Journal of Global Environment Engineering, Vol. 13, pp.1-20, 2008

LIFE CYCLE ASSESSMENT AND SCENARIO ANALYSIS OF MUNICIPAL SOLID WASTE DISPOSAL SYSTEMS: THE CASE OF BEIJING

Yonghai XUE[1]
Toru MATSUMOTO[2]
Jian ZUO[3]

Abstract

Predictions of Municipal Solid Waste (MSW) generation and collection, as well as a scenario analysis of future demand for MSW treatment and disposal facilities, were done as a preliminary investigation for improving strategies for Beijing's MSW treatment and disposal system. In particular, a multiple regression analysis model was built to predict the collected MSW amount per capita. The number of necessary new MSW disposal facilities through 2020 were estimated according to three scenarios. Moreover, Life Cycle Energy (LCE), Life Cycle CO_2 ($LCCO_2$), and cost assessment also were applied to estimate the total costs and environmental loads. The results indicate that the total cost of the MSW system from 2008 to 2020 was the highest in scenario 2 (Incineration as priority), but environmental performance (energy consumption and CO_2 emission) is the best. In contrast, in scenario 1 (Landfill as priority), the total cost is lowest but environmental performance is the worst. In scenario 3 (Beijing's plan), the total cost and LCE are close to that in scenario 2, but the $LCCO_2$ is moderate.

KEYWORDS: *Municipal Solid Waste, prediction, Life Cycle Assessment, scenario analysis, multiple regression analysis*

1. Introduction

The rapid development and increased urbanization and consumption levels in the cities of China have been accompanied by a great increase in the quantity of municipal solid waste (MSW). The composition of the MSW has also changed, with an increased proportion of plastic and paper (Zhou et al., 2004). At the same time, the MSW disposal systems have numerous problems, including inadequate MSW disposal facilities, pollution caused by inadequate technology and management levels at the disposal facilities, and a lack of suitable available landfill sites (Ru et al., 2001). In the future, with the predictable increase in MSW collection rates and the expansion of collection areas into suburban and rural areas, the pressure on MSW disposal systems will be further intensified.

The rapid development of the Chinese economy has also been accompanied by increases in

1 Ph.D student, Graduate School of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Japan
2 Associate Professor, Faculty of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Japan.
3 Senior Consultant, Chengdu office, ERM (Environment Resource Management) Group, Inc., Chengdu, China

resource consumption and imports, both of which cause concern about a possible lack of resources in the future. Therefore, building a "Recycling-based Society" that aims to reduce MSW and final disposal amounts and to increase resource utilization rates by promoting recycling and reuse of resources has become an essential Chinese environmental strategy. In 2003, the Government of Beijing (2003) published a "White Paper Concerning Waste Disposal in Beijing", which refers to "3R" implementations like separated collection in residential complex areas, private recycling activities being promoted to reduce waste, reuse and recycling rate in Beijing.

In 1996, a research entitled as "Options for domestic solid waste treatment in Beijing" was completed by the Beijing Environmental Sanitation Administration (BESA) (1996) for the "Metropolitan Environmental Improvement Program" which was sponsored by the World Bank. In this research, a waste disposal plan covering the years 1996 to 2015 was made, and total cumulative construction cost and operation cost by three scenarios were estimated. The cost had been underestimated while the waste treatment quantity and operation cost were also underestimated: according to BESA (1996), the MSW quantity was estimated to be 2.84 million tons in 2002, but in fact it was 3.21 million tons (Beijing Municipal Bureau of Statistics, 2003). For the Olympics in 2008, Beijing has accelerated its waste disposal plan, and is paying more attention to the environmental performance of the waste disposal system. Therefore, it is necessary to reconsider the MSW management situation of Beijing, to assess its future needs and loads. The first step in assessing a future MSW system is predicting waste quantity. Forecasting future MSW is of major importance for decision-making and planning (Karavezyris et al. 2002). Forecasting is mostly based on the analysis of historical data for both waste and waste-related information on social, economic, or other border conditions (den Boer et al. 2005). Conventional forecasting methods for solid waste generation frequently use demographic and socioeconomic factors on a per capita basis.

Life Cycle Assessment (LCA) is a process for analyzing the materials, energy, emissions, and waste of a product or service system, over the whole life cycle "from cradle to grave", i.e., from raw material acquisition through manufacture, distribution, use, possible reuse/recycling and then final disposal. LCA is an environmental management tool that allows prediction of the environmental loads associated with a product or service over the whole life cycle from cradle to grave. This technique can be applied to waste management to assess environmental sustainability. At the same time, a parallel economic assessment can determine the economic sustainability of a waste management system. The life cycle technique has been used to compare specific options for waste management. Ayalon et al. (2000) used LCA to make comparisons of different disposal options (e.g., recycling, incineration, or landfilling) of soft drink packaging. Song and Hyun (1999) did a comparison study on the various waste management scenarios of polyethylene terephthalate (PET) bottles using LCA methodology. Finnveden and Ekvall (1998) used LCA on recycling and incineration with energy recovery of paper packaging materials as an example to discuss the usefulness of LCAs. The LCA technique has been also used to assess complete waste management systems. A life cycle inventory model for integrated waste management has been developed by McDougall et al. (2001), and several other models are under development. This approach considers the whole waste stream, rather than focusing on a single fraction of the waste stream, and assesses the environmental performance of the solid waste system, while keeping the measures economically affordable and socially acceptable. The environment agency of the United Kingdom is developing a flexible, user-friendly life cycle tool called Waste and Resources Assessment Tools for the Environment (WRATE) to enable waste managers and decision-makers to compare the environmental loads and impacts of waste management system options for MSW within a framework of the best practicable environmental options. A research project, entitled "The use of LCA tools for the development of integrated waste management (IWM) in rapid growing economies", was conducted with unique expert cooperation across the European Union (den Boer et al. 2005). In that research, a waste prognosis tool and a waste management assessment tool (LCA tools that consider the three pillars of sustainability: environmental protection, economic development, and social responsibility) were developed to help European countries with rapid development fulfill a number of requirements while adjusting to the European standard. Therefore, LCA technology has been used by many countries in different areas as an effective tool for environmental assessment of MSW management systems. But in developing countries like China, most research concerning LCA for waste are focusing on single fractions of the waste stream (Lin et al., 2004; Ma et al., 2004), or possible scenarios compared to the current system (Yang et al., 1999; Yu, 2004). In China, "The Law on Environmental Impact Assessment (EIA) of the People's Republic of China" (2002) requires that any construction project that might cause significant environmental impact implement EIA before construction. Therefore, MSW disposal facilities must implement EIA before construction, but few concerns are raised about environmental issues in the planning period, and the MSW management system is not viewed holistically. The operations within any waste management system are clearly interconnected. The collection and sorting method employed will affect the ability to recover material or produce marketable compost. Similarly, the recovery of material from the waste stream may affect the viability of energy recovery schemes. It is necessary, therefore, to consider the entire waste management system in a holistic way. LCA could be a useful tool for estimating the environmental performance of entire waste management system and helping decision-makers to develop economically affordable, socially acceptable and environmental effective waste management systems.

This research is the first time LCA has been used in the planning period in a developing city to predict the waste amount in the future and also to develop scenario analyzing necessary disposal facilities and their environmental performance and economic burden. In this study, we take Beijing, whose population exceeded 14.95 million in 2002 and will keep increasing in the future, as case study city. We first predicted the collected waste amounts for the years from 2003 to 2020. Socioeconomic factors (population, number of tourists, gross domestic product (GDP), urban population rate, total retail sales, etc.) were chosen for linear correlation analysis with per capita waste. The non-agriculture population rate (non-agricultural population/total population) and the rate of the tertiary industry GDP in the total GDP were determined as the explanatory variables in the multiple regression analysis model for the prediction of per capita waste. Then we simulated the MSW disposal system, estimated the number of new disposal facilities that would be necessary, and built MSW disposal flow models based on three scenarios. Finally, we completed LCA and cost analysis for the disposal system making use of these three scenarios.

2. Prediction of Collected Waste Amount

2.1 Calculation method

In Beijing, collected waste amount per capita and collection rate varies by area. For the purpose of our study, Beijing was divided into three areas: city zones and suburbs, combined zones including urban and rural areas, and outer suburban areas. The total collected waste amount was calculated by equation (1):

$$W = \sum w_i P_i r_i \qquad (1)$$

where,

- W: collected waste amount,
- w_i: collected waste amount per capita,
- P_i: population,
- r_i: collection rate, and
- i = 1: city zones and suburbs; 2: combined zones including urban and rural areas; and 3: outer suburban areas.

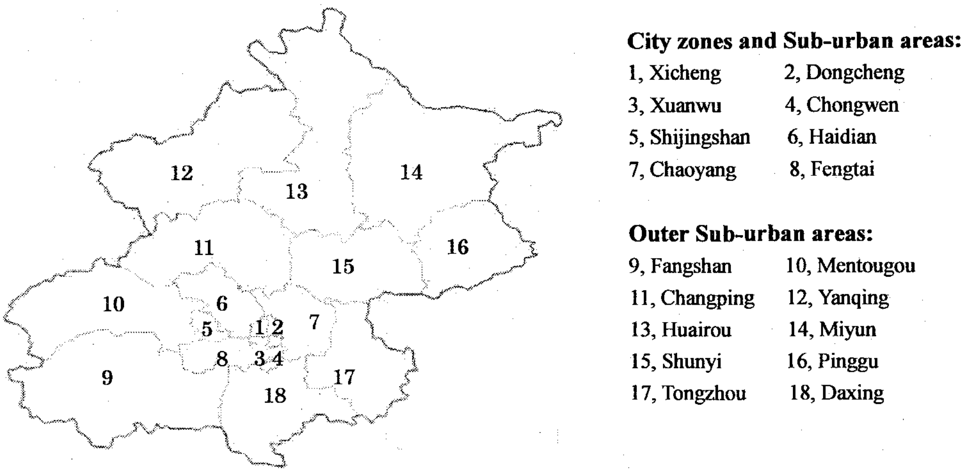


Figure 1. Administrative map of Beijing

According to administrative map of Beijing as shown in Figure 1, we divided Beijing into two area: city zones and suburbs and outer suburban areas. And there is rapid urbanization at the edges of urban and adjacent rural areas. A large number of temporary residents and low-income registered residents gather in adjacent rural areas (mainly in the adjacent area of districts of 5-Shijingshan 6-Haidian 7-Chaoyang 8-Fengtai, 9-Fanghsan, 10-Mentougou, 11-Changping, 15-Shunyi, 17-Tongzhou, and 18-Daxing), where lack of infrastructure, Coal as the main fuel and the MSW collection system still under development. We defined these adjacent rural areas as combined zones. An estimated 1.2 million people live in combined zones at present. Combined zones will change with the development of the city, but because of a continuing need for low-cost housing by low-income residents, the population should remain stable. The population of combined zones was assumed to remain at about 1.2 million from 2003 to 2020. The population composition in combined zones is complicated, including population from city zones and suburban areas, as well as from outer suburbs.

The collection rate, as show in Table 1, was assumed to reach 100% in city zones and suburban areas in 2002, and the rate was assumed to reach 100% after 2007 in outer suburbs and combined zones in accordance with Beijing's planning.

Table 1. Collection rate change in Beijing

year	2003	2004	2005	2006	2007-2020
City zones and Suburban	100%	100%	100%	100%	100%
Out suburban	30%	50%	80%	90%	100%
Combined zones	30%	50%	80%	90%	100%

2.2 Prediction of population

The total population is composed of registered residents and temporary residents (those living in Beijing more than 6 months without a registration card). The population of registered residents is further divided into agricultural and non-agricultural populations.

The population in city zones and suburban areas, as well as in the outer suburbs, was predicted using the average rates of non-agricultural and registered resident population increase in the past 5 years in the two areas. The population of temporary residents was estimated using the predictions of the Government of Beijing (2005) (< 4.5 million in 2020).

Table 2. Population change in Beijing

Year		Total (million persons)	Registered Resident	Non -Agriculture	Agriculture	Temporary Resident
Beijing total	1990	11.04	10.32	6.4	3.92	0.71
	2002	14.95(-1.2)*	11.36	8.07	3.29	3.59
	2008	15.88(-1.2)*	12.01	9.26	2.75	3.87
	2015	17.05(-1.2)*	12.83	10.97	1.86	4.23
	2020	17.95(-1.2)*	13.45	12.45	1	4.5
City zones and suburban	1990	6.56	5.99	5.39	0.6	0.57
	2002	9.45(-0.6)*	6.89	6.45	0.44	2.56
	2008	9.96(-0.6)*	7.45	7.1	0.34	2.52
	2015	10.68(-0.6)*	8.15	7.95	0.2	2.54
	2020	11.17(-0.6)*	8.69	8.61	0.08	2.48
Outer suburban area	1990	4.48	4.34	1.01	3.32	0.14
	2002	5.5(-0.6)*	4.47	1.62	2.86	1.03
	2008	5.92(-0.6)*	4.57	2.16	2.41	1.35
	2015	6.37(-0.6)*	4.68	3.02	1.66	1.69
	2020	6.79(-0.6)*	4.76	3.85	0.92	2.03
Combined zones	2002-2020	1.20**	-	-	-	-

Predicted population

* Inside () means the population should be subtracted to distribute to combined zones

** The population in Combined zones are 50% come from city zones and 50% outer suburban area and keep stable at 1.2 million.

The predicted population was then distributed into the two areas. Taking into consideration the developing tendencies and future policy, we assumed the distribution rate of temporary residents in city zones and suburban areas to be 70% from 2003 to 2005, 65% from 2006 to 2010, 60% from 2011 to 2015, and 55% from 2016 to 2020. The calculated results show that the population in city zones and suburban areas will continue to increase and reach 11.17 million in 2020; the outer suburbs will reach 6.79 million (Table 2).

In this research, the population of the combined zones was assumed to be 50% from city zones and suburban areas, and 50% from outer suburbs. That means, during population prediction period, Beijing was divided into two part (Urban area and outer suburban area), and then 0.6 million of each area will be distributed into combined area.

2.3 Collected waste amount per capita

The collected waste amount per capita in combined zones was assumed to remain at the current level of 1.95 kg/day. The data for this value came from investigations at the Beijing Municipal Administration Commission. The main fuel in these areas is coal, which generates great amounts of ash, and at the same time, the large number of small-scale construction activities in these areas also contributed more construction wastes to MSW. Therefore, the collected waste amount per capita in combined zones is higher than it is in other areas.

Socioeconomic factors from 1980 to 2002 (Total Non-agriculture Population, Number of tourists to Beijing, GDP, Non-agriculture population rate, Total retail sales, Rate of the tertiary industry GDP in total GDP, Gas use rate and Final consume expenditure) were chosen for linear correlation analysis with per capita waste from 1980 to 2002. "Stepwise forward selection method" was used for chose the most proper explanation. The results show that non-agriculture population rate and the rate of the tertiary industry GDP in total GDP have better relationship with per capita collected waste amount and represent two opposite tendencies in the per capita collected waste data (Xue, 2005). The increased non-agriculture population rate, represented as a relative increase of non-agricultural residents, increases the per capita waste collected. More industrial products (and packaging) and paper are consumed. Therefore, the paper and plastic content in waste composition increases too. On the other hand, the increased rate of tertiary industry GDP in total GDP, representing an increase of services and infrastructure, has a negative impact on the per capita collected waste. For example, the increased use of gas as a household fuel decrease the amount of coal ash in the waste, and the pre-processing of vegetables to eliminate useless part and dirt before it be transported into city, therefore, organic waste was decreased.

The rate of tertiary industry GDP in total GDP increase from 26.7% in 1980 to 61.5% in 2003, as predicted by government planning, the rate of tertiary industry GDP to total GDP will reach 75% in 2020 (Government of Beijing, 2005).

The collected waste amounts per capita for the other two areas were predicted using the multi-regression,

$$w = 2.2282 p_{urb} - 0.3023 g_{third} - 0.2718 \qquad (R^2 = 0.8911) \qquad (2)$$

where,

w: collected waste amount per capita;

p_{urb}: Non-agriculture population rate (non-agriculture population/total population);

g_{third}: the rate of the tertiary industry GDP (GDP from tertiary industry which including mainly commercial, transportation and service industry) in total GDP.

The predicted amount of per capita collected waste for the whole city increase gradually from 2003 to 2020, in 2003 per capita waste amount is 0.8kg/day and reaches 0.94kg/day in 2010, 1.02kg/day in 2015 and 1.11kg/day in 2020, respectively.

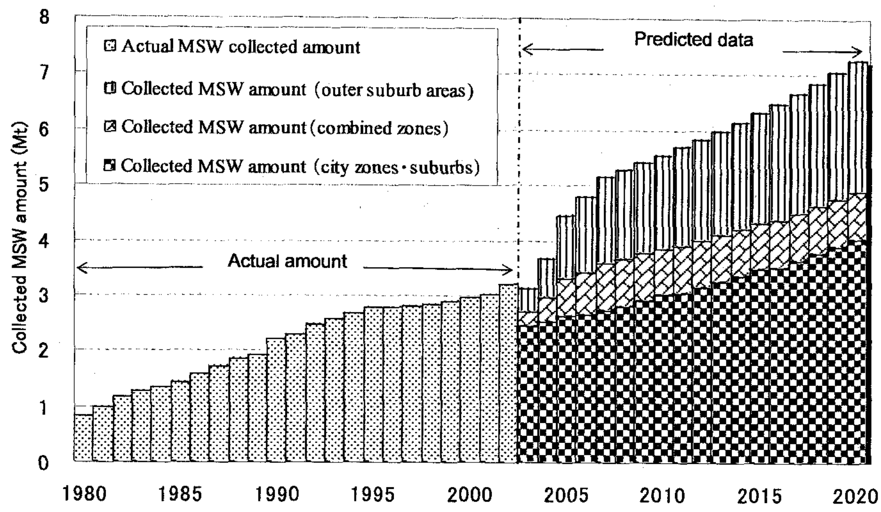


Figure 2. Change in collected MSW amount in Beijing

The statistical data for the collected amount of MSW does not use the actual weight but, instead, it uses the carrying capacity of transport vehicles for the years 1990 to 1999. For example, a truck with carrying capacity of 5 ton transported 6 m^3 of waste with density of 0.5 ton/ m^3 would be recorded as 5 ton of waste. Therefore, taking into consideration the carrying volume of the vehicles and the waste density, in Figure 2 the actual amount of MSW from 1990 to 1999 was the statistical data multiplying a conversion rate of 0.60 (the data came from investigations at the Beijing Municipal Administration Commission and Wu (1998)). The actual amount of MSW from 2000 to 2002 came from statistical data from the Beijing Municipal Bureau of Statistics (1996–2003).

The predicted total collected MSW amounts (Calculated by equation (1) and show in Figure 2) indicate that the amount of collected waste will increase from 2004 to 2020, reaching 5.56 million tons in 2010, 6.33 million tons in 2015, and 7.26 million tons in 2020. The increase in urbanization, increase in collected waste per capita, and increase in collection population in the three areas have influence on the increase in collected waste amount correlates (World Bank, 2005). Economic development, increases in consumption level, and increases in MSW collection rate are the main reasons for the increase in the collected amount of MSW.

By collection of data on waste composition changes of Tokyo (Tokyo Metropolitan Research Institute for Environmental Protection, 1965-2002), and Hong Kong (Environmental protection department, 1997-2005), it is clearly indicated that the proportion of waste paper and plastics will increase during their development period, whereas the proportion of ashes and organic waste will decrease. Based on the waste composition of Beijing (Zhou et al., 2004) in recent years and analyze the composition of Tokyo and Hong Kong under the same purchase power parity (PPP) with Beijing, and estimate the average increase or decrease rate of each composition (increase of Paper, Plastic, Metal, Textile, and Glass, and decrease of Organic waste, Construction waste, Ashes, and woods). The waste composition of Beijing was estimated as shown in Figure 3. By 2020, organic waste, paper, and plastics will make up over 80% of total MSW.

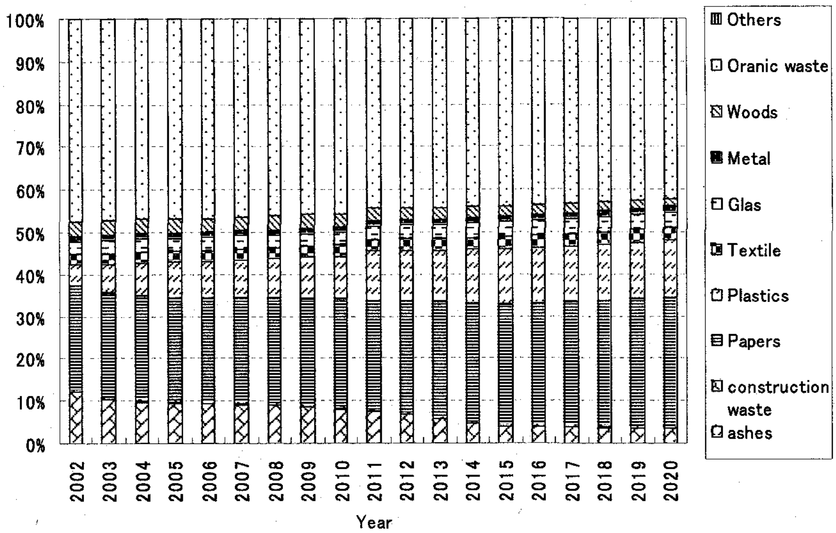


Figure 3. Change in MSW composition in Beijing

3. Scenario Analysis for Necessary Facilities and Disposal Flow

3.1 Scenario assumptions

At present, most recycling of MSW were implemented by informal sector in Chinese cities. Because the huge income difference between urban and rural residents, west China and east China, and resource demand, the status quo will keep for a long period. Beijing government also promote separate collection of recyclable material in public institution and high income residential area, but separated recyclable material mostly were bought by informal sector instead collected by public service. Therefore, Environmental Experts Group of Beijing Government (2003) estimated about 25% of MSW generation were recycled before collection and keep on for a long time. This research concentrate on disposal of collected MSW, and at present, most popular disposal method in China are landfilling, incineration and composting that is according with Beijing's Plan (Environmental Experts Group of Beijing Government, 2003). Under this situation, we assumed three scenarios as follows :

Scenario 1 (landfill as priority): New disposal facilities are all sanitary landfills.

Scenario 2 (incineration as priority): The collected waste amount (except recycled MSW) that exceeds the disposal capacity of existing facilities will be incinerated and necessary sanitary landfill capacity will be added for the disposal of intermediate treatment residue.

Scenario 3 (Beijing's disposal plan): In 2020 the disposal rate will be 30% for landfills, 35% for recycling (compost 30% and recycling 5%), and 35% for incineration.

To estimate construction timeframes and the scale of necessary new disposal facilities (compost facilities, incinerators, and landfills), we simulated the disposal system using three scenarios. Assumptions for new disposal facilities are as follows. Disposal capacity of a single compost facility is 1000 tons/day, a single incinerator is 1500 tons/day. For a single sanitary landfill is assumed to accept MSW of 2000 tons/day. Operation and maintenance periods for a compost facility and incinerator are 20 years each, and sanitary landfills are assumed to operate for 20 years to receive MSW. Compost residue (10% of the disposal amount by compost facilities) and incineration residue (15% of the disposal amount by incineration facilities) were combined as intermediate treatment residue and sent to sanitary landfills for final disposal. Beijing's actual data of 10% compost residue productivity was used. For compost productivity, we used experiential data, which was 35% of the disposal amount (wet base) (Den Boer, 2005).

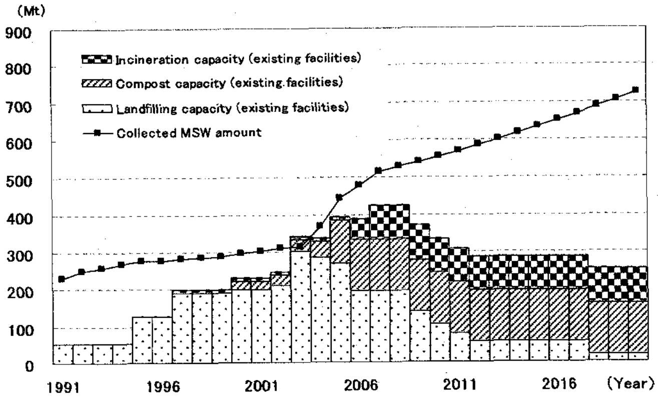
3.2 Scenario analysis for necessary disposal capacity and new facilities

In 2002, the sanitary disposal rate of collected MSW in Beijing was 88%, of which 5% was recycled, 11% was composted, 3% was incinerated, and 81% was landfilled (simple landfill and sanitary landfill) (Environmental Experts Group of Beijing Government, 2003). Beijing's target sanitary disposal rate is 91% for 2003, 95% for 2004, 98% for 2005, and 100% after 2006 (Environmental Experts Group of Beijing Government, 2003). Figure 4(a) shows the collected waste amount and disposal capacity of existing facilities, including incinerators, compost facilities, and sanitary landfills. Simple landfill was not included in the existing facilities, but in the research the planned (but not yet completed) disposal facilities (3 Compost facilities, 2 Incinerator and 1 Landfill) according Beijing's government plan were take into account as existing facilities.

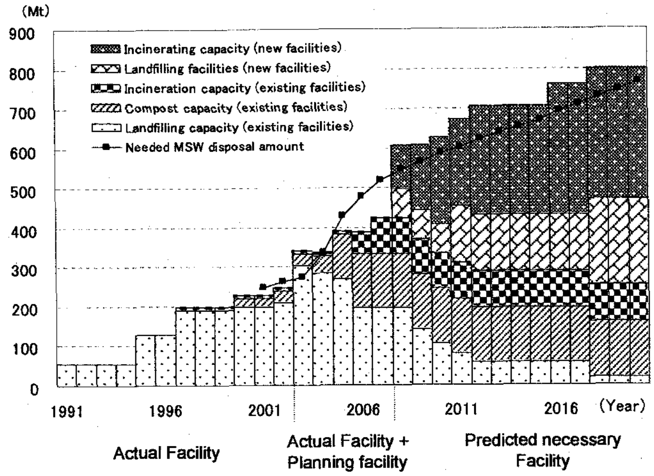
That shows, the disposal capacity of existing facilities will reach its maximum of 4.3 million tons in 2007. Existing capacity will fall sharply to 2.5 million tons by 2017 because of a reduction in existing landfill volume. In 2020, the sanitary disposal amount of MSW other than recycled waste (collected MSW amount × sanitary disposal rate × [1 – recycling rate]) will exceed the disposal capacity of existing facilities' by 4.4 million tons. Therefore, construction of new facilities will be urgent for Beijing government to complete their MSW disposal target.

The simulation results of the three scenarios are shown in Figures 4(b), (c) and (d). The amount of MSW needing to be disposed of includes the intermediate treatment and final disposal amounts (including intermediate treatment residue). The intermediate treatment amount is the disposal amount in compost facilities and incinerators, excluding recycled waste. The summation of the intermediate treatment amount, the intermediate treatment residual amount, and the direct landfill amount was defined as the amount of MSW needing to be disposed of. In the prediction model, the MSW collection amount and the disposal capacity of existing facilities in each year are fixed, but the amount of MSW needing to be disposed of changes in different scenarios. In this situation, the difference between the amount of MSW needing to be disposed of and the disposal capacity of existing facilities is different too. The numbers of necessary new facilities under different scenarios are shown in Table 3.

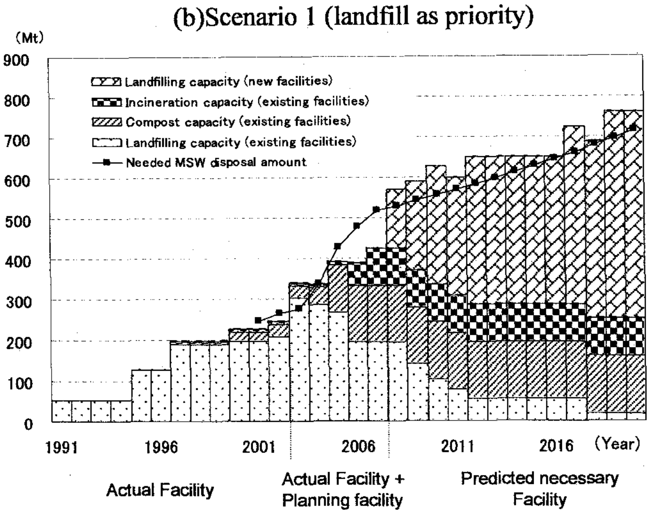
Under scenario 1 (Figure 4(b), in 2020, the amount of necessary MSW disposal capacity is 7.2 million tons, 4.7 million tons more than the disposal capacity of existing facilities. By 2020, seven new sanitary landfills will need to be built. Under scenario 2 (Figure 4(c)), in 2020, the amount of necessary MSW disposal capacity is 7.7 million tons, 5.2 million tons more than the disposal capacity of existing facilities. By 2020, three new sanitary landfills and six new incinerations need to be built. Under scenario 3 (Figure 4(d)), in 2020, the amount of necessary MSW disposal capacity is 7.5 million tons, 5 million tons more than the existing disposal capacity. By 2020, two compost facilities, three incinerators, and four new sanitary landfills need to be built.



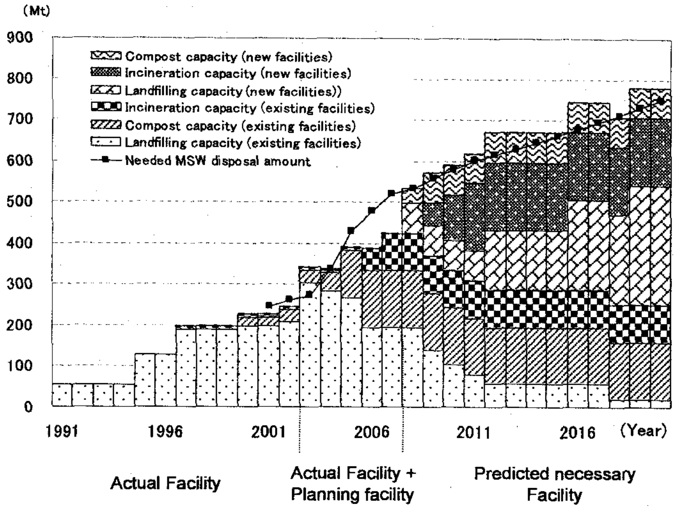
(a)Collected MSW amount and disposal capacity



(b)Scenario 1 (landfill as priority)



(c)Scenario 2 (incineration as priority)



(d)Scenario 3 (according with Beijing's Planning

Figure 4. Prediction on needed MSW disposal amount and necessary disposal facilities
***Needed disposal amount = Intermediate treatment amount (Composting and Incineration) + Final disposal amount (Direct landfilling amount and residue from intermediate treatment)**

Table 3. Necessary new facilities

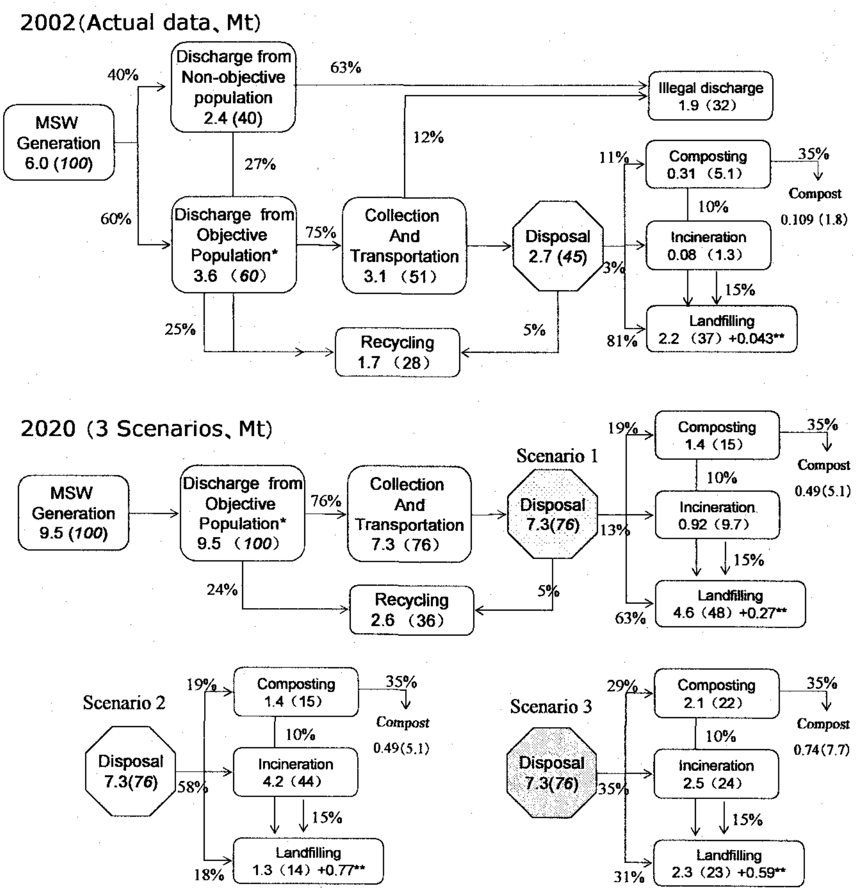
Year	Scenario 1	Scenario 2		Scenario 3		
	Landfill	Landfill	Incineration	Landfill	Composting	Incineration
2008	2	1	2	1	1	-
2009	3	1	3	1	2	1
2010	4	1	4	1	2	2
2011	4	2	4	1	2	3
2012	5	2	5	2	2	3
2013	5	2	5	2	2	3
2014	5	2	5	2	2	3
2015	5	2	5	2	2	3
2016	5	2	6	3	2	3
2017	6	2	6	3	2	3
2018	6	3	6	3	2	3
2019	7	3	6	3	2	3
2020	7	3	6	3	2	3

Cumulative necessary new disposal facilities

3.3 Disposal flow models

Disposal flow models were devised for the MSW disposal system in 2002 and for each of the three scenarios in both 2008 and 2020. These models include MSW generation, collection, recycling, composting, incinerating, and landfilling. The amounts of MSW generated include not only collected waste amounts and illegal discards (here illegal discards means open dumps and any other illegal discards that not included into the official collection system), but also recycling wastes which were recycled before being collected. Because there is no statistical data about the amount of recycling that takes place before collection, the recycling rate in the city zones and suburban areas was assumed to be 25% of waste generation per capita. In the combined zones, the per capita waste recycling amount was assumed to be 0.25 kg/day.

Based on these assumptions, the collection rate and sanitary disposal rate is calculated to reach 100% in 2020, whereas in 2002 about 32% of MSW consisted of illegal discards (Figure 5). The MSW disposal methods in the three scenarios clearly vary: In scenarios 1 and 2, 19% of MSW is disposed of at compost facilities, as opposed to 29% in scenario 3. The incineration rate is 19% in scenario 1, 58% in scenario 2, and 35% in scenario 3.



*Objective population means population included in the waste collection plan, their waste will be collected by public. On the contrast, Non-objective population means population not included in the waste collection plan.

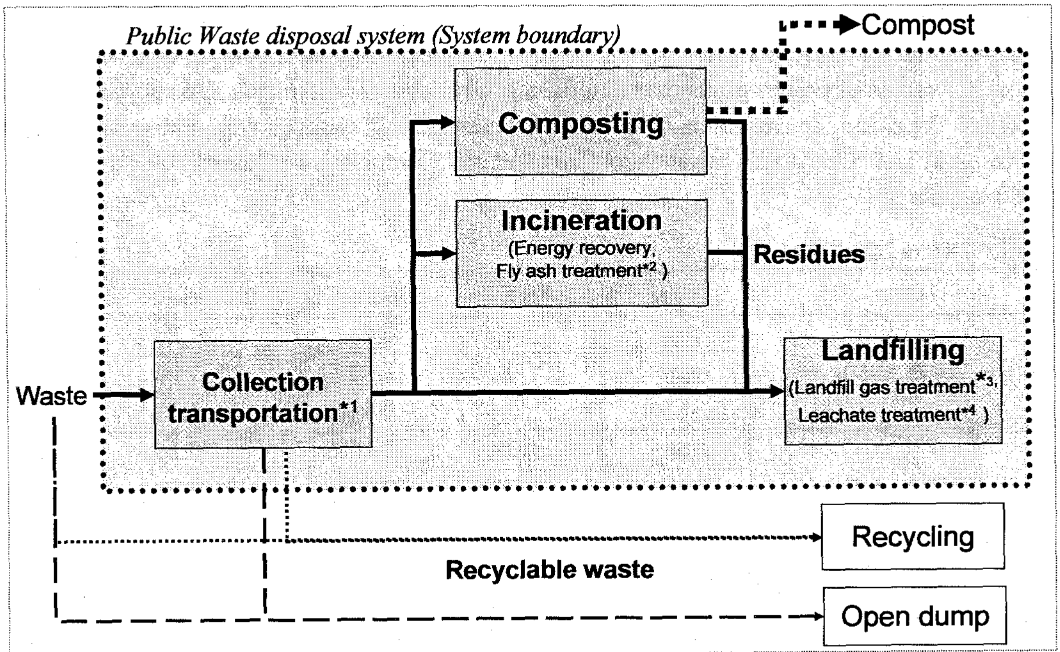
**Residue and fly-ash from incineration and compost

Figure 5. Predicted disposal flow chart of MSW

4. LCA AND COST ANALYSIS

4.1 LCA

The assessments of environmental loads and cost analysis were done for the waste disposal system in 2002 and for the three scenarios in 2008 and 2020. LCA was carried out for the disposal system considering MSW collection and transportation, intermediate treatment, and final disposal. The system boundary is shown in Figure 6. IWM-2 Model (McDougall, 2001) was used for modeling waste flow and environmental loads. The emission intensity data for the Life Cycle Inventory (LCI) came partly from the Research Center for Eco-environmental Sciences, Chinese Academy of Science through their investigation in Chinese facilities (Yang et al. 2002; Xu et al. 1999 and 2000; Yang and Liu, 2006).



*1: In the some transportation centre, separation is included, recyclable material and suitable compost material were separated for recycling and composting.
*2: In China, fly-ash was defined as hazardous waste and treatment is necessary before transferred to landfill. In this research fly-ash treatment is assumed as stabilization with cement. Assumption for treatment rate show in table 4.
*3: Landfill gas treatment means landfill gas collection and energy recovery. Assumption for landfill gas treatment rate show in table 4.
*4: leachate treatment was assumed as biological treatment plus filtration and disinfection. And treatment rate was assumed in table 4.

Figure 6. System boundary of LCA

In the calculation of $LCCO_2$, CH_4 and N_2O were converted into CO_2 equivalents according to their 100 years global warming potential (GWP100). Assumptions for treatment rate of incineration fly-ash, treatment rate of landfill leachate, and collection and energy recovery rates of landfill gas are shown in Table 4 (Environmental Experts Group of Beijing Government, 2003).

Table 4. Assumptions for LCA

		Treatment of Fly-ash	Leachate treatment		Landfill gas	
			Collection	Disposal	Collection	Energy Recovery
2002	Actual Data	0%	50%	80%	0%	0%
2008	Scenario 1	50%	80%	80%	30%	50%
	Scenario 2	50%	80%	80%	30%	50%
	Scenario 3	50%	80%	80%	30%	50%
2008	Scenario 1	50%	100%	100%	50%	100%
	Scenario 2	50%	100%	100%	50%	100%
	Scenario 3	50%	100%	100%	50%	100%

Based on emission intensity data and composition change of local facilities in Beijing, we calculated the main greenhouse gas emission and energy consumption data for analysis as show in Table 5. Because of change of treatment on fly-ash, leachate and landfill gas, and composition change of waste, the energy consumption and greenhouse gas emission changed with time as shown in table 5. Result of LCE and $LCCO_2$ are shown in Figure 7 and accumulative LCE and $LCCO_2$ from 2008 to 2020 in table 6.

Table 5. Main LCI Data

Item	Year	Collection	Compost	Incineration	Landfill
LCE GJ/t	2002	1.59	0.0373	-3.26	0.11
	2008	1.30	0.0392	-3.94	-0.21
	2020	1.08	0.0363	-4.28	-1.02
$LCCO_2$ t-C/t (GWP100)	2002	0.040	0.0007	0.11	0.50
	2008	0.032	0.0008	0.13	0.45
	2020	0.027	0.0007	0.12	0.33
CO_2 emission intensity of grid electricity			0.000297 t-c/KWh		

Table 6. Accumulative LCE and $LCCO_2$ from 2008 to 2020

		Collection and transportation	Composting	Incineration	Landfilling	Total
LCCO2 (Mt) total	Scenario 1	238	1	148	1,934	2,322
	Scenario2	254	1	575	1,046	1,876
	Scenario3	249	2	372	1,029	1,651
LCE (GJ) Total	Scenario 1	9,494	68	-4,914	-3,282	1,366
	Scenario2	10,101	68	-19,173	-1,305	-10,309
	Scenario3	9,919	102	-12,388	-2,129	-4,495

The results calculated based on the above-mentioned assumptions are as follows:

1) LCE: Because incinerating with energy recovery is a priority in scenario 2, energy use in scenario 2 is the best, and scenario 3 takes second place.

2) $LCCO_2$: Accumulative Greenhouse gas emissions in scenario 3 are the lowest, constituting about 71% of that in scenario 1 and 88% of that in scenario 3.

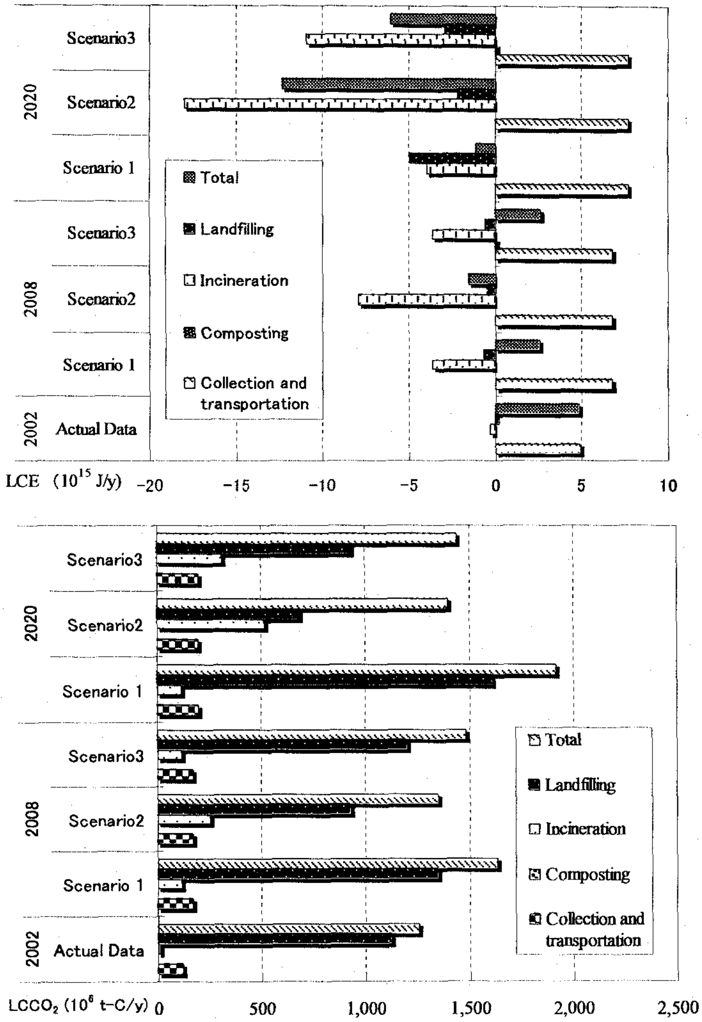
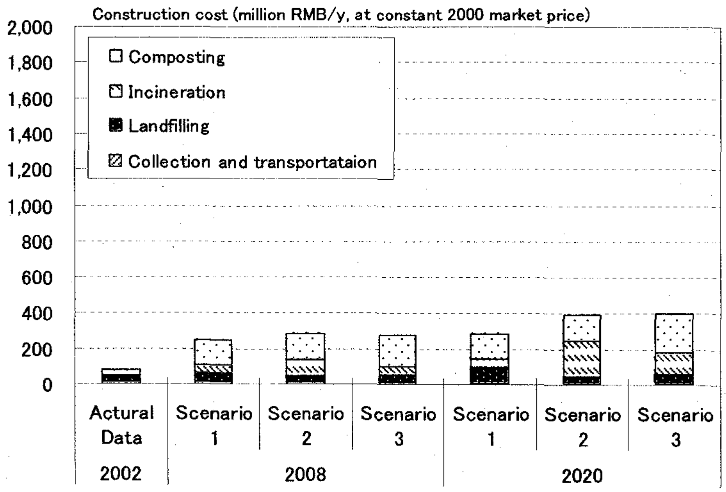


Figure 7. LCE and $LCCO_2$

4.2 Cost analysis

The cost analysis in Figure 8 shows the construction and operation costs of collection and transportation, recycling, composting, incineration, and landfilling for 2002 (actual data) and for the three scenarios in 2008 and 2020. The monetary unit is constant at the 2000 market price. Zuo et al. (2001) compared the investment in landfill and incineration in China and Japan and found that for a disposal facility the investment at purchase power parity have a linear relationship with disposal capacity. That means with the change of year the investment at constant price will not change a lot. Construction and operation costs were calculated by using the construction cost per ton of MSW, operation cost per ton of MSW, and the total disposal amount of MSW. Construction cost per ton of MSW was calculated by using the investment and operation time of different facilities: transportation center, 30 years; incineration and compost facilities, 20 years; and landfill, calculated by the landfill volume was estimated to be able in operation for 20 years. Because there was no large incineration facility in Beijing, the operation cost used was the average operation cost of incineration facilities in other Chinese cities. Table 7 shows basic cost data which obtained by investigation of local facilities in Beijing and interview of experts of Chinese Research Academy of Environmental Science and Beijing Municipal Administration Commission.



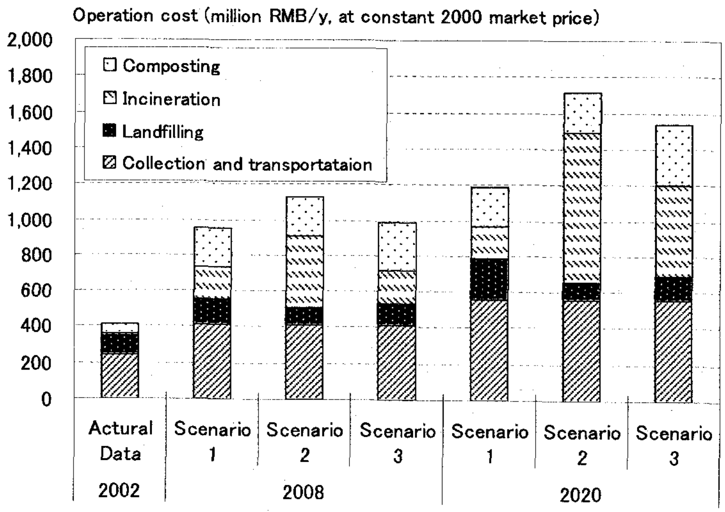


Figure 8. Cost analysis

Table 7. Basic cost data of Beijing

Item	Collection	Compost	Incineration	Landfill
Operation Cost (RMB/t)	77	158	200	47
Construction Cost (1000 RMB/t·day)	7	570	360	25RMB/m^3

The operation costs of other facilities used actual data from Beijing (the data came from investigations at the Beijing Municipal Administration Commission). Scenario 2 has the highest total cost (including both construction and operation costs), and scenario 3 takes second place. In 2020, the total cost of scenario 2 is projected to be 1.7 times that of scenario 1, while that of scenario 3 is projected to be 1.5 times that of scenario 1. Comparing the two costs, construction cost was about one quarter of the operation cost.

Finally, we compared the cumulative construction costs and operation costs from 2008 to 2020. Cumulative construction cost means the total investment for new facilities from 2008 to 2020. Cumulative operation costs were calculated using the operation cost per ton of MSW and the amounts disposed of at different facilities from 2008 to 2020. The calculated cumulative total construction and operation costs are shown in Table 8. The highest cumulative construction cost was 4.6 billion RMB (at constant 2000 market price) in scenario 3. The highest total cumulative cost (totaling both construction and operation costs) is found in scenario 2, which reached 23.5 billion RMB, followed by 22.3 billion RMB in scenario 3, and the lowest total cumulative cost are 15.9 billion RMB in scenario 1.

Table 8. Accumulative necessary investment and operation cost of three scenarios

	Necessary Investment($\times 10^6$RMB)			Percentage			Comparison		
	Total	Investment	Operation	Total	Investment	Operation	Total	Investment	Operation
Scenario 1	15,886	2,100	13,786	100%	13%	87%	1	1	1
Scenario 2	23,461	4,140	19,321	100%	18%	82%	1.5	2.0	1.4
Scenario 3	22,336	4,591	17,745	100%	21%	79%	1.4	2.2	1.3

* At constant 2000 Market Price

5. Discussion

In the "White Paper Concerning Waste Disposal in Beijing", the policy-makers of Beijing determined that 3Rs (reduce, reuse, recycle) policy should play a more important role in future, but the concrete plans are mostly about construction plans for end-of-pipe disposal facilities. The LCA results in this research indicated that in Beijing the best environmental performance requires greater expenditures. The scenario analysis was based on assumptions that only end-of-pipe disposal method would be changed, without considering of impact of 3Rs police changes, so the result shows only changes in the end-of-pipe disposal method will lead to greater costs in order to reduce environmental impact.

The results raise a question for future research. Could there be other choices which could reduce environmental loads more dramatically and somehow without much increase or even reductions in cost? In developed countries, municipal solid waste management had transferred their emphasis from end-of-pipe methods to 3Rs methods, and gained valuable expertise during their development of integrated waste management systems. All of these could be useful references for developing countries when they develop their own integrated waste management systems.

For example, Taipei city developed their end-of-pipe facilities quickly with an estimation of waste increases from the 1980s to the 1990s, and three big incinerations with total capacity of 4,200 ton/day were built from 1992 to 1999. Then, since the 1990s they have paid more attention on 3Rs policies, like promotion of separate collection activities and introduction of a per bag trash collection fee system to reduce waste and increase recycling in 2000. All these measures resulted in a dramatic reduce in waste amount from 3,500 ton/day in 1995 to 1,500 ton/day in 2005, and an increase in recycling rate from 0.72% in 1995 to 38.27% in 2005 (Department of Environmental Protection, Taipei City Government, 2006).

This example lead to a number of significant conclusions: Firstly, implementation of 3Rs policies and activities reduced the waste amount, increased waste recycling and saved operation costs. However, because the construction plan for end-of-pipe disposal facilities was not considered together with reduction effects by 3Rs policies, in 2005 the total waste amount in Taipei is just one third of total incineration capacity. Obviously, such waste of investment should be avoided by other Asia cities during their development of waste management systems.

The development of waste management systems in developed countries in the past 20 years might provide useful information for the development of waste management systems by many Asian cities like Beijing in the next 20 years. Therefore, in future research, policy changes such as separated collection of kitchen waste, promotion of recycling, and changes in charge systems should be considered and more scenario analyses should be mad considering impacts by changes in end-of-pipe disposal method together with changes of 3Rs policies.

6. CONCLUSIONS

We investigated a representative Chinese metropolis (Beijing) as a case study, and used a multiple regression model to estimate the amount of waste collected per capita. We combine the intermediate and final disposal amounts to determine the amount of MSW needing to be disposed and necessary new facilities for the three scenarios (landfill as priority, incineration as priority, and Beijing's disposal plan).

The results show, the total collected waste amount will increase along with increasing of per capita waste amount and expanding of collection areas, from 3.21 million ton in 2002, reaching 5.56 million tons in 2010, 6.33 million tons in 2015, and 7.26 million tons in 2020. Till 2020, total seven new sanitary landfills under scenario 1, three new sanitary landfills and six new incinerations Under scenario 2, two compost facilities, three incinerators, and four new sanitary landfills under scenario 3, will need to be built.

We also used $LCCO_2$, LCE, and cost assessments for the three scenarios through 2020. Results indicate that the total cost of scenario 1 (15.886 billion RMB) is the lowest, but the environmental loads for this scenario are the highest (2322 million t-c Greenhouse gas emission and 1366 GJ Energy consumption). In contrast, the total cost of scenario 2 is the highest (23.461 billion RMB) with the lowest environmental loads (1876 million t-c Greenhouse gas emission and 10369 GJ Energy generation), followed by scenario 3, which has relatively lower total costs and less effective environmental performance than that in scenario 2.

Future research will concentrate on impact of collection and transportation changes over time and recycling policy change on waste amount change.

Acknowledgments

The authors would like to thank Mr. Qi Wang (Director, Institute of Solid waste management and disposal technology, Chinese Research Academy of Environmental Science), Dr. Jianxin Yang (Research Center for Eco-Environmental Sciences, the Chinese Academy of Sciences) and Prof. Jin Chen (Beijing Normal University) for their cooperation in collecting data and valuable suggestions. The authors are also grateful for anonymous referees for their helpful comments. Research project on "Development of Environmental Assessment Tool for Asian Cities" has been undertaking supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan as the Special Coordination Funds for Promoting Science and Technology. This paper presents a part of its results.

References

Ayalon, O., Avnimelech, Y., and Shechter, M. (2000): Application of a comparative multidimensional life cycle analysis in solid waste management policy: the case of soft drink containers, Environmental Science & Policy, Vol.3, No.2-3, pp.135-144.

Beijing Environmental Sanitation Administration (1996): Options for domestic solid waste treatment in Beijing, the Metropolitan Environmental Improvement Program working paper series, the World Bank.

Beijing Municipal Bureau of Statistics (1997-2004): Beijing Statistics Yearbook (1996-2003), China Statistics Press (in Chinese).

den Boer, E., den Boer, J. and Jager, J. (2005): Waste Management Planning and Optimization: Handbook for Municipal Waste Prognosis and Sustainability Assessment of Waste Management Systems, Ibidem Press, Germany.

Department of Environmental Protection, Taipei City Government (2006): Waste Amount Statistic Table (http://www.epb.taipei.gov.tw/report/bulletin.aspx).

Environmental Experts Group of Beijing Government, Beijing Environmental Health Design Institute (2003): Study of a Strategy for Municipal Solid Waste Control for a Green Olympics in 2008 (in Chinese).

Environment Protection Department of Hong Kong (1997-2005): Monitoring of Solid Waste in Hong Kong.

Finnveden G. and Ekvall T. (1998): Life-cycle assessment as a decision-support tool—the case of recycling versus incineration of paper, Resources, Conservation and Recycling, Vol.24 No.3-4,: pp.235-256.

Government of Beijing (2005): Overall Urban Planning of Beijing for 2004 to 2020: http://www.bjpc.gov.cn/fzgh/csztgh/ (in Chinese).

Government of Beijing (2003): White Book for Waste Disposal in Beijing (http://www.bjd.com.cn/zfzx/wj/200605/t20060523_13471.htm).

Hokkaido University, Faculty of Solid Waste Disposal Engineering (1998): Study of an Assessment and Calculation System for Municipal Solid Waste General Management, Japan (in Japanese).

Karavezyris, V., Timpe, K., and Marzi, R. (2002): Application of system dynamic and fuzzy logic to forecasting of municipal solid waste, Mathematics and Computers in Simulation, Vol.60, pp.149-158.

Lin F.C. and Yang K. (2004): Comparison of Two Kinds of Fast Food Container Using the Life-Cycle Assessment (LCA) Methodology, Journal of Eastchina Normal University(Natural Science), Vol.4, pp.124-132.

Ma X.C. and Xu Y. (2004): The influence of paper and plastic packaging on environment are assessed by LCA, World Plastics, Vol.5, pp.33-35.

McDougall, F.R., White, P.R., Franke, M., and Hindle, P. (2001): Integrated Solid Waste Management: A Life Cycle Inventory, McDougall, Blackwell Science, Ltd., United Kingdom.

Niu H. (2001): ASSESSMENT OF THE DISPOSAL OF URBAN'S "WHITE WASTES" BY LCA METHOD, Environmental Engineering, Vol.1, pp.52-53.

Ru Y.H., Lu W., Si I.Y. and Xu B. (2001): Control Countermeasures of Mun icipal Refuse in Be ij ing, CH INA M ECHAN ICAL ENGINEERING, Vol.12, No.3, pp.343-346.

Song, H. and Hyun, J.C. (1999): A study on the comparison of the various waste management scenarios for PET bottles using the life-cycle assessment (LCA) methodology, Resources, Conservation and Recycling, Vol.27, No.3, pp.267-284.

The Law on Environmental Impact Assessment of the People's Republic of China (2002): http://www.people.com.cn/GB/shehui/212/3572/3574/20021029/853043.html.

Tokyo Metropolitan Research Institute for Environmental Protection (1968-2002): Investigation report for municipal waste quantity and quality,(In Japanese).

World Bank (2005): Waste Management in China: Issues and Recommendations, Urban Development Working Papers.

Xu, C., Yang, J. and Wang, R. (1999): Life cycle assessment of municipal solid waste in Guanghan city, ACTA SCIENTIAE CIRCUMSTANTIAE, Vol.19, No.6, pp.631-635.

Xu, C., Yang, J. and Wang, R. (2000): Life cycle assessment for municipal solid waste treatment and utilization, Journal of Environmental Sciences, Vol.12, No.2, pp.225-231.

Xue Y.H., Matsumoto T. and Zuo J. (2005) Scenario Analysis and strategic Assessment of Municipal Solid Waste Disposal System For Beijing from 2003 to 2020, Proceeding of International Conference on the Circular Economy and Regional Sustainable Development, pp.312-318, Hangzhou, China.

Yang, J. and Liu, J. (2006): Life cycle management of municipal solid waste in Chinese Mega-cities. Proceedings of The seventh International Conference on EcoBalance, pp.123-124.

Yang, J., Xu, C. and Wang, R. (2002) Methods and Applications of Life Cycle Assessment for Production, Chinese Weather Press, Beijing, China (in Chinese).

Yu H.Y. (2004): Introduce the Method of LCA in Solid Waste Resource Recovery, China Resources Comprehensive Utilization, Vol.1, pp.38-40.

Zhou C.H., Lu M.X. and Wu W.W. (2004): On prediction of municipal solid waste classification in Beij ing, Journal of Safety and Environment, 4(5):37-40.

Zuo, J., Imai, A., Nakamura, H., Matsumoto, T., and Imura, H. (2001): Need prediction and strategies for disposal of municipal solid waste in China, Proceedings of Environmental System Research Vol.29, pp.273-281, Japan.