types of wastes; and
- This research proposed comprehensive policies on promoting regional recycling through IS.

These works could contribute to both research and practices. In terms of contributions to research, first, the empirical findings would become valuable references in the field of waste management and IE. Second, the finding on identifying the mechanism and key factors that determine the appropriate recycling boundaries for different types of wastes contributes also to research in fields of waste management and IE. It offers novel insights for analyzing the spatial feature of recycling activities from a perspective of cost minimization. Third, by demonstrating the economic and environmental benefits of region recycling through IS, this research would encourage relevant research on the topic of regional recycling and waste management. Such research can be conducted from different perspectives in addition to cost minimization and environmental benefit assessment, such as from a management point of view on facilitating collaboration among municipalities, risk management and green supply chain management of industries that receive wastes, allocation of benefits and emission reduction credits to participating municipalities, and so forth.

In practice, findings of the case study could contribute to planning for regional recycling of non-PET waste plastics in the NCR. By illustrating the difference between incineration costs and recycling costs in various cost-sharing schemes, the research outcomes could also help select proper areas with high incentives for putting forward pilot programs. Such a plan pertains closely to the ongoing discussion on establishing a sound material-cycle society and recycling blocks in Japan. Second, the general findings on the mechanism and key factors that determine recycling boundary could serve as a reference for the planning on recycling networks for other types of wastes and in other regions.

7.3 Future Research

Future research could be expected in both empirical studies and modeling for regional recycling and IS. In terms of empirical study, the results from this study are induced from empirical data of recycling facilities in Japanese eco-towns. It is necessary to examine if the results would remain valid in other countries and regions.

As for modeling, this research took into account the influence of scale on construction and operation costs of recycling centers. The model could be further revised in the future to test, for example, specific constraints on facility capacity and more types of industries as potential recipients of wastes. In addition to minimizing the total costs, future studies could also examine the flexibility and resilience of regional recycling networks if significant shocks to the network strikes, such as closing down of industrial facilities that receive waste in the plan or regional recycling centers due to either operational reasons or natural disasters.

Finally, optimization of the use of virgin and waste material flows can further bring about increase in the efficiency of industrial production and recycling. Because this research focuses on planning for the recycling network, how waste is utilized in industrial facilities is based on the current practices. If the waste material flows, especially flows of steam and water that can be cascaded, in an industrial complex could be optimized among different plants, the efficiency of recycling would be further improved.

APPENDIX I

Survey Questionnaire to Recycling Facilities in Eco-Towns

Source: MoE. 2010. FY2009 Report on the Project to Survey and Examine Measures to Further Promote Eco Town Programs. Tokyo, Japan: Waste Management and Recycling Department, Ministry of the Environment.

Note: this survey was not designed particularly for this dissertation. We shared the data and conducted analysis to form this research on top of the work by the Study Group. Therefore, some data acquired from this questionnaire were not analyzed in this research. The questionnaire survey was originally distributed in Japanese. Ministry of the Environment of Japan provided English translation in its English version report.

Questionnaire on Measures to Further Promote Eco Town Programs **Sheet 1**

Q1 Outline of the eco town facility

(1-1) Outline of the office

Please provide details of your office below.

Name of office			
Address			
Department			
Name of respondent		Telephone	

(1-2) Outline of the facility

Please provide details of your facility below.

Name of facility			
Address			
Date construction started		Date of completion	
Date operations started		Website	
Brief description of facility			
Recycling method			
Facility capacity		Operating rate $\left(\frac{\text{Actual amount accepted in FY 2007}}{\text{Amount planned to be accepted}}\right)$	%
Recycling processes (Leave this blank if the facility has been co-approved by the MOE and METI as the Eco Town Plan and received subsidies for its development (subsidized facility).)	※1: Please attach a brochure or other such material describing recycling processes, if any, and leave this box blank.		

(1-3) Utilization of subsidy programs

If your facility is receiving subsidies under any national or municipal programs other than the subsidy program for the Eco Town Program implemented jointly by the MoE and METI, please enter the names of such programs.

Q2 Acceptance of waste and by-products; FPs, RMs, and by-products produced in the recycling process; and recycling residue

Please enter actual results for your facility for FY2007 (April 1, 2007 through March 31, 2008) for each item under (2-1) Acceptance, (2-2) Processing and utilization, and (2-3) Recycling residue.

If you need more space, please photocopy the blank sheet or ask the survey organization for additional copies; if you are using the electronic version, please simply add columns.

Sheet 2

(2-1) Input of waste and by-products

If electricity, gas, and/or steam is supplied by other facilities as CRs for use at your facility, please enter the amounts on Sheet 3 under Q3 (3-2).

		①Materials accepted		②Acceptance category	③Acceptance conditions	④Annual volume accepted	⑤Origins of waste and by-products accepted			
		Please specify waste/by-products accepted. If a material is accepted as both domestic waste and industrial waste, please use one column for each and circle "domestic" or "industrial" in the Material category column.	Material category	Fee arrangement (All that apply) A: Accept for a fee B: Accept at no charge C: Collect recycling fees *Excl. collection/transport. expenses	If the waste/by-products are of a special kind or have special properties, please explain below.	Please enter the actual annual volume of waste/by-products accepted (in tons).	Please enter the breakdown of annual volume accepted (④) for each origin of waste/by-products accepted. ※If the volume cannot be specified for each origin, please contact the survey organization.			
							Within the Eco Town Plan region		Outside the Eco Town Plan region	
							⑤A Within the city/town where your facility is located	⑤B Outside the city/town where your facility is located	⑤C Within the prefecture where your facility is located (Note: Please leave this blank if the target region covers the entire prefecture.)	⑤D Outside the prefecture where your facility is located
Answer column	1		Domestic Industrial	A B C		t	t	t	t	t
	2		Domestic Industrial	A B C		t	t	t	t	t
	3		Domestic Industrial	A B C		t	t	t	t	t
	4		Domestic Industrial	A B C		t	t	t	t	t
	5		Domestic Industrial	A B C		t	t	t	t	t

→

⑤a. Cooperation among operators under the Eco Town Plan
If ⑤A or ⑤B is applicable and resources are circulated in cooperation with other facilities under the same Eco Town Plan, please enter the names of the operators supplying the waste/by-products and volume accepted at your facility.

→

⑤b. List of prefectures
Please list the prefectures applicable under ⑤D.

※Please refer to the attached survey material, "Eco Town Plans across the Nation and Their Target Areas," for the details of the Eco Town Plan regions.

(2-2) Production of FPs, RMs, and by-produ

If electricity, gas, and/or steam is supplied by other facilities as CRs for use at your facility, please enter the amounts on Sheet 3 under Q3 (3-3).

		①FPs/RMs produced	②Utilization category	③Utilization conditions	④Annual production	⑤Destinations of FPs, RMs, and by-products			
		Please specify FPs, RMs, and by-products produced.	Fee arrangement (All that apply) A: Supply for a fee B: Supply at no charge C: Pay recycling fees *Excl. collection/transport. Expenses	Please explain the properties of FPs, RMs, and/or by-products at the time of utilization at other facilities after being processed or recycled at your facility.	Please enter the actual annual volume of FPs, RMs, and/or by-products produced (in tons).	Please enter the breakdown of annual production (④) for each FP, RM, and/or by-product processed or recycled at your facility.			
						Within the Eco Town Plan region		Outside the Eco Town Plan region	
						⑤A Within the city/town where your facility is located	⑤B Outside the city/town where your facility is located	⑤C Within the prefecture where your facility is located (Note: Please leave this blank if the target region covers the whole prefecture.)	⑤D Outside the prefecture where your facility is located
Answer column	1		A B C		t	t	t	t	t
	2		A B C		t	t	t	t	t
	3		A B C		t	t	t	t	t
	4		A B C		t	t	t	t	t
	5		A B C		t	t	t	t	t
	6		A B C		t	t	t	t	t
	7		A B C		t	t	t	t	t

→

⑤a. Cooperation among operators under the Eco Town Plan
If ⑤A or ⑤B is applicable and resources are circulated in cooperation with other facilities under the same Eco Town Plan, please enter the names of the operators to whom the waste/by-products are supplied and volume supplied.

→

⑤b. List of prefectures
Please list the prefectures applicable under ⑤D.

※Please refer to the attached survey material, "Eco Town Plans across the Nation and Their Target Areas," for the details of the Eco Town Plan regions.

(2-3) Disposal of recycling residue, i.e. residue for landfill disposal (incl. residue outsourced for intermediate treatment and to be disposed of as landfill in the end)

		①Residue to be disposed of	②Properties of residue to be disposed of and disposal method	④Annual disposal volume	⑤Geographical areas where recycling residue is disposed of			
		Please specify recycling residue.	Please explain the properties of recycling residue to be disposed of and the disposal method.	Please enter the actual annual volume of recycling residue (in tons).	Please enter the breakdown of annual disposal volume (④) for each category of recycling residue.			
					Within the Eco Town Plan region		Outside the Eco Town Plan region	
					⑤A Within the city/town where your facility is located	⑤B Outside the city/town where your facility is located	⑤C Within the prefecture where your facility is located (Note: Please leave this blank if the target region covers the entire prefecture.)	⑤D Outside the prefecture where your facility is located
Answer column	1			t	t	t	t	t
	2			t	t	t	t	t
	3			t	t	t	t	t

→

⑤b. List of prefectures
Please list the prefectures applicable under ⑤D.

※Please refer to the attached survey material, "Eco Town Plans across the Nation and Their Target Areas," for the details of the Eco Town Plan regions.

Sheet 3

Q3 Use of electricity, gas, and other energy sources at the facility

Please enter actual results for your facility for FY2007 (April 1, 2007 through March 31, 2008) for each item under (3-1) Use of electricity, gas, oil, and other energy sources for the operation of your facility, (3-2) Supply by other facilities, and (3-3) Supply to other facilities.

(3-1) Electricity, gas, oil, and other energy sources used to operate the facility

Please enter the amount of energy sources such as electricity, gas, and oil required to operate your facility (use column 4 for an energy source other than electricity, gas, and oil). As for the refuse derived fuel, enter the amount under Q2-(2-1) on Sheet 2.

		①Energy source	②Annual consumption	
		Please specify the types of respective energy sources except for electricity and explain their properties in parentheses.	Please enter the annual amounts consumed and their units.	Unit
Answer column	1	Electricity		
	2	Gas ( )		
	3	Oil ( )		
	4	( )		

※When the amount of energy consumption of the eco town facility cannot be determined accurately because a recycling project not under the Eco Town Program is also being carried out at the same plant, please prorate it using such factor as the estimate included in the facility's design and production value.

(3-2) Electricity, gas, and other energy sources supplied by other facilities

If electricity, gas, steam, and/or other energy sources generated at other facilities are used to operate your facility, please enter the amount of the respective energy sources used (use columns 3 and 4 for energy sources other than electricity and gas). As for the refuse derived fuel, please enter the amount under Q2- (2-1) on Sheet 2.

		①Energy source	②Annual amounts accepted		③Origins of energy sources	
		Please specify the types of respective energy sources except for electricity and describe their properties in parentheses.	Please enter the actual annual amounts of energy sources supplied by other facilities and their units.	Unit	Please enter the breakdown by the origin of energy sources.	
					③A Within the Eco Town Plan region	③B Outside the Eco Town Plan region
Answer column	1	Electricity			%	%
	2	Gas ( )			%	%
	3	( )			%	%
	4	( )			%	%

→

③a. Cooperation among operators under the Eco Town Plan
If ③A is applicable and resources are circulated in cooperation with other facilities under the same Eco Town Plan, please enter the names of the operators supplying the energy sources.

※Please refer to the attached survey material, "Eco Town Plans across the Nation and Their Target Areas," for the details of the Eco Town Plan regions.

(3-3) Electricity, gas, and other energy sources supplied to other facilities

If electricity, gas, steam, and/or other energy sources generated at your facility are used at other facilities, please enter the amount of the respective energy sources supplied (use columns 3 and 4 for energy sources other than electricity and gas). As for the refuse derived fuel, please enter the amount under Q2- (2-2) on Sheet 2.

		①Energy source	②Annual amounts supplied		③Destinations of energy sources	
		Please specify the types of respective energy sources except for electricity and describe their properties in parentheses.	Please enter the actual annual amounts of energy sources supplied to other facilities and their units.	Unit	Please enter the breakdown by the destination of energy sources.	
					③A Within the Eco Town Plan region	③B Outside the Eco Town Plan region
Answer column	1	Electricity			%	%
	2	Gas ( )			%	%
	3	( )			%	%
	4	( )			%	%

③a. Cooperation among operators under the Eco Town Plan
If ③A is applicable and resources are circulated in cooperation with other facilities under the same Eco Town Plan, please enter the names of the operators to whom the energy sources are supplied.

※Please refer to the attached survey material, "Eco Town Plans across the Nation and Their Target Areas," for the details of the Eco Town Plan regions.

Q4 Waste, by-products, energy sources, and other resources generated at your facility **Sheet 4**

(4-1) Waste and by-products generated at your facility but unutilized

Is there any recycling residue generated at your facility that is presumably recyclable but not actually utilized? Please place a circle (○) on either A or B below, and if you circle "B," please specify the unutilized waste/by-products and their properties and explain the reasons for not utilizing them.

A There are unutili B There are no unutilized resources.

↓ (Please specify the waste and/or by-products and their properties.)

(Reasons for not utilizing them)

(4-2) Steam and hot water generated at your facility but unutilized

Are there any energy sources such as steam and hot water generated at your facility that are presumably recyclable but not in fact utilized? Please place a circle (○) on either A or B below, and if you circle "B," please specify the unutilized energy sources and their properties and explain the reasons for not utilizing them.

A There are unutili B There are no unutilized resources.

↓ (Please specify the recyclable energy sources and their properties.)

(Reasons for not utilizing them)

Q5 Operating status of facilities (part 1)

Sheet 5

(5-1) ① Procurement of waste and by-products

Please place a circle (○) in appropriate boxes with respect to the procurement status of waste and by-products at your facility for FY2007 and FY2008 (at the time of responding to the questionnaire). (Please check all that apply.)

	Answer column All that apply for each year	
	FY2007	FY2008
a) No particular concerns		
b) Unstable procurement due to intensifying competition (in the tendering process) with other companies		
c) Decrease in waste and by-products available in the market		
d) Difficulty in procurement in neighboring areas		
e) Desire procurement from distant regions, but concerned about the cost of long-distance transportation		
f) Other Specify: ( )		

(5-1) ② Efforts to stabilize and expand waste/by-product procurement

Please place a circle (○) in appropriate boxes with respect to efforts made and measures taken to stabilize and expand waste/by-product procurement for "past efforts with successful outcomes" and "measures needed in the future" and describe such efforts and measures in parentheses under each item title. Please place an "X" if no particular efforts are being made or if you think no future measures are necessary.

	Answer column All that apply for each category	
	Past efforts with successful outcomes	Measures needed in the future
① Provision of information to waste generators alone or in cooperation with other operators under the Eco Town Plans ( )		
② Adjustment utilizing warehouses ( )		
③ Transportation utilizing vehicles returning from deliveries and joint transportation with other companies ( )		
④ Municipal promotion of eco town facilities (environment-conscious product certification etc.) ( )		
⑤ Stable supply of domestic waste from municipalities ( )		
⑥ Favorable recycling-related laws and regulations ( )		
⑦ Efforts/measures other than ① to ⑥ above, if any ( )		

Q5 Operating status of facilities (part 2)

Sheet 6

(5-2) ① Utilization status of recycled products and by-products

Please place a circle (○) in appropriate boxes with respect to the utilization status of recycled products and by-products produced at your facility for FY2007 and FY2008 (at the time of responding to the questionnaire). (Please check all that apply.)

	Answer column All that apply for each year	
	FY2007	FY2008
a) No particular concerns		
b) Unstable markets due to intensifying competition with other companies		
c) Unstable markets due to price fluctuations in virgin materials		
e) Difficulty in securing facilities wanting supply in neighboring areas		
d) Desire supply to distant regions, but concerned about the cost of long-distance transportation		
f) Other Specify: ( )		

(5-2) ② Efforts to stabilize and expand the utilization of recycled products and by-products.

Please place a circle (○) in appropriate boxes with respect to efforts made and measures taken to stabilize and expand the utilization of recycled products and by-products for "past efforts with successful outcomes" and "measures needed in the future" and describe such efforts and measures in parentheses under each item title. Please place an "X" if no particular efforts are being currently made or if you think no future measures are necessary.

	Answer column All that apply for each category	
	past efforts with successful outcomes	measures needed in the future
① Provision of information to users alone or in cooperation with other operators under Eco Town Plans ( )		
② Adjustment utilizing warehouses ( )		
③ Transportation utilizing vehicles returning from waste/by-product procurement and joint transportation with other companies ( )		
④ Municipal promotion of eco town facilities (environment-conscious product certification, green purchasing, etc.) ( )		
⑤ Utilization by municipalities and public sector organizations ( )		
⑥ Favorable recycling-related laws and regulations ( )		
⑦ Efforts/measures other than ① to ⑥ above, if any ( )		

Q5 Operating status of facilities (part 3)

Sheet 7

(5-3) Profitability of the Eco Town Programs

Please place a circle (○) in appropriate boxes with respect to the profitability of your programs for FY2007 and FY2008 (at the time of responding to the questionnaire).

	Answer column All that apply for each year	
	FY2007	FY2008
① No particular concerns		
② Relatively tough		
③ Extremely tough		
④ Other Specify ( )		

(5-4) Cooperation among operators within the target regions of Eco Town Plans

Please place a circle (○) on either A, B, or C with respect to cooperation to be started or enhanced among operators within the target regions of Eco Town Plans for recycling waste/by-products, producing FPs, exchanging information, etc.

A New/enhanced cooperative measures ne B Satisfied with the current situatio C Undecided

↓ ※If you circle "A," please be specific.

( )

(5-5) Other challenges, and expansion measures needed for CRs such as waste and by-products

If your facility is facing any other challenges or if you feel other measures are needed to expand the utilization of CRs such as waste and by-products, not covered under Q5-1 through 5-4, please explain below.

~ Thank you for your cooperation. Please return the sheets by post in the enclosed self-addressed

APPENDIX II

Determining Model Parameters

1. Parameters for Calculating Construction Costs

The construction of waste treatment and recycling facilities, as well as many other types of plants, has economies of scale. That is, as the scale of facility increases, the cost per unit treatment capacity decreases. Figure 1 shows samples of MRCs built in the last decade in Japan and clearly illustrates a pattern of decreasing unit cost as capacity increases. It is widely known that an exponential rule holds for construction costs of chemical plants and many other types of facilities (Berthouex, 1972). MOE (2006) of Japan also recommended to apply the exponential relationship between construction costs and facility scales for waste treatment facilities, in which the exponent equaled to 0.6:

$$y = y_n \left(\frac{Q}{Q_n}\right)^{0.6} \qquad \text{(eq. 1)}$$

where y denotes the construction cost of a facility with capacity Q, and y_n and Q_n denote the construction cost and capacity of a known facilities with similar functions.

Some MRCs shown in Figure 1 were designed to receive different types of wastes including waste plastics, paper, glass, and, in some cases, large items such as furniture. These wastes are treated in separate plants on the same site. In order to estimate the construction cost of RRCs only for recycling non-PET plastics, the construction cost of a known facility, y_n, was taken from the average of four of MRCs only for non-PET waste plastics, which have similar functions to the proposed RRCs (Table 1). Annual working time was assumed to be 240 days.

The service time of RRCs was assumed to be 25 years. Due to the low interest rate in Japan and for the sake of simplicity of calculation, the annual construction cost was estimated according to a straight line depreciation model, and the residue value was assumed to be 0 (eq. 5.2).

$$Annual\ construction\ cost = \frac{Initial\ construction\ cost - Residue\ value}{Service\ time} \qquad \text{(eq. 2)}$$

Thus the annual construction costs of a RRC is:

$$CON_j(1000\,JPY) = 112.84{w_j}^{0.6}(t/y) \quad (w_j \leq 100000\ t/y) \qquad \text{(eq. 3)}$$

where CON_j denotes construction cost of a RRC in municipality j; and w_j denotes the treatment capacity of that center.

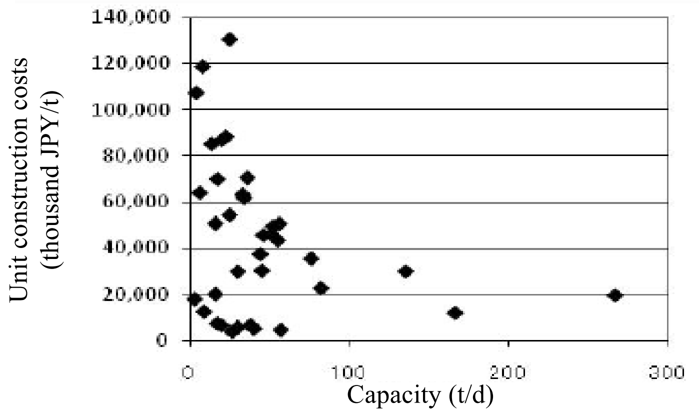


Figure 1 Construction costs of municipal recycling centers with different capacity in Japan

Source: Japanese Environmental Sanitation Center. Cited in Oyama City, Tochigi Prefecture. Basic vision of infrastructure for promoting material recycling. Retrieved in June, 2011 at http://www.city.oyama.tochigi.jp/kouiki/gomisyorisisetu/matekihonnkousou.html

Table 1 Costs of municipal waste plastics recycling centers

Municipality	capacity	construction cost
	t/d	1000JPY
Fukushima City	10	138,000
Nagasaki City	25	552,330
Western Matsumoto Region Cooperative	11	268,000
Toyohashi City	29	968,000
Average	19	481,583

Source: Japanese Environmental Sanitation Center. Cited in Yinzai Region Clean Center, Recycling center construction research commission: the 12th workshop reference material – construction costs of recycling center. Retrieved in June, 2011 at http://www.inkan-jk.or.jp/creen/2106jikikentouiinkai.html

2. Parameters for Calculating Operation Costs

In this research, the total amount of non-PET waste plastics generated in the TMR is considered the functional unit. Therefore, the operation costs included costs of running both RRCs and incinerators for treating unseparated waste plastics. For the operation costs of RRCs, costs of labor (salaries), overhead, maintenance, electricity, bailing materials, diesel, and heavy equipments (e.g. cranes and forklifts) were taken into account. The parameters for calculating these costs are tabulated in Table 2. The values of these parameters were set by referencing previous relevant case studies on Kawasaki (Geng et al., 2010) and consultation with an engineering company that designs recycling facilities. Similar to the calculation of annual construction costs, the annual costs of purchasing heavy equipments were also estimated according to the straight-line depreciation model with a service time of 7 years and a residue value of 0. Detailed settings of operation costs of RRCs are summarized in Table 2. The results of operation costs of RRCs, together with annual construction cost, are shown in Figure 2. Labor costs, which are highly correlated with treatment capacity, account for a large proportion of the operation cost. As a result, the total annual operation cost has a linear line that fits to treatment capacity.

$$OPR_j(1000\,JPY) = 8.28w_j(ton) + 71036 \qquad (w_j \leq 100000\ t/y) \qquad \text{(eq. 4)}$$

Where OPR_j denotes the operation costs of a RRC in municipality j.

Table 2 Parameters for calculation operation costs of RRCs

Item	Quantity	Unit
Payment	4500	thousand JPY/y/cap
Overhead	20%	Total payment
Facility maintenance	1.4%	Construction cost
Days of operation	240	d
Diesel	0.12	thousand JPY/l
Diesel consumption	1.6	l/t-waste
Bailing materials	1.1	thousand JPY/t-waste
Electricity	0.014	thousand JPY/kwh
Electricity consumption	25	kwh/t-waste
Crane	7600	thousand JPY
Forklift	3500	thousand JPY
Expected service time of cranes and lifts	7	year

Table 3 Settings of operation costs of RRCs

Labors needed

capacity	t/8h(d)	10	20	40	60	80	100	120	140	160	180	200
Office	Manager	1	1	1	1	1	1	1	1	1	1	1
	Assistant	1	1	1	2	2	2	2	2	2	2	2
Platform	Measuring & guiding	1	1	1	2	2	2	2	2	3	3	3
	Crane	1	1	1	2	2	3	3	3	4	4	4
	Separation	8	10	14	18	22	26	30	34	38	42	46
Maintenance	Safety/maintenance	2	2	2	2	2	3	3	3	4	4	4
Stockyard	Forklift	1	1	1	2	2	3	3	3	4	4	4
Total		15	17	21	29	33	40	44	48	56	60	64

Construction cost

Capacity	Unit	10	20	40	60	80	100	120	140	160	180	200
Cost (power=0.6)	thousand JPY	327,658	496,637	752,761	960,089	1,140,972	1,304,430	1,455,223	1,596,238	1,729,390	1,856,028	1,977,147
Expected service time	year	25	25	25	25	25	25	25	25	25	25	25
Annual cost	thousand JPY	13,106	19,865	30,110	38,404	45,639	52,177	58,209	63,850	69,176	74,241	79,086

Operational cost fixed cost variable cost thousand JPY/yr

Item	Capacity(t/yr)	2400	4800	9600	14400	19200	24000	28800	33600	38400	43200	48000
1	Payment	67,500	76,500	94,500	130,500	148,500	180,000	198,000	216,000	252,000	270,000	288,000
2=1*0.2	Overhead	13,500	15,300	18,900	26,100	29,700	36,000	39,600	43,200	50,400	54,000	57,600
3=1.4%*construction cost	Maintenance	4,587	6,953	10,539	13,441	15,974	18,262	20,373	22,347	24,211	25,984	27,680
4	Electricity	840	1,680	3,360	5,040	6,720	8,400	10,080	11,760	13,440	15,120	16,800
5	Bailing material	2,640	5,280	10,560	15,840	21,120	26,400	31,680	36,960	42,240	47,520	52,800
6	Diesel	461	922	1,843	2,765	3,686	4,608	5,530	6,451	7,373	8,294	9,216
7	Heavy equipment	1,586	1,586	1,586	3,171	3,171	4,757	4,757	4,757	6,343	6,343	6,343
8=sum(1:7)	Total	91,114	108,220	141,288	196,857	228,871	278,427	310,020	341,476	396,007	427,262	458,439

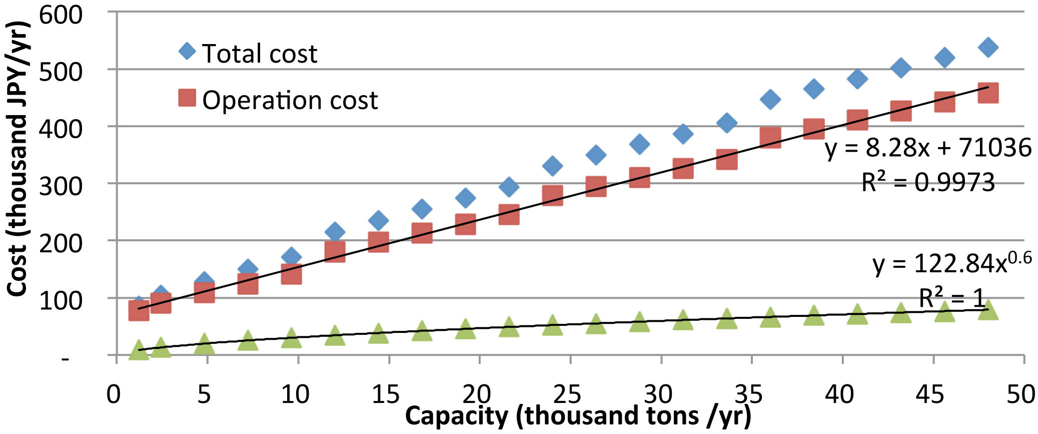


Figure 2 Costs of RRCs in different scales

To estimate the costs of treating unseparated waste plastics, we assumed waste plastics were incinerated together with other combustible wastes in each municipality or waste management cooperative. The cost for treatment waste plastics (*INIC*$_i$) is the share of total incineration cost in each municipality or waste management cooperative on a weight basis:

$$INIC_i = TINIC_i \cdot \frac{uw_i}{TW_i \times \gamma} \qquad \text{(eq. 5)}$$

where $TINIC_i$ is the total cost of incineration, uw_i is the unseparated waste plastics, and TW_i is the total wastes in municipality *i*, and γ is the proportion of waste incinerated. The average γ currently is 75%, and the waste plastics recycling rate of waste plastics is 20% (1.5% of total waste generation). When the waste plastics recycling rate increases to 50%, γ decreases to 73%. Initial investment on construction ($\mathrm{CONI_i}$) and operation costs of incineration ($\mathrm{OPRI_i}$) were taken into account as follows:

$$TINIC_i = CONI_i + OPRI_i \qquad \text{(eq. 6.0)}$$

$$CONI_i = N_i \cdot \frac{(1+GT) \times CONI_0 \left({}^{S_i}/_{S_0} \right)^{0.7}}{TI} \qquad \text{(eq. 6.1)}$$

$$OPRI_i = Cp_i + Cm_i \qquad \text{(eq. 6.2)}$$

$$Cp_i = N_i \cdot \propto_p (Np + b_1 \cdot n + b_2 \cdot S_i) \qquad \text{(eq. 6.3)}$$

$$n = \begin{cases} 1 & (0 < S \leq 100\ t/d) \\ 2 & (100 < S \leq 150\ t/d) \\ 3 & (150 < S \leq 900\ t/d) \end{cases} \quad \text{(eq. 6.4)}$$

$$Cm_i = \propto_m \cdot (CONI_i \cdot TI) \quad \text{(eq. 6.5)}$$

where GT is share of the additional cost of gas treatment equipments to the construction cost (default value is 0.1); CONI_0 is the initial construction costs given a standard scale S_0 (200 t/d) (default value is 10 billion); S_i is the treatment capacity ($0 < \mathrm{S}_\mathrm{i} \leq 900$ t/d) of incinerators in municipality i or in the waste cooperative(s) that municipality i belongs to. If more than 900 t/d combustible wastes were generated in municipality i or its waste management cooperatives, N_i incineration plants with an equal capacity less than 900 t/d were assumed to be built. TI is the service time of incinerators (default value is 20 years); Cp_i is the personnel costs; $\propto_\mathrm{p}$ is the annual salary (6 million JPY/yr); Np is the need of personnel for basic operation (default value is 28); b_1 is the need for additional operators per stocker (default value is 4); b_2 is the need for additional operators per unit treatment (default value is 0.02 per 1 t/d); n is the number of stockers; Cm_i is the maintenance cost; $\propto_m$ is the ratio of annual maintenance cost to the total investment (default value is 0.02).

3. Parameters for Calculating Transportation Costs

Municipalities were presented as polygons on the base map. The center point of each polygon was taken as the source of waste plastics in each municipality. Waste generation on large cities, including Tokyo, Yokohama, Kawasaki, Chiba, and Saitama, were allocated to ward level according to population. Totally 397 municipalities/wards were analyzed.

Intuitively, RRCs should be located in relatively large municipalities because industrial facilities and large sources of waste plastics are in large cities. Locating RRCs away from both sources and industrial facilities would not lead to an optimal solution. In order to save calculation time, 141 municipalities with population over 0.1 million were extracted as the candidate locations for RRCs. Because this research focused on the strategic level, it did not specify the available location of RRCs in each candidate municipality. The center points of the 141 chosen polygons were taken as the potential location of RRCs for calculating transportation distance and time. At the operational level, existing recycling centers and outdated incinerators that would soon undergo renewal are more likely to be the location of RRCs in the future.

Distances of the shortest routes via the road network were calculated by the tool of network analysis in ArcGIS® (version 9.3). The JMC data on road network distinguish five types of road. Traveling times on the shortest routes were also calculated by network analysis by referring to the average speed of vehicles on different types of roads. Waste plastics were assumed to be transported by collection trucks from municipalities to RRCs and by container trucks from RRCs to recycling and industrial facilities. The flow of estimating transportation costs is shown in Figure 3 and parameters are summarized in Table 4. It should be noted that costs of collection within municipalities are excluded because they remain unchanged regardless of the presence of RRCs.

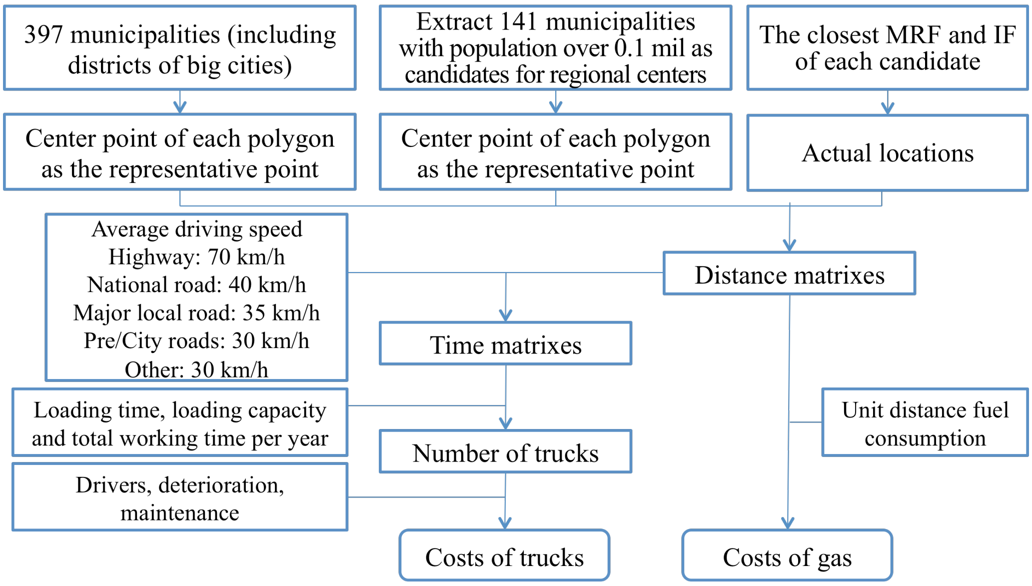


Figure 3 Flow chart of estimating transportation costs

Note: The average driving speed on different types of road was referring to “Changes in Average Travelling Speed” by Ministry of Land, Infrastructure, Transport and Tourism, retrieved in May, 2011 at www.mlit.go.jp/road/ir/ir-data/data/109.xls

Table 4 Parameters for calculating transportation costs

	unit	Collection truck	Container truck
Maintenance [a]	1000 JPY/year	1260	1425
Depreciation [b]	1000 JPY/year	1260	1425
Loading capacity	t/trip	2	10
Loading rate	%	50	79
Fuel efficiency (diesel)	l/km	0.25	0.5
Loading time	Hour/trip	1	1
Driver	1000 JPY/year	6000	6000
Working time	hour/year	240	240

a: Maintenance costs are assumed to be 15% of the costs of truck. Collection and container trucks cost 8.4 and 9.5 million, respectively.

b: Annual depreciation is assumed to be 15% of the costs of trucks

4. Parameters for Environmental Assessment

GHG emission reduction and fossil fuel savings from transportation, construction of RRCs, operation of RRCs, substitute effect due to recycling, and incineration of unseparated waste plastics were taken into account. The emission factors of diesel, electricity, and construction are listed in Table 5.

GHG emissions and fossil fuel consumption of transportation and construction can be obtained by multiply these emission factors with the outputs from the optimization model on diesel and electricity consumption under different scenarios. According to the estimation of diesel and electricity consumption in the operation process of RRCs, GHG emissions and fossil fuel consumption for treating one unit waste plastics in the RRCs were calculated. In terms of the substitute effect, high-quality waste plastics are assumed to be recycled to substitute virgin plastic resins (50% of polyethylene and 50% of polypropylene). Waste plastics recycled in iron plants are assumed to substitute cokes as reductant, and in cement plant to substitute coal as fuel. Unseparated waste plastics are assumed to be incinerated for power generation with an efficiency of 10%. The environmental impacts of these processes under the baseline condition (i.e. incineration without energy recovery) and the recycling condition are summarized in Table 6.

Table 5 Emission of utilities and construction

Utility		CO_2	Coal	oil
	Unit	kg	kg	kg
Diesel [a]	l	2.73	--	--
Electricity [a]	kWh	0.42	0.08	0.02
Construction [b]	1000 JPY	4.4	0.08	0.02

Source: a: (JCPRA, 2007); b: (Matsutou, 2005)

Table 6 Environmental impacts of treating 1 kg waste plastics

Facility	Category	CO_2	Coal	oil
	Unit	kg	kg	kg
RRC	baseline	--	--	--
	recycling	0.01	0.00	0.00
	sub-total	**0.01**	**0.00**	**0.00**
Mechanical recycling into resins [a]	baseline	5.10	0.02	0.63
	recycling	2.29	-0.21	0.02
	sub-total	**-2.81**	**-0.23**	**-0.61**
Recycling as reductant in iron/steel plant [a]	baseline	6.34	1.19	0.08
	recycling	3.03	0.02	0.07
	sub-total	**-3.31**	**-1.17**	**-0.01**
Recycling as fuel in cement plant [a]	baseline	5.65	1.18	0.01
	recycling	2.74	0.02	0.00
	sub-total	**-2.91**	**-1.16**	**0.00**
Incineration for power generation [a]	baseline	3.06	0.08	0.02
	recycling	2.66	0.00	0.00
	sub-total	**0.40**	**0.08**	**0.02**

Source: a: (JCPRA, 2007).

Reference

Berthouex, P. M. (1972). Evaluating Economy of Scale. *Journal of Water Pollution Control Federation, 44*(11), 2111-2119.

Geng, Y., Fujita, T., & Chen, X. (2010). Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. *Journal of Cleaner Production, 18*(10-11), 993-1000.

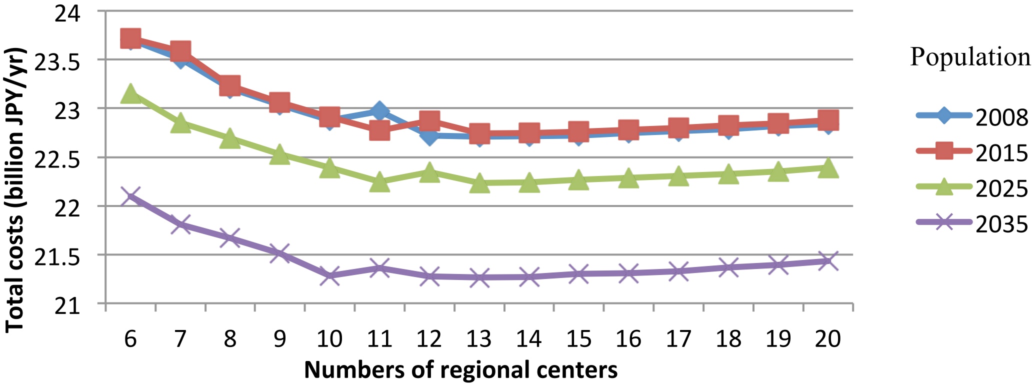
JCPRA (The Japan Containers and Packaging Recycling Association). (2007). *The Environmental Impacts of Plastic Containers and Packaging Recycling (in Japanese)*. Tokyo, Japan: JCPRA.

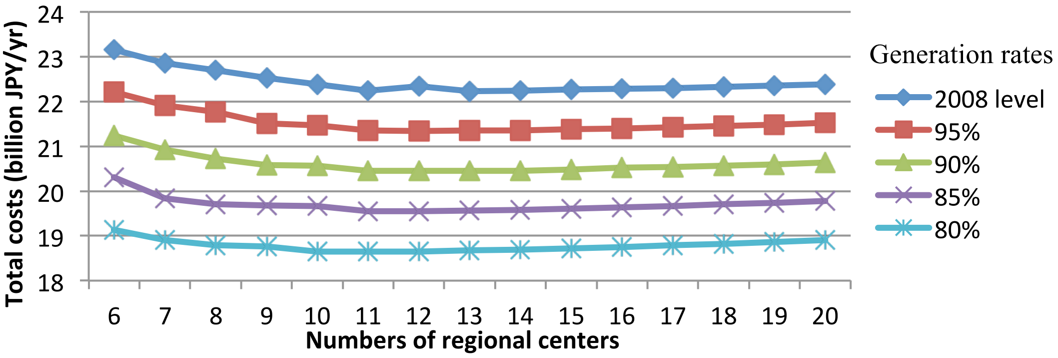
Matsutou, T. (2005). *Analysis, Planning, and Assessment of Urban Waste Treatment Systems: Material Flow and LCA Programs*. Tokyo, Japan: Gihoto Shuppan.

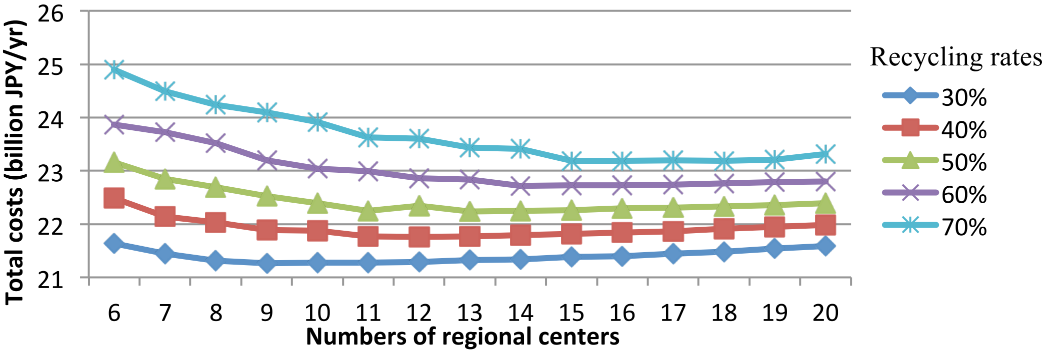
MOE. (2006). Procedures for bidding and contracts of constructing waste treatment facilities (廃棄物処理施設建設工事等の入札・契約の手引きについて) [Electronic Version], from http://www.env.go.jp/hourei/syousai.php?id=11000360

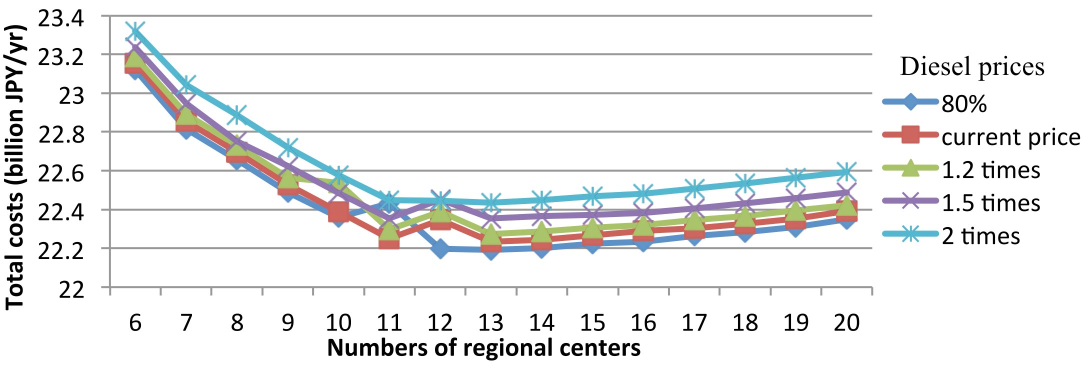
APPENDIX III

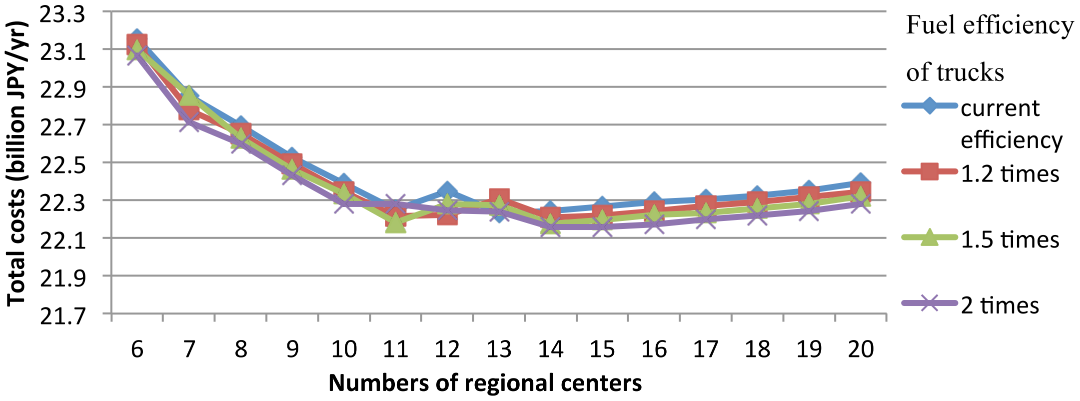
Total Cost of Regional Recycling Centers under Scenarios

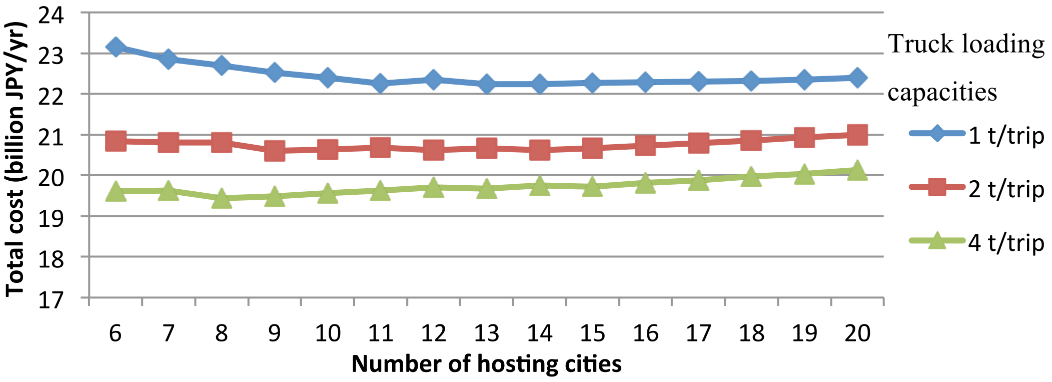


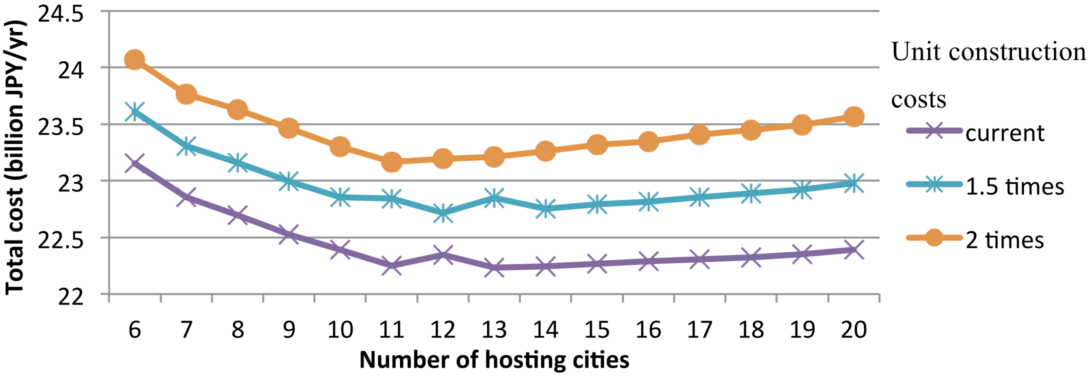


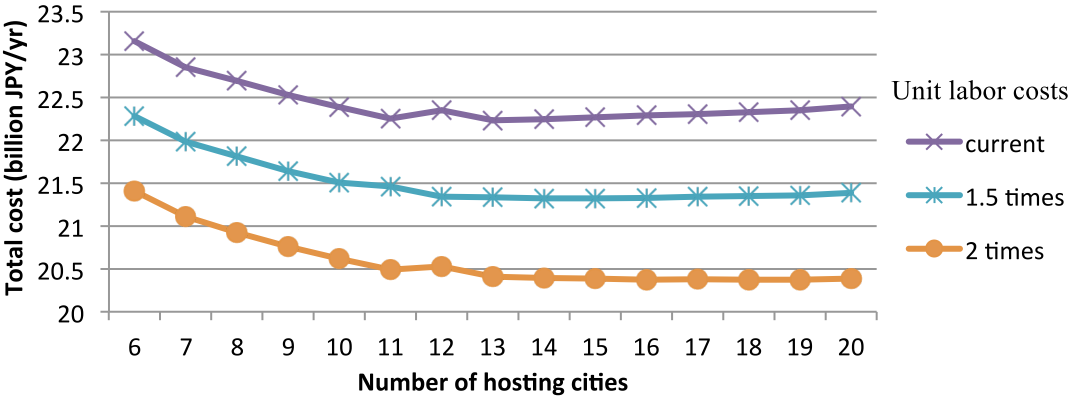





Total costs (billion JPY/yr)
23.3
23.1
22.9
22.7
22.5
22.3
22.1
21.9
21.7
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Numbers of regional centers
Fuel efficiency of trucks
current efficiency
1.2 times
1.5 times
2 times

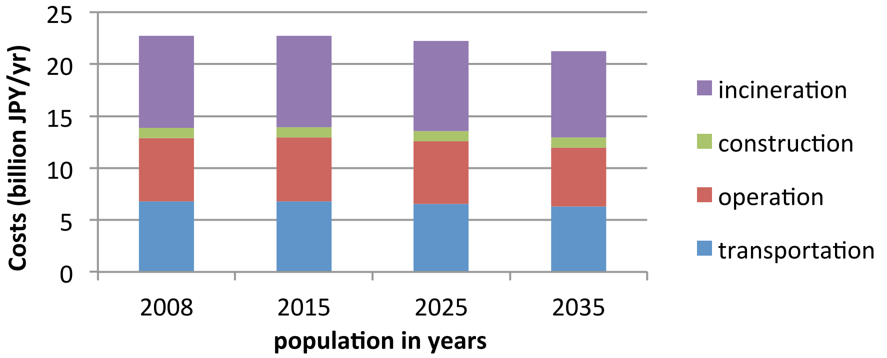

Total cost (billion JPY/yr)
24
23
22
21
20
19
18
17
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Number of hosting cities
Truck loading capacities
1 t/trip
2 t/trip
4 t/trip

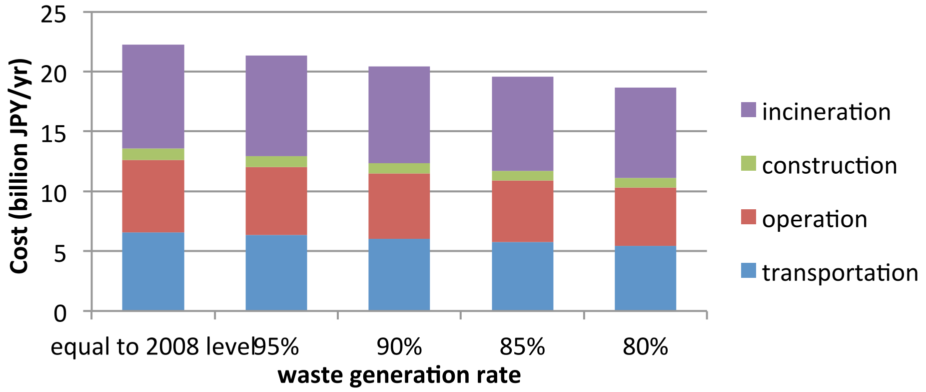

Total cost (billion JPY/yr)
24.5
24
23.5
23
22.5
22
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Number of hosting cities
Unit construction costs
current
1.5 times
2 times

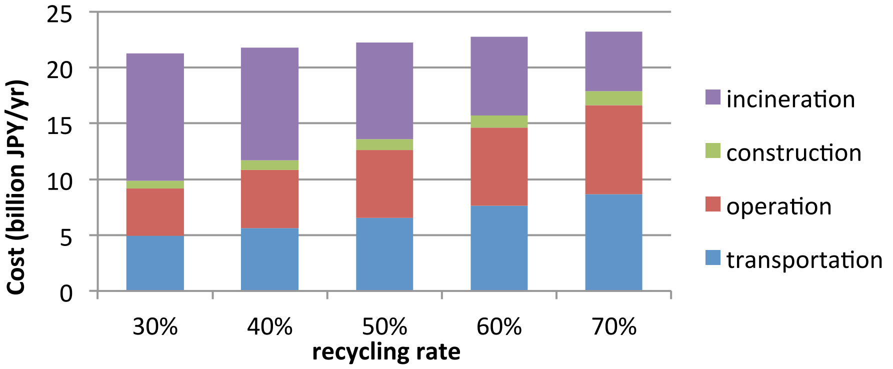

Total cost (billion JPY/yr)
23.5
23
22.5
22
21.5
21
20.5
20
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Number of hosting cities
Unit labor costs
current
1.5 times
2 times

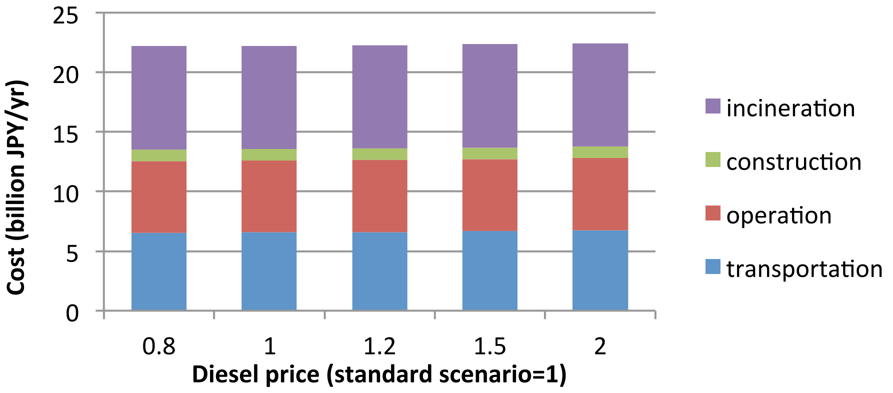
APPENDIX IV

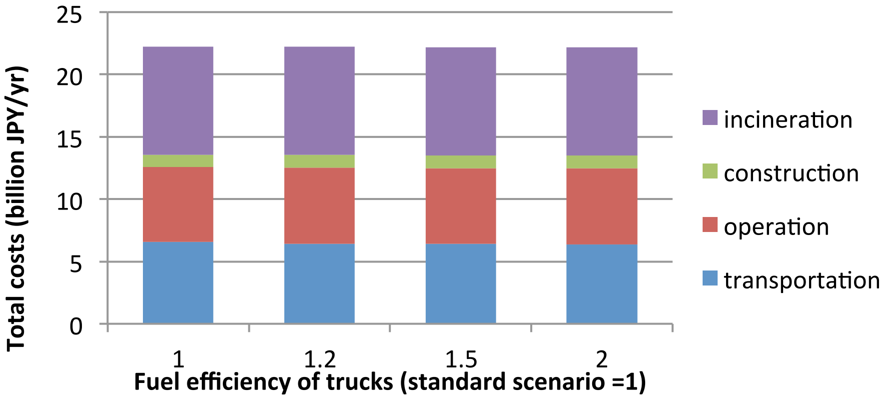
Cost Breakdowns under scenarios

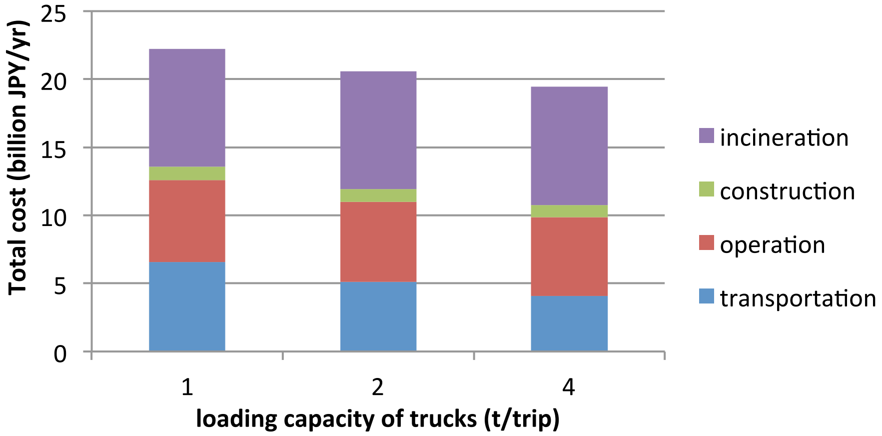


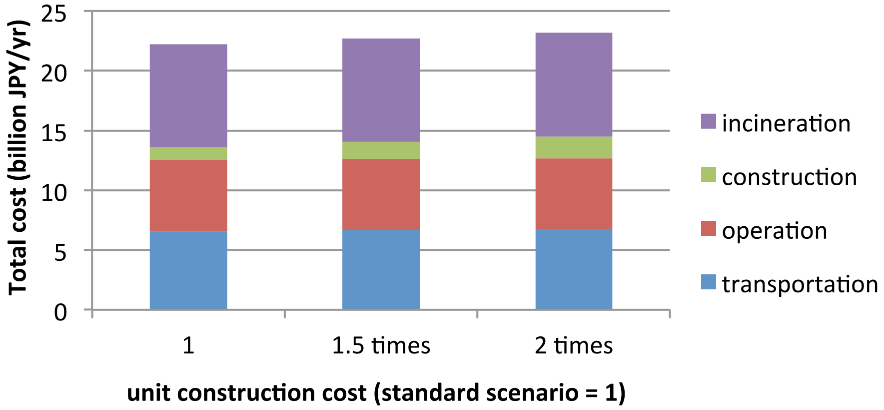


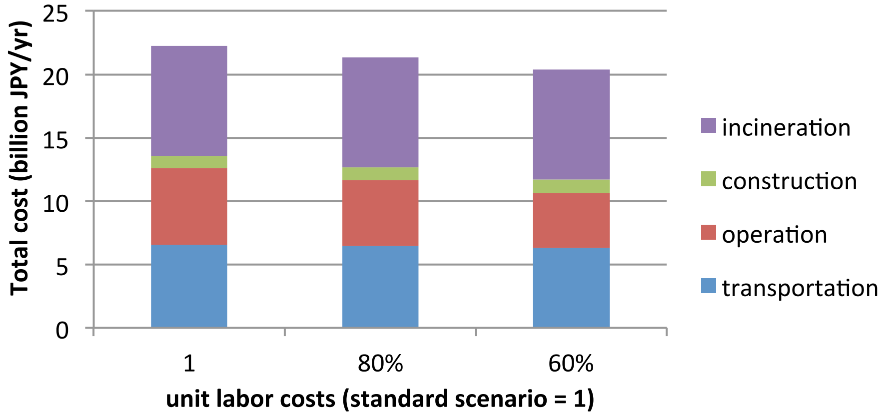





Total costs (billion JPY/yr)
25
20
15
10
5
0
1
1.2
1.5
2
Fuel efficiency of trucks (standard scenario =1)
incineration
construction
operation
transportation

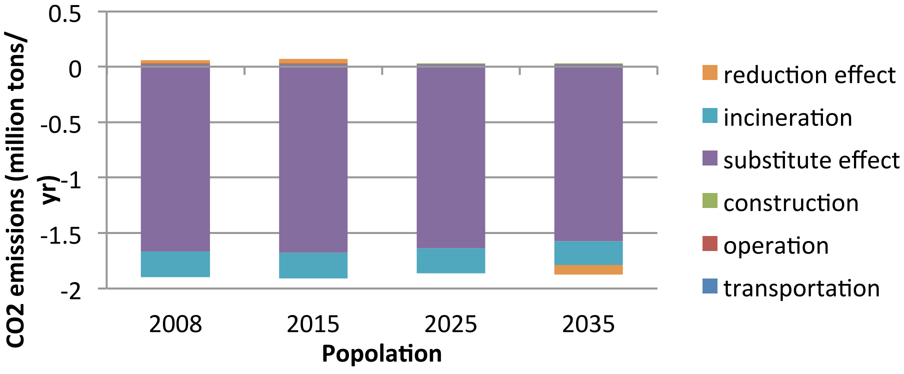

Total cost (billion JPY/yr)
25
20
15
10
5
0
1
2
4
loading capacity of trucks (t/trip)
incineration
construction
operation
transportation

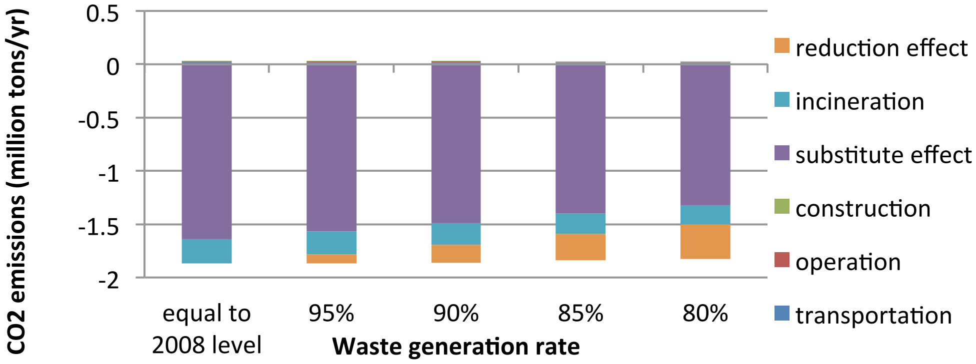

Total cost (billion JPY/yr)
25
20
15
10
5
0
1
1.5 times
2 times
unit construction cost (standard scenario = 1)
incineration
construction
operation
transportation

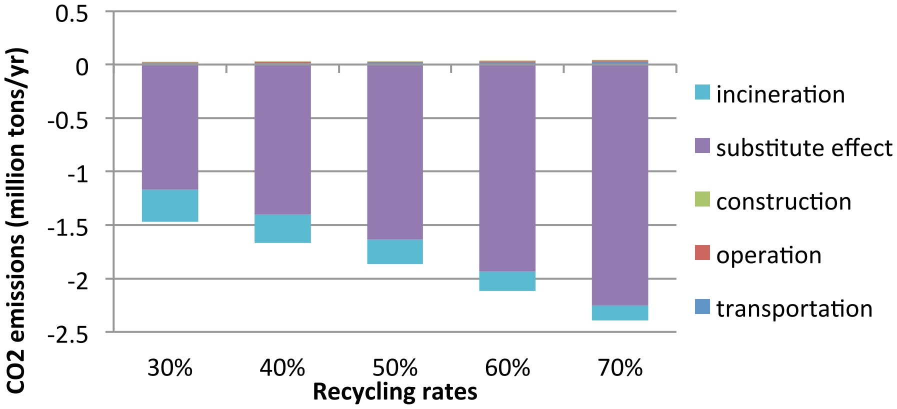

Total cost (billion JPY/yr)
25
20
15
10
5
0
1
80%
60%
unit labor costs (standard scenario = 1)
incineration
construction
operation
transportation

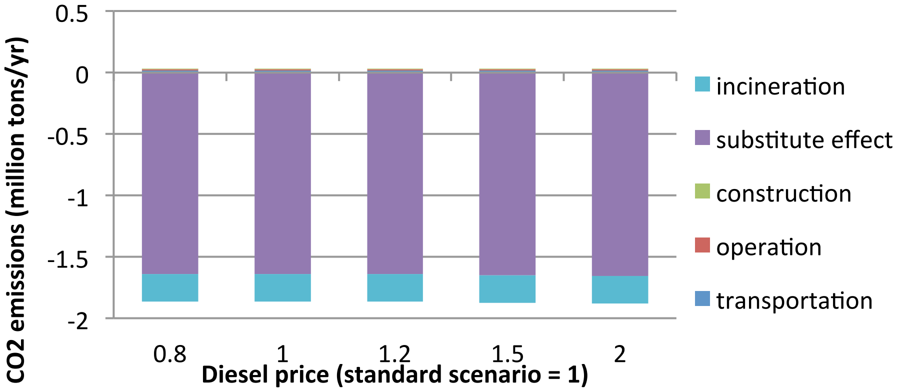
APPENDIX V

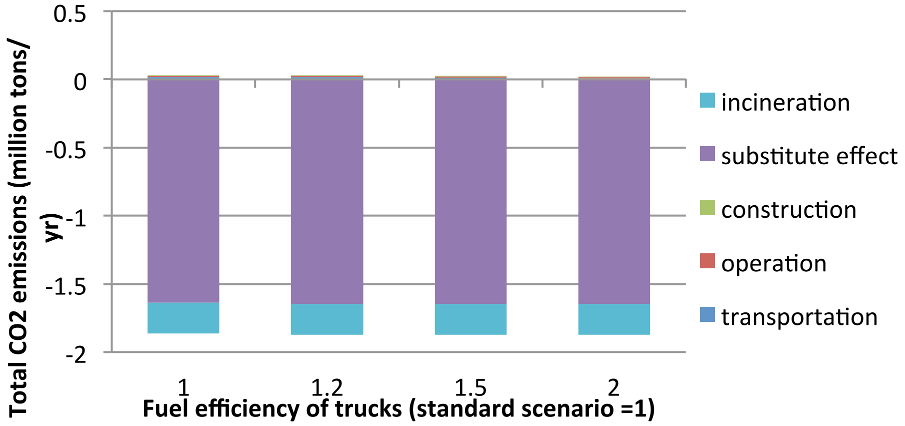
Reduction in CO$_2$ Emissions under Scenarios

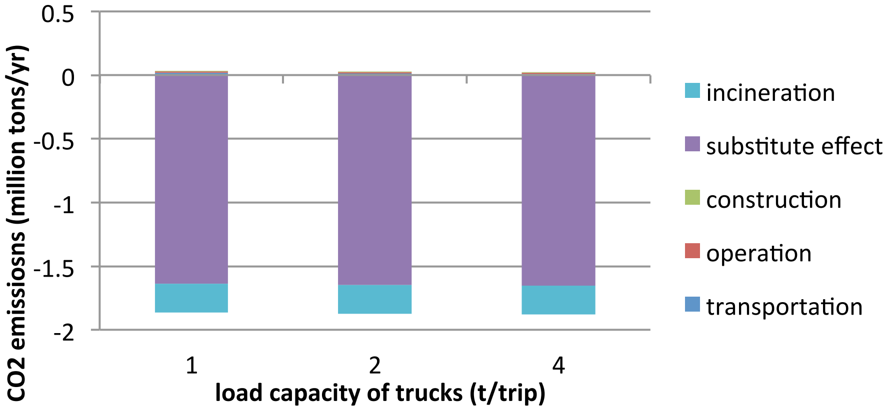


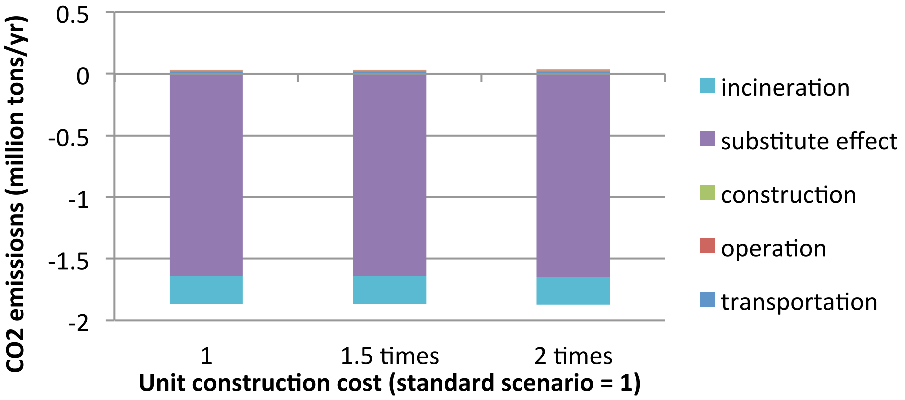


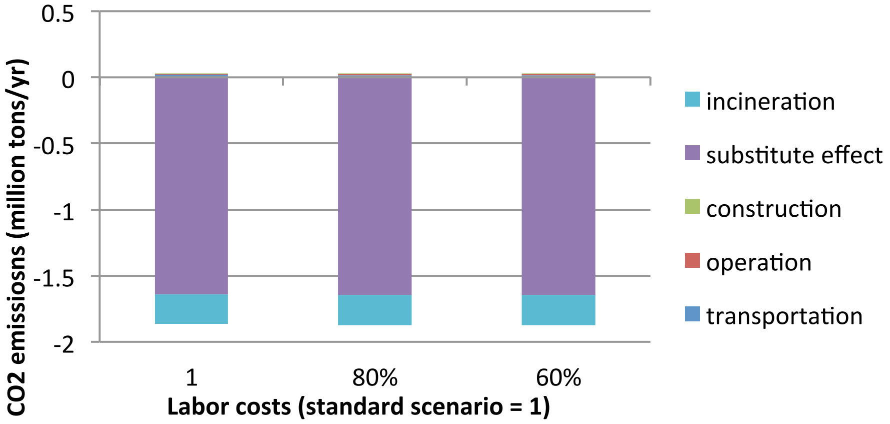





Total CO2 emissions (million tons/yr)
0.5
0
-0.5
-1
-1.5
-2
1
1.2
1.5
2
Fuel efficiency of trucks (standard scenario =1)
incineration
substitute effect
construction
operation
transportation

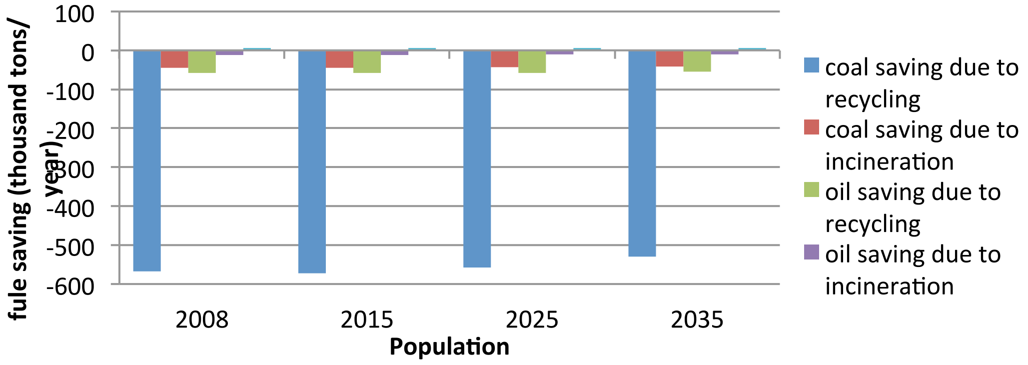

CO2 emissiosns (million tons/yr)
0.5
0
-0.5
-1
-1.5
-2
1
2
4
load capacity of trucks (t/trip)
incineration
substitute effect
construction
operation
transportation

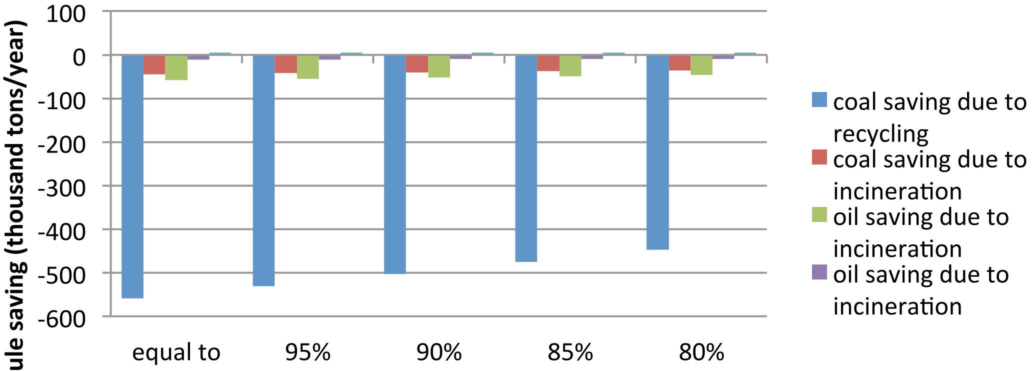

CO2 emissiosns (million tons/yr)
0.5
0
-0.5
-1
-1.5
-2
1
1.5 times
2 times
Unit construction cost (standard scenario = 1)
incineration
substitute effect
construction
operation
transportation

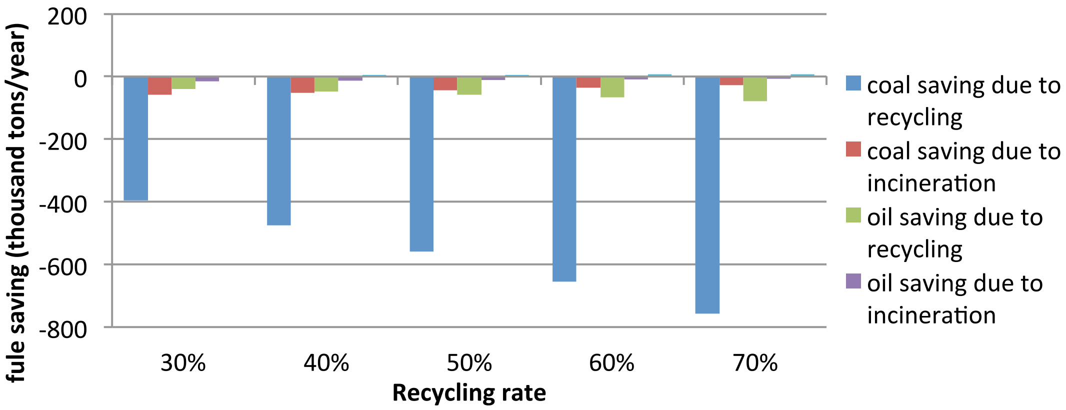

CO2 emissiosns (million tons/yr)
0.5
0
-0.5
-1
-1.5
-2
1
80%
60%
Labor costs (standard scenario = 1)
incineration
substitute effect
construction
operation
transportation

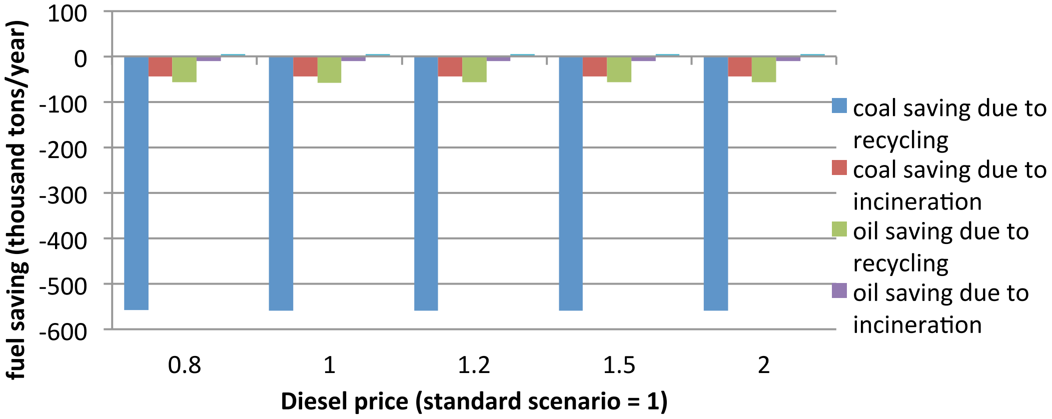
APPENDIX VI

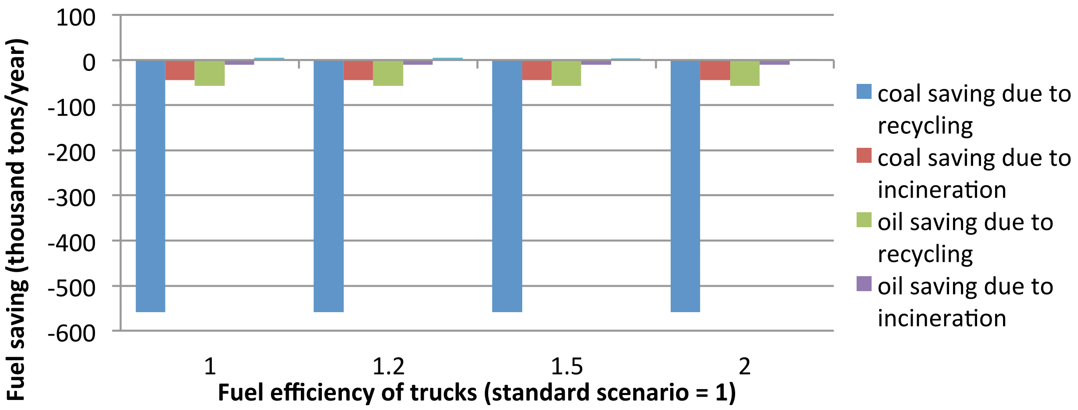
Fossil Fuel Savings under Scenarios

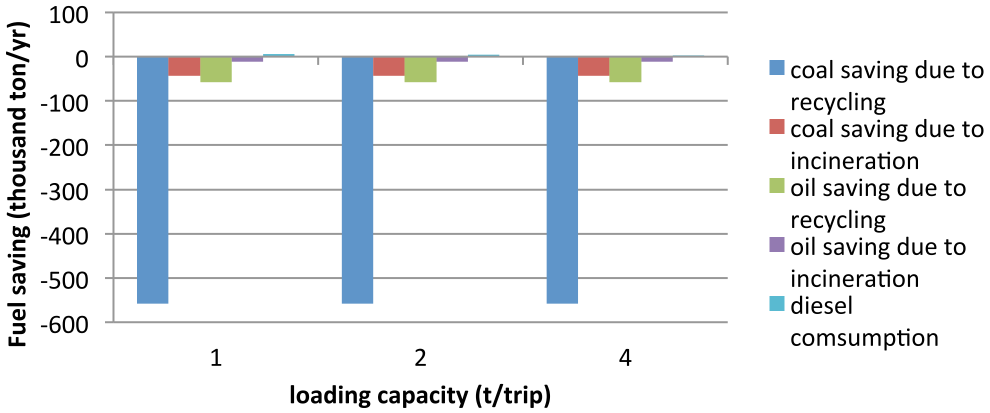


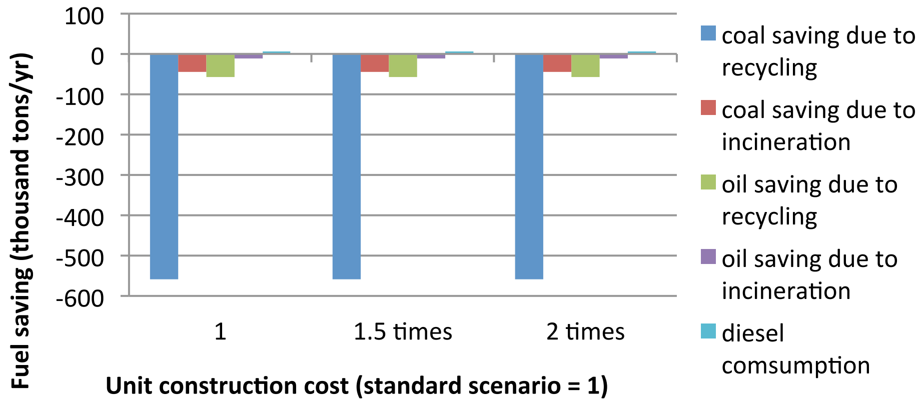


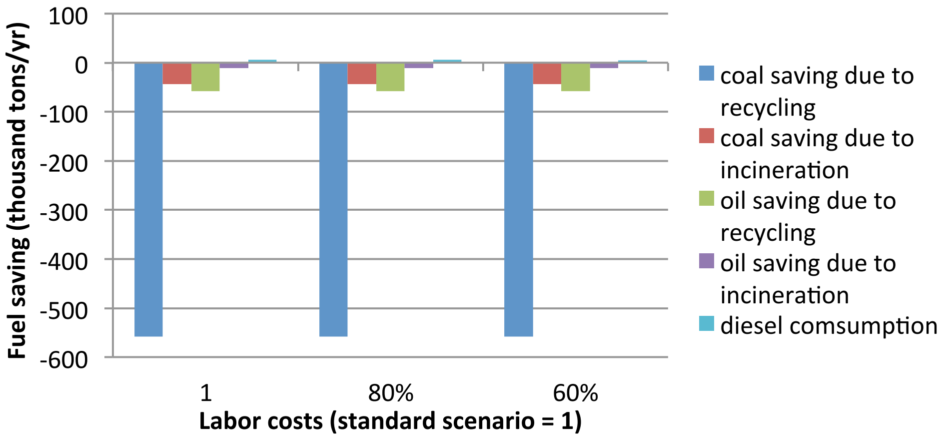





Fuel saving (thousand tons/year)
100
0
-100
-200
-300
-400
-500
-600
1
1.2
1.5
2
Fuel efficiency of trucks (standard scenario = 1)
coal saving due to recycling
coal saving due to incineration
oil saving due to recycling
oil saving due to incineration


Fuel saving (thousand ton/yr)
100
0
-100
-200
-300
-400
-500
-600
1
2
4
loading capacity (t/trip)
coal saving due to recycling
coal saving due to incineration
oil saving due to recycling
oil saving due to incineration
diesel comsumption


Fuel saving (thousand tons/yr)
100
0
-100
-200
-300
-400
-500
-600
1
1.5 times
2 times
Unit construction cost (standard scenario = 1)
coal saving due to recycling
coal saving due to incineration
oil saving due to recycling
oil saving due to incineration
diesel comsumption


Fuel saving (thousand tons/yr)
100
0
-100
-200
-300
-400
-500
-600
1
80%
60%
Labor costs (standard scenario = 1)
coal saving due to recycling
coal saving due to incineration
oil saving due to recycling
oil saving due to incineration
diesel comsumption