Application of System Dynamics for Municipal Waste Management in China: A Case Study of Beijing

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Abstract

Municipal domestic waste is the most complex one among the solid wastes. Its improper disposal will easily cause serious environmental pollution, occupy substantial landfill and waste the recyclable resources. System dynamics methodology presents special merits in the study of the municipal waste management. In this paper, 16 study achievements of the system dynamics are summarized with regard to the solid waste management in China; studies on the system dynamics models are focused for the municipal waste management in Beijing, covering the relatively detailed structure designs for population subsystem, waste discharge subsystem, waste disposal subsystem, waste charging subsystem, waste pollution/landfill loss subsystem, and macro-economy and green GDP accounting subsystem; the preliminary simulation findings are described and a conclusion is proposed; finally, it is envisioned that the system dynamics models of municipal domestic waste management should combine with the GIS technology to facilitate the spatial presentation of findings, with the optimization technology to screen the best decision-making plan, and with the safety & early-warning technologies to prepare emergency plans.

Keyword: system dynamics, municipal domestic waste, solid waste management, decision-making

1. Introduction

Municipal waste refers to the solid waste produced by the urban residents in their daily life or enterprises and institutions when they provide daily services for residents as well as those regarded as domestic waste according to requirements of the laws and administrative regulations, which is one major component of the solid waste.

Since the reform and opening up to the outside world, with the high speed development of the social economy in China, increasingly improving living standard of residents, continuously accelerating urbanization process and large population migration and flow toward cities, the municipal waste output has been soaring and the components have been becoming more and more complicated. Because of relatively small construction capital input, seriously insufficient infrastructures, slowly improving technical levels of sanitation cleaning and waste disposal, single disposal method and rigid management system, the municipal waste disposal system is overburdened and causes a series of social, economic and environmental problems. At present, among 661 cities throughout the country, about 2/3 cities has been surrounded by the waste and even about 1/4 cities find nowhere for landfills. Therefore, it is of considerable practical significance for the environmental protection, sustainable development and living quality improvement of urban and rural residents to further and systematically analyze reasons and influence of the domestic waste, predict the future changes and trends of the municipal waste problems, find efficient ways to solve problems, comprehensively coordinate behaviors of the public, enterprises, institutions and governments and realize the whole and systematic management.

Many methods are available for the study of the municipal waste management, but the system dynamics has special advantages as it not only may predict the future trends, study the system characteristics and find effective ways to solve problems [1], but also provides the most interfaces for its relatively easy connection with other models. However, the system dynamics models also have their own disadvantages, which may be made up by grating other models so as to achieve optimization of decision plans and multi-dimensional display of simulation results [2].

In this paper, study achievements of the system dynamics since China introduced the system dynamics in 1980s are summarized with regard to the waste management system, studies on the municipal waste management in Beijing are focused, covering the relatively detailed structure designs for the population subsystem, waste discharge subsystem, waste disposal subsystem, waste charging subsystem, waste pollution & landfill loss subsystem, and the subsystem of macro-economy and green GDP accounting; the preliminary simulation and findings are described and a conclusion is proposed; finally, specific plans for model improvement are presented.

2. Literature Review

Early in 1973, J. Randers and D. L. Meadows began to study the solid waste management by the system dynamics [3]. By the end of 2012, at least over 20 study achievements have been obtained [4-25]. Such achievements have been or are being studied and referred to by Chinese scholars.

Since the system dynamics is introduced to China in early1980s, it has been widely applied in fields such as the natural science, humanities and social sciences and engineering technology. By far, about 16 study achievements on solid waste management have been obtained. They roughly may be divided into three categories: I. the study submodel for the solid waste is embedded in that for the regional sustainable development; II. the study models with the whole solid waste management as the core; III. management models for the single variety of solid waste.

In 1984-1985, the Solid Waste Management Office of the National Environmental Protection Agency, Beijing Municipal Research Institute of Environmental Protection, Tsinghua University and the Soil and Fertilizer Institute, Chinese Academy of Agricultural Sciences have jointly completed the study on the environmental impact of the solid waste and the countermeasures in 2000 [26]. This study relatively comprehensively analyzes influence of the production, utilization and consumption on main solid wastes such as industrial residue, hazardous waste, town refuse and partial agricultural waste output as well as the general rules of stock, utilization and disposal amount accumulation, establishes a common model in the DYNAMO language of the system dynamics, predicts the output of more than 10 kinds of waste residues in three main categories and put forward some countermeasures and suggestion on the overall management of the solid waste, which is the earliest example in China to study the waste issue by system dynamics methods; thereinto, the analysis on the study object is relatively comprehensive and parameters involved with the model are relatively many. However, comprehensive simulation model has not yet been built; instead more than 10 kinds of wastes in three main categories are predicted respectively.

In 1991, Hu Xuehai (Jinzhou Research Institute of Environmental Protection) and Liu Weisheng (Chinese Academy of Sciences) et al, according to Chinese population, economy and society prospects, simulated and analyzed the trends on output, comprehensive utilization volume and discharge volume of 4 categories of main solid wastes (industrial solid waste, toxic and hazardous waste residue, animal manure, and municipal waste and manure). However, their published work didn't give specific model structure and simulation description [27].

In 1997, Huang Zhenzhong et al stateside, on the basis of the "Threshold 21: National Sustainable Model" (Edition 1994) completed in the US Millennium Institute, developed the China's Sustainable Development Computer Model 1.0. In the environment submodule, study submodule for solid wastes are embedded. The solid waste mainly includes industrial solid waste and municipal domestic waste; the former is divided into the fly ash, smelting slag, coal gangue and others while the latter is only related to the domestic waste. However, it doesn't not state whether the domestic waste includes the construction waste and others [28].

In 2003-2005, Guo Huaicheng et al completed the Guiyang urban environmental economic system planning study; one of its focuses is to construct the "Guiyang Environmental Economic System SD Model" [29]. The model divides the overall system into 5 subsystems: population subsystem, water resource subsystem, industry subsystem, energy subsystem and pollution subsystem. Thereinto, in the pollution subsystem, industrial solid waste output and municipal waste disposal submodule is embedded. The submodule covers elements such as urban population, domestic waste output per capita, existing waste disposal capacity, central waste disposal and disposal cost per unit.

In 2005, Li Yongjin et al completed the dynamic simulation study "Gansu Resource - Environmental - Economic System", which constructs a model by the system model methods [30]. The model mainly includes 8 subsystems. Thereinto, the environmental pollution subsystem includes the solid waste discharge volume module. The solid waste discharge volume is the accumulated value of differences between the solid waste output and the solid waste disposal volume; the former is the sum of the domestic waste output and industrial solid waste output. The domestic waste output is calculated by population size and output per capita while the industrial solid waste output is calculated by the GDP and solid waste output per unit GDP; the disposal volume depends on the disposal capital investment and disposal capital coefficient for solid wastes per ton.

In 2005, Cai Lin took Beijing for example to, by the system dynamics methods, establish a system dynamics conceptual model with regard to the coordinated development of Beijing population, economy and waste disposal, including 6 submodules and discussed the interaction and feedback relationship between elements such as waste output changes with the population and economic growth, waste pollution and landfill loss, and combined collection plan for the domestic waste and construction waste of households, enterprises and institutions [31].

In 2007, Zhang Lei et al from the Department of Environmental Sciences, Beijing University of Chemical Technology, by Vensim software, developed a system dynamics model for the prediction of domestic waste in Shenzhen [32]. This study divided the municipal waste output system into 5 systems: ① domestic waste subsystem; ② commercial waste subsystem; enterprise and institution waste subsystem; ④ cleaning waste subsystem; ⑤ transportation and other waste subsystems. On the basis of the parameter verification and optimization, they carried out the natural tendency and regulation scheme simulation analysis.

In 2007, Hou Yan, Wang Hua and Bi Guihong et al from the Faculty of Information Engineering and Automation, Kunming University of Science and Technology, constructed a Kunming domestic waste management system dynamics model [33]. The model took the population as the core to predict the total waste collection, analyzed the proportion of the total waste disposal investment in the GDP on the basis of the investment required for the general landfill, sanitary landfill and incineration, simulated the disposal volume, profit and loss of each disposal method according to 3 management plans to provide management plan analysis and development basis for the domestic waste management decision maker. Neither this study was in the consideration of the industrial structure influence on the population size nor waste output per capita, nor related to the landfill and pollution loss due to the waste discharge; with regard to the waste disposal methods, the structure design for the composting and comprehensive disposal methods is not available, either.

In 2008, Wang Huihong from the Department of Environmental Engineering, Beijing University of Civil Engineering and Architecture, finished a master thesis "Prediction and Environmental Impact Analysis on Kitchen Waste Output in Beijing" [34]. This study through the Vensim software, established a system dynamics model including 4 subsystems (registered population, temporary population, economic aggregate GDP and average household income) and made prediction on the kitchen waste output in the catering industry.

In 2008, Jian Lihao, Martyn James Hill and Li Yinshen from the Department of Building & Real Estate, the Hong Kong Polytechnic University, developed an on-site system dynamics model for the disposal of construction and disassembly waste so as to provide decision support tools for better management effects [35]. In this study, Stella software was used to construct a model, which included 6 stocks of the construction and disassembly waste output, on-site sort capacity, sorting equipment capacity, total cost, landfill and bedding in public places.

In 2008, Lin Zijian from the School of Mathematical Sciences, Naikai University and Lu Lianggang et al from the Macao Science and Technology Association, through studying the composition and process of the waste in Macao and by STELLA software, constructed a model which was consisted of 4 submodels (permanent population, area and population density, immigrant population and solid waste output) and predicted the total waste volume, domestic waste volume and others (industrial and commercial waste as well as large waste), which provided data support for the adjustment of waste disposal policy in Macao [36].

In 2008, Lei Kampeng and Zhou Shaoqi from the College of Environmental Science and Engineering, South China University of Technology studies the driving factors of construction waste growth in Macao, constructed a simulation model for the generation of construction waste in Macao including 5 subsystems which are population subsystem, new entertainment venues and hotel system, interior decoration for residential building, public infrastructure and private building, old and small community renovation by STELLA software, simulated the construction waste output in 2001-2018, compared the fitting degree between the final simulation output of the total construction waste and the actual output and put forward policy measures to improve the disposal capacity of sustainable construction waste [37].

In 2009, in the master thesis of Chen Yan from the Management School, Hangzhou Dianzi University, by Vensim-PLE software, Hangzhou was taken as an example to establish a comprehensive coordination model for the municipal waste management system dynamics including 4 subsystems; subject to the data in 2005, it carried out a simulation analysis on population, waste output, waste collection and waste disposal volumes of Hangzhou in 20 years under the current trend and different policy regulation combinations and put forward some regulation suggestions for the domestic waste management system thereunder [38].

In 2009, Hong Hongjia et al from the South China Institute of Environmental Sciences, MEP (SCIES), took the old computers in Guangzhou for example to establish a model including 4 subsystems (economic aggregate GDP, population, policy, generation volume due to primary and secondary uses of old computers) by combined method of qualitative and quantitative as well as Vensim software, and simulated the development trend of the output by the old computers in 2001-2020 in Guangzhou, which provided an example for the prediction and effective management of the municipal electronic waste output [39].

In 2012, Wang Jinqiong from the School of Resource and Environmental Engineering, Wuhan University of Technology, established a model for the domestic waste management system which was divided into 4 subsystems, including total population subsystem, waste output subsystem, waste collection and recycling volume subsystem and waste disposal subsystem, and carried out simulation analysis on the domestic waste output and bio-safety disposal volume according to the current constant policy and combined regulation policy [40].

In 2012, Zhang Haizhen et al from the Department of Management Science & Engineering, Qingdao University, took the recycling of waste washing machines in Qingdao as an example to construct a "System Dynamics Simulation Model to Encourage the Recycler to Recycle and Dispose the Waste Home Appliances" covering the quantity of used home appliances, the quantity of waste home appliances, the quantity of recycled waste home appliances and the quantity of disposed waste home appliances, simulated the influence of the disposal capital, worker employment adjustment time, environmental protection publicity expenses and secondary utilization rate on the recycling and disposal rate and reached the conclusion that it could improve the recycling and disposal rate of the waste home appliances by improving the secondary utilization rate and strengthening the environmental protection publicity [41].

From the above, we can observe that models of only 6 studies take all the solid wastes as the core and only 3 studies' structures and objectives are relatively comprehensive; therefore, more effects still shall be paid to it.

3. Beijing Case Study

Beijing, the capital of China, is the political, economic and cultural center with large total population, fast growth speed and complex social-economic structure. However, at present, Beijing discharges 18,000 tons of waste everyday while the landfilling volume is only about 8,000t; the others are randomly incinerated or stacked in the suburb, which causes serious air and water pollution. Therefore, the management system desperately needs to be improved and it is of typical meaning to take Beijing as the study case.

This study is extended on the basis of the conceptual model constructed by the Author in 2005 and is still a work in process. Here only the preliminary study achievements are introduced.

3.1 System analysis

This study divides the municipal waste management system into the waste discharge, waste administration and waste disposal systems. The system analysis focuses on the waste source, category, output, component change, disposal method, management policy and discharge conditions

3.1.1 Waste discharge system

In the "Law of the People's Republic of China on Prevention of Environmental Pollution Caused by Solid Waste", the solid waste is divided into industrial solid waste, domestic waste, hazardous waste and agricultural solid waste. Thereinto, the environmental protection department is in charge of the administration and disposal of the industrial solid waste and hazardous waste; the agricultural sector is in charge of the administration and disposal of the agricultural solid wastes, including domestic waste and waste cleaning. The municipal department is in charge of the administration and disposal of the domestic waste and construction waste from the enterprises and institutions.

In this study, based on the measure of waste administration, the municipal waste is divided into three main categories: domestic waste, enterprise and institution waste and civil construction waste.

3.1.2 Waste administration system

The municipal sanitation system is charge of the collection, transportation and disposal of the municipal waste and construction waste; their management measures mainly include charge and recycling encouragement.

The current waste charging system is mainly involved in three aspects: I. domestic waste charging against residents; II. construction waste charging; III. waste charging against organizations (mainly catering organization). According to the Beijing domestic waste management provisions, RMB3 is charged against each household per month; RMB2 is charge against each immigrant person per month. RMB16 per ton is charged on the construction waste cleaning and shipping; for the enterprises and institution waste, RMB 40 in total is charged on the waste cleaning, shipping, digestion and save.

Since 1996, Beijing has conducted pilot work for the waste classification; as for the classification methods, according to the principle "rough classification for main categories", the domestic waste is divided into recyclable waste, kitchen waste and others. However, by far, neither the waste classification is still thoroughly nor the supporting measures are complete. Majorities of waste are mixed together finally.

3.1.3 Waste disposal system

The overall principles for Beijing waste disposal are minimization, recycling and decontamination. While the minimization and recycling are vigorously promoted, engineering measures (landfilling, composting, incineration, classification recycling and disposal, and comprehensive disposal) are adopted and explored to carry out bio-safety disposal for the waste. The future overall disposal thinking for the domestic waste will be in accordance with the basic principle "giving priority to the sanitary landfill and paying equal attention to multiple disposal methods" so as to gradually increase the proportion of the incineration power generation disposal.

3.2 Model construction

The domestic waste management is closely related to the urban population size and consumption behavior changes, land resources supply, purchase and occupancy expenses, waste disposal methods, economic growth scale and speed as well as the future waste charging and management system, which is a complex system work. Therefore, it is of vital importance to comprehensively analyze their relationship and construct a system model which not only gives consideration to the current and future, but also may be flexibly regulated.

3.2.1 Model study framework

According to the structure analysis of the system and basic requirements of sustainable development, the construction of the Beijing domestic waste management system model is considered from the following aspects: I. waste discharge is studied with the population size and behaviors as the center; II. waste disposal expenses and various loss are taken as the measurement objective; III. system factor selection and structure setting are carried out according to the international advanced experience and future development trend, instead of the limitation to the existing waste disposal system; IV. Aiming at facilitating the regulation and administration of policies, window design is carried out from the utilization of the policy regulation and management so as to give full play to the role of the system dynamics policy regulation laboratory.

On basis of the above guideline, the Beijing domestic waste management model may be divide into 6 subsystems (population subsystem, waste discharge subsystem, waste disposal subsystem, waste charging subsystem, waste pollution and landfill loss subsystem, and macro-economy and green GDP accounting subsystem. The interaction and feedback relationship between elements in the system is detailed in Figure-1.

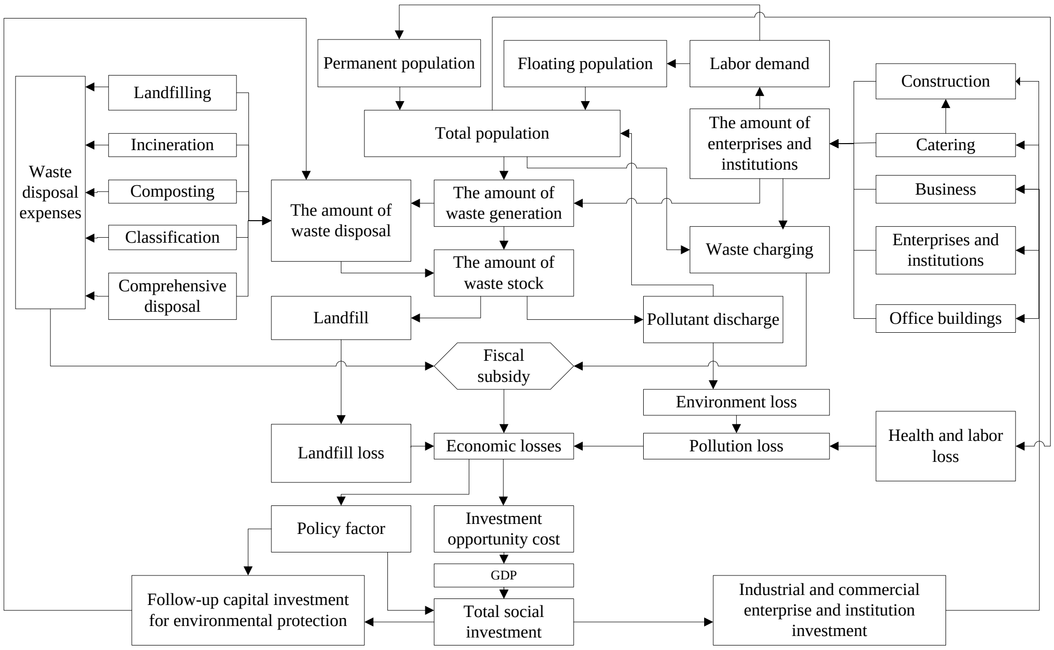

Figure-1 Dynamics Model Study Frame for Beijing Domestic Waste Management System

3.2.2 Structural relationship analysis on the model design and subsystem

This part mainly covers submodel construction, external influence factor and impact analysis of main factors in the model and the feedback relationship analysis on the submodel.

(1) Population submodel

Population growth and activity are min driving forces of the waste discharge. Not only the domestic waste discharge is closely related to the population size and behaviors, the waste discharge due to social production, service and other behaviors is because of the fulfillment of the increasing living demands. Therefore, it is the primary task of model construction to study the relationship between the population growth and relevant factors.

The system dynamics models describing the population situation are single-group population situation model and multi-group population situation model. As the population waste discharge behaviors basically have no age and race difference, the population submodel shall be designed with the total population as the core according to the single-group population situation model.

Total population includes permanent population and floating population.

Total number of permanent population is the accumulated value of the difference between the population growth and population decline. The former is jointly affected by the population births and population immigration, which is the sum of the population births and population immigration while the latter is jointly affected by the population deaths and population emigration, which is the sum of the population deaths and the emigration population.

The population births are mainly affected by 4 external factors: I. normal birth coefficient; II. environmental pollution factor; III. family planning; IV. impact factor of the total number of permanent population. More permanent population, larger population births; in addition, the environmental pollution and birth control reduce the population births.

The population deaths are mainly affected by three factors: I. natural death coefficient; II.

pollution; and III base number of the permanent population. The larger base number of the permanent population is, the larger deaths are. In addition, the environmental pollution will increase population deaths.

The influence factors of the population immigration are mainly the total number of permanent population, the normal immigration coefficient, the labor demand impact factor and the population environmental capacity impact factor.

The driving factors of the population immigration may be represented by the labor demand impact factor. The labor demand factor depends on the labor supply-demand ratio. The labor supply-demand ratio is the labor supply to the labor demand.

Another driving factor (the limit of the population environmental capacity) also affects the population immigration. The driving role of the population environmental capacity is expressed in the population environmental capacity impact factor which is the function of the population capacity ratio of the total number of permanent population to the population environmental capacity. If the total number of permanent population is less than the population environmental capacity, the population environmental capacity immigration regulation factor will have no any difference on the population immigration; on the contrary, the driving role will be greatly strengthened.

For the population in one place, the immigration and emigration always coexists. The influence factor of the population emigration includes the total number of permanent population, the normal emigration coefficient, the influence of the labor demand on the emigration and the influence of the environmental capacity on the emigration.

Normal emigration includes export personnel, retirees, graduates, overseas settlers and other outgoing migrant workers. The influence of the labor demand on the emigration is expressed in the impact factor of the labor demand on the emigration which is also the function of the labor supply-demand ratio; the driving role of the environmental capacity on the population emigration is expressed in the impact factor of the environmental capacity on the emigration which is also a function of the population capacity.

According to the management provisions on personnel without registered permanent residence, the temporary population among the floating population is uniformly incorporated into the permanent population; the floating population is defined as the personnel on business trip, transfer personnel and those who go home to visit their relatives and friends go sightseeing and stay for over half a year.

As the floating population may form an accumulative effect in one area, the floating population also needs to be designed into a stock variable. Total floating population is the accumulated value of initial floating population and floating population growth per year.

According to the analysis results of the main impact factors for the above population subsystem, a population subsystem model flow chart shown in Figure-2 may be constructed.

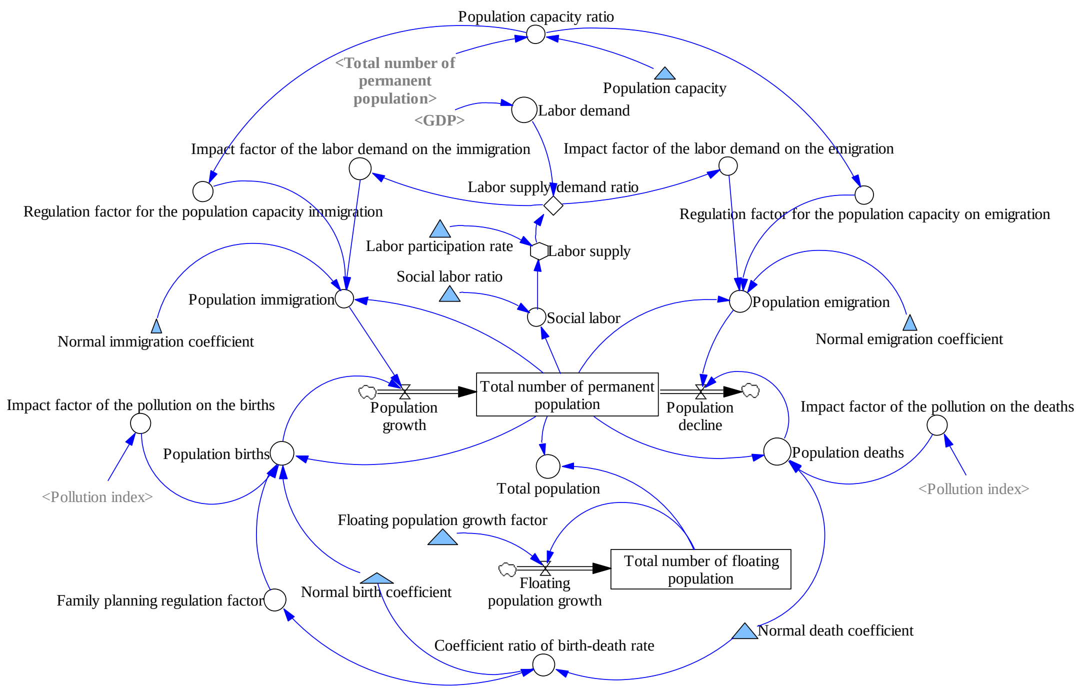

Figure-2 Model for the Population Subsystem

(2) Waste discharge submodel

It is shown from the source and the discharge system analysis of waste in Beijing that, although the discharge sources of waste are many, only daily domestic waste and construction waste are permitted to be disposed in municipal waste disposal system.

Although great differences exist in quantity, compositions and disposal method between domestic waste and construction wastes, waste stock has great influence on landfill and environmental pollution. Therefore in this study, domestic waste and construction waste are combined in a submodel with all the waste stock as the core, and then their own impact factor and the relationship are analyzed respectively.

Stock of all the waste is the sum of stock in domestic waste and construction waste.

Domestic waste stock is determined by stock rate, and the stock rate refers to the quantity of domestic waste which is not disposal every year, it is the difference between discharge volume of domestic waste and waste disposal volume.

Domestic waste discharge covers two parts: domestic waste discharge of resident and domestic waste discharge of enterprises, institutions and administrative organization.

Disposal volume of domestic waste is determined by collection volume and disposal rate of domestic waste; collection amount refers to the collected part in all the discharging domestic waste. Generally, it is influenced by collection rate.

In current waste discharge-disposal system, not all the waste is collected. With further development of environment protection and strengthening of disposal capacity and operating capacity, the collection rate shall be enhanced with time goes by. Furthermore, not all the collected waste is obtained bio-safety disposal, a majority of waste is dumped in one place haphazardly; it is also being called waste stock. With continuous input of disposal funds for domestic waste and continuous perfection of disposal technology, the disposal rate will be enhanced as time goes by, so the disposal rate is also determined by time.

Construction waste of Beijing is obtained disposal basically, disposal method is generally pit-landfilling or stacking. Although the pollution of construction waste is not large, the land landfilled or stacked by construction waste is hardly to be used. With large stock of construction waste, more and more land resources are occupied, so it is an accumulative variable quantity.

Through the above analysis, model flow chart of waste discharge subsystem is obtained and it is detailed in Figure-3.

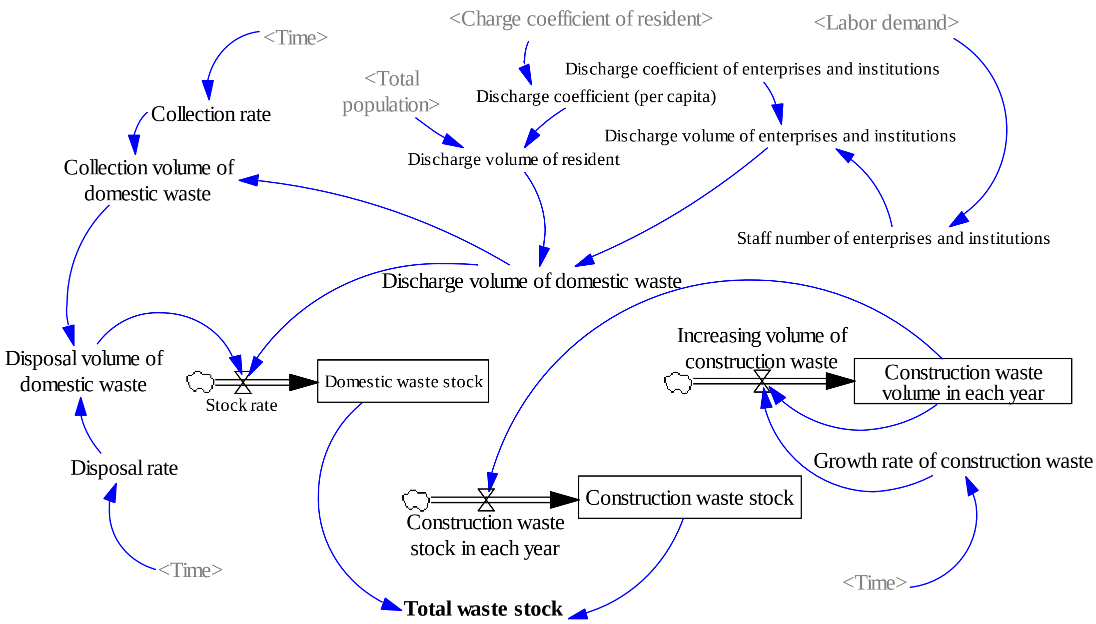

Figure-3 Waste Discharge Submodel

(3) Waste disposal submodel

From the point of sustainable development, running expenses of waste disposal are critical. The optimal disposal method is not only free from secondary pollution in disposal process but cheap in expenses. Therefore different combined modes are adopted in waste disposal according to different characteristics of waste in different types.

Waste disposal expenses are regarded as the core in this study, and waste disposal submodel is constructed according to possible variation method in current and future.

Waste disposal expenses=disposal expenses of domestic waste + disposal expenses of construction waste

1) Disposal expenses of domestic waste

Disposal methods of domestic waste cover five types: landfilling, composting, incineration, source separation and comprehensive disposal. They are with merits and faults respectively. According to current disposal system and the development trend of waste disposal method, combining form of the five disposal methods shall be adopted and adjusted gradually, so as to develop the better combined mode. Therefore the domestic waste disposal expenses are the sum of separated expenses in five methods combined with different proportions.

Waste landfilling expenses are determined by waste landfilling volume and unit waste disposal expenses (landfilling expenses index); landfilling volume is for the landfilling disposal adopted in total disposal volume. Calculation method of landfilling expenses is as follows:

Landfilling expenses=waste disposal volume*landfilling proportion*landfilling expenses index

Other expense calculation methods of four disposal methods are the same as those of waste landfilling.

2) Disposal expenses of construction waste

Great difference exists between construction waste and domestic waste in produce method, output and composition. Construction waste covers land clearing of construction engineering, removing of dilapidated or old building, earthwork excavation and construction waste et al. The composition is relatively single, pollution is relatively small. The disposal method is quite simple such as pit landfilling or simple stacking; So far the reuse rate is quite low. Therefore the disposal expenses are basically referred to the one-off paid landfill expenses.

Construction waste disposal expenses=landfill of construction waste*unit land acquisition costs

Landfill of construction waste=Construction waste volume in each year *land occupancy coefficient of construction waste

Unit land acquisition costs are variable with land resources consumption and market readjustment. Therefore it is time variable data and may be measure with statistical forecasting model.

Flow chart of waste disposal submodel on the basis of above-mentioned structural analysis is detailed in Figure-4.

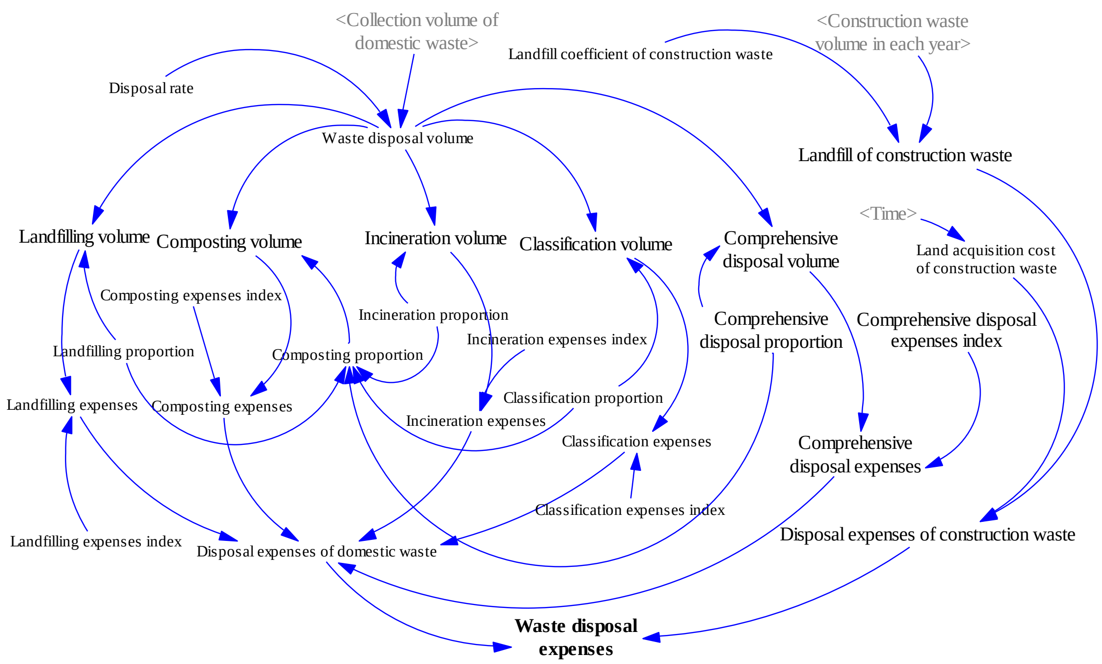

Figure-4 Waste Disposal Submodel

(4) Waste charging submodel

So far, the domestic waste charging of Beijing covers the construction waste charging, domestic waste charging for resident and domestic waste charging for organization.

Resident charge=total number of permanent population*charge coefficient of resident

Construction waste charging=construction waste volume in each year*construction waste charging coefficient

Mode of organization charge is diverse. Charge by vehicle number or weight calculation is generally adopted as the charge modes in Beijing. But dispute between waste discharge organization and waste-cleaning and disposal organization are always caused by such two modes. So charge by staff is the reasonable mode.

Charge according to staff number of enterprises and institutions are adopted in this study. The organization charge coefficient is actually measured according to staff, or it is determined by the per capita discharge volume of domestic waste corrected by activity rule of each person.

Model flow chart of domestic waste charging subsystem established according to the above-mentioned structural analysis is detailed in Figure-5.

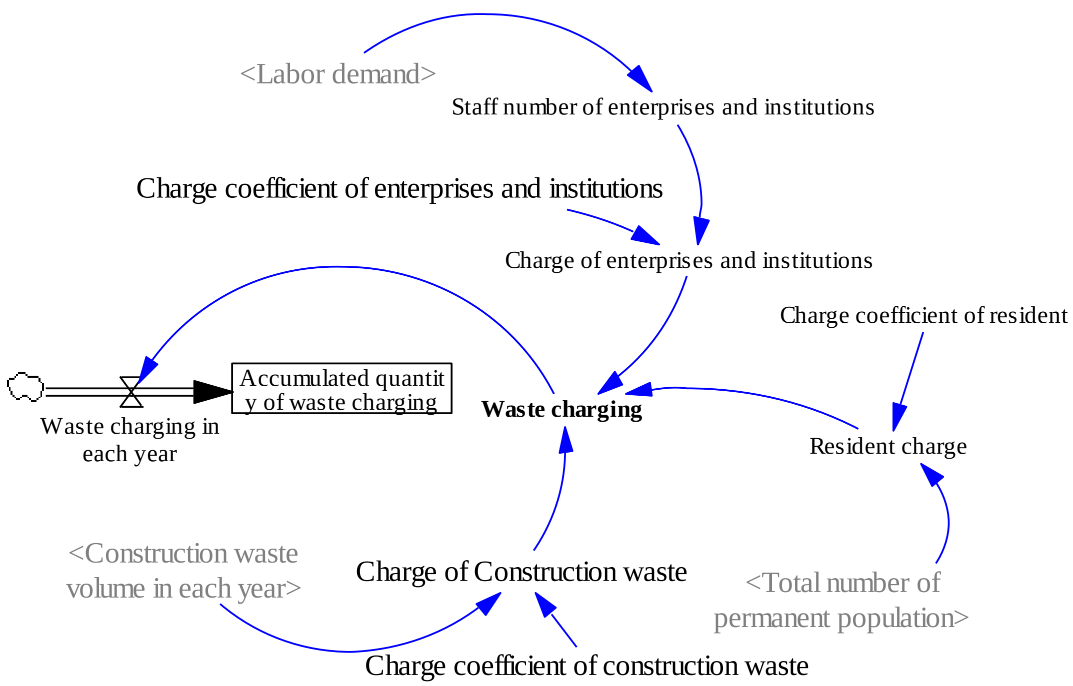

Figure-5 Domestic Waste Charging Subsystem

(5) Waste pollution and landfill loss submodel

Waste pollutant is discharged dispersively in regions, and complex in composition: not only with inorganic pollutant but organic pollutant, not only with general pollutants but hazardous waste. Increasingly serious environmental pollution loss and landfill loss are caused by waste discharge and pollution. Total loss of waste discharge covers accumulated total pollution loss and accumulated landfill loss.

1) Accumulated total pollution loss

There are two main reasons for the pollution loss; one is the environmental pollution caused by the non-collected waste scattered in vast urban and rural area and the other is the environmental pollution caused by collected waste which is not disposed timely or even not disposed bio-safely. Abundant water and air pollutants are produced from the waste which is not bio-safely disposed, the former may cause serious pollution and later dissipates easily causing relatively smaller pollution loss. Pollution of shallow groundwater is caused by infiltration of water pollutants, and the polluted water resource is difficult to be used, so the value loss of water resource is produced. As for the people live in the region with no other water resource, they have to use polluted water so their bodies are deeply damaged then health and labor loss are produced. Therefore the total loss caused by waste pollution covers pollution resource loss as well as the health and labor loss.

Pollution recovery expenses method is adopted in this study to calculate water resource loss caused by waste pollution.

Many methods may be used to calculate the health and labor losses caused by environmental pollution, such as opportunity cost rating method of environmental quality, recovery expenses method, extended antitheses of environmental quality, wage differential method, human capital approach, traveling expenses method and measurement method et al. The most used human capital approach is adopted to calculate health and labor loss in this study.

2) Landfill loss of waste discharge

Waste discharge not only leads to serious environmental pollution and pollution loss but also occupies abundant land resources and brings landfill loss.

Though landfill cost for dumping of construction wastes and collected undisposed domestic waste has been paid by municipal departments, this is only one-off payment, and cannot compensate for loss generated by landfill of waste. Therefore, it shall be counted in calculation of landfill loss for waste discharge.

As for uncollected domestic waste basically shattered in urban suburb, and the landfill cost has not been paid at all.

In addition, the occupied land shall give output annually, so the landfill loss of waste discharge is a kind of accumulated loss which shall be calculated with level variable.

Annual landfill loss=total landfill*coefficient of landfill loss

Accumulated landfill loss=INTEG (annual landfill loss and initial value of landfill loss)

Due to the great difference between landfill coefficients of domestic waste and construction wastes, the total landfill is calculated in two parts, one is the accumulated landfill of domestic waste and the other is that of construction wastes. Their calculation methods are as follows:

Accumulated landfill of domestic waste=domestic waste stock*landfill coefficient of domestic waste

Accumulated landfill of construction waste=construction waste stock*landfill coefficient of construction waste

Submodel flow chart of domestic waste pollution as well as landfill loss drawn on the basis of the above-mentioned structural analysis is detailed in Figure-6.

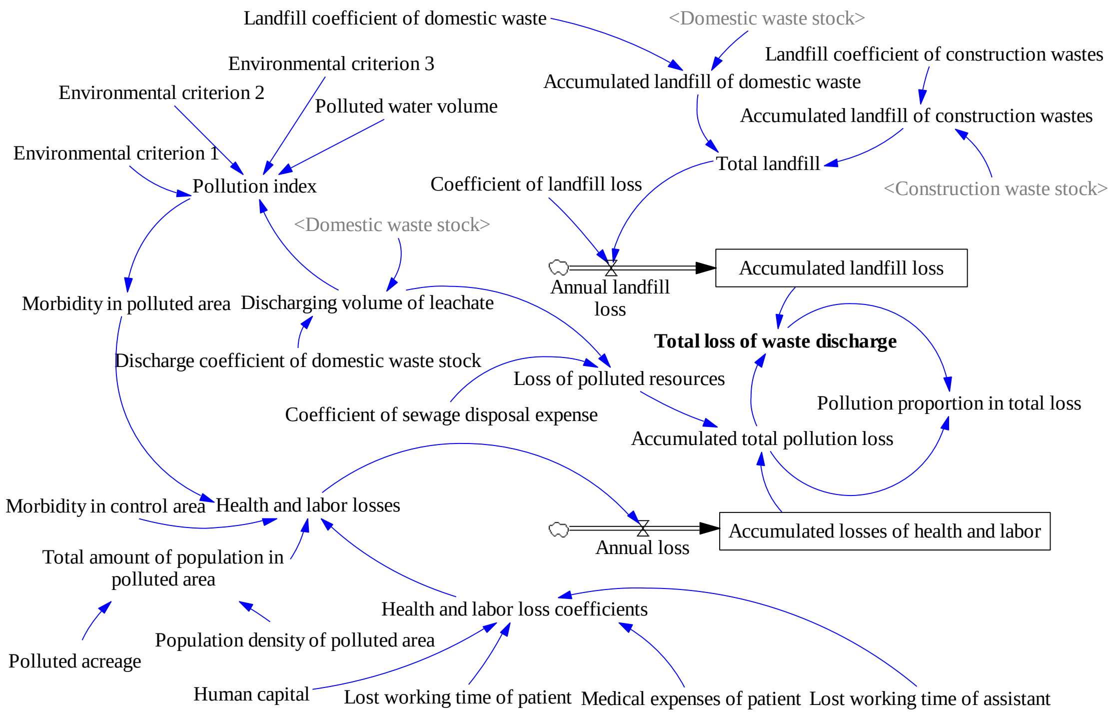

Figure-6 Submodel for Domestic Waste Pollution and Landfill Loss

(6) Submodel of macro economy and green GDP accounting

The gross domestic product (GDP) is most commonly used to measure the economic indicator in a country and region; however, the conventional economic accounting gives no consideration of the losses of resources and environment, which leads to the "distortion" of economic indicator, and what's worse, resources are reducing continuously, pollution is increasingly serious, ecology is deteriorating rapidly, and invisible economic losses are escalating. Therefore, the exploration of green GDP accounting method is of great importance.

The so called green GDP refers to the difference between the current statistic GDP and the economic losses caused by factors such as environmental pollution and natural resource degeneration. Compared with general GDP, the green GDP may be understood as the "actual GDP" which reflects not only the quantity of economic growth, but also its quality; it is able to measure the actual development and improvement of a nation and region more scientifically.

The general formula of green GDP accounting is as follows:

Green GDP=GDP-resource consumption and damage losses-pollution damage loss

Thereinto, resource consumption loss refers to the loss of resource reduction; damage loss refers to the loss cause by the damage of resource and its associated ecological environment during the process of resource exploitation and utilization; and the environmental pollution damage loss covers the damage losses on resources, production and health and welfare of people.

As a result of no compensation or little compensation for the resource and pollution damages cause by waste discharge, it is apparent that the mere reduction of damage loss in the current year cannot reflect the perniciousness of waste discharge. Therefore, the accumulated values of the annually resource consumption and damage loss and the annually pollution damage loss in the current year are adopted in the submodel.

Green GDP accounting formula adopted in this model:

Green GDP=economic aggregate-total loss of waste discharge

Thereinto, the total loss of waste discharge has been determined above. It is the sum of accumulated landfill loss and accumulated total pollution loss and may be used directly.

The economic aggregate can be calculated by several methods, and the statistical model is adopted generally in order to make a prediction. However, in the actual economic development, a certain proportion of capital is always prepared for the disposal of environmental pollution, moreover, it belongs to intermediate expenditure, and no value-added effect will be generated. Therefore, Definition of economic aggregate in this research is as follows:

$$GDP_i = \sum_{i=0}^{n} \left[GDP_{i-1} + \Delta GDP_i \right]$$

$$\triangle GDP_i = (GDP_{i-1} - \text{Annually waste disposal investment}) * R_i$$

Where, GDP_i - the economic aggregate of certain year, RMB 00,000,000; $\triangle GDP_i$ - the annual economic growth, RMB 00,000,000; R_i - the growth coefficient of certain year, %; n= 1,2,3…

The annual GDP growth is influenced by the annual waste disposal investment. The greater the waste disposal investment is, the less the economic growth is. In essence, as the difference between waste disposal expenses and waste charging, the annual waste disposal investment is a kind of fiscal subsidy for waste disposal.

When the waste disposal expense is greater than the waste charging, fiscal subsidy will be in need; and a certain amount of fiscal surplus may be obtained when the waste disposal expense is less than the waste charging. However, the actual condition is that a certain amount of fiscal subsidy is in need annually.

Submodel flow chart of macro economy and green GDP accounting established according to the above-mentioned discussion and analysis is detailed in Figure-7.

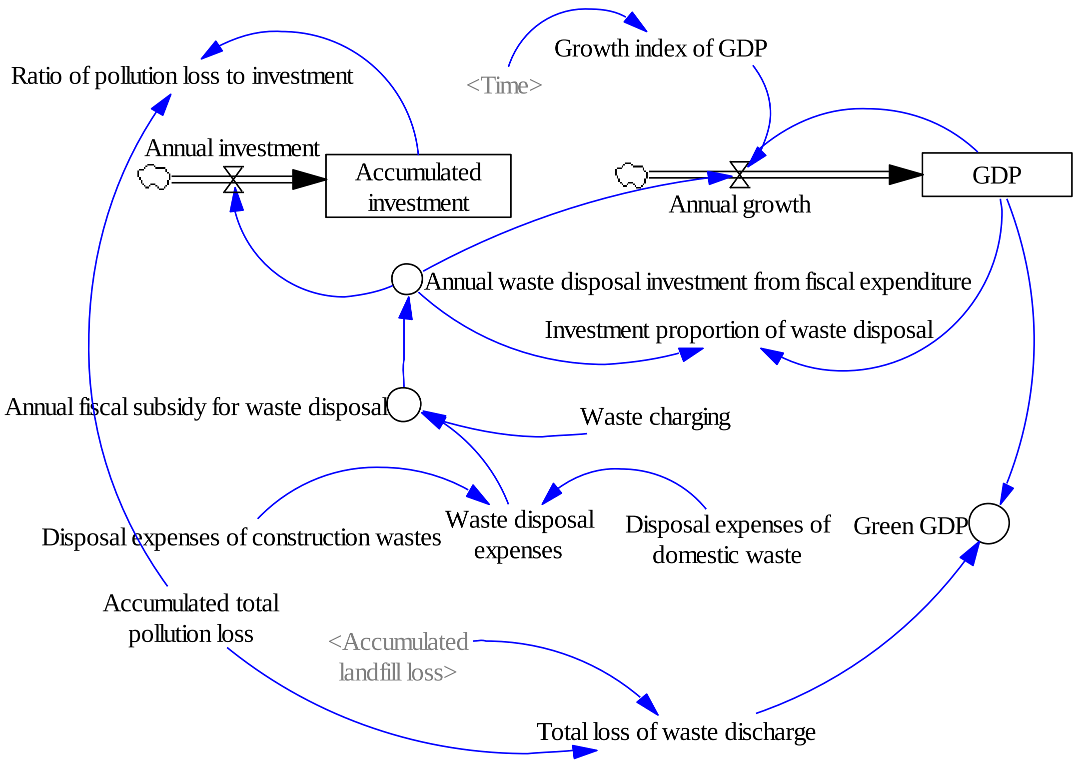

Figure-7 Submodel for Macro Economy and Green GDP Accounting

3.3 Simulation analysis and discussion

The above submodels are established in the model window of Vensim software and combined into a general model. Beijing social, economic and resource environmental data in 2000 are utilized to debug them. Through theoretical inspections such as consistency between the model structure and the real system, consistency between the equation and dimension, and strength inspection of model structures as well as the consistency between the model behaviors, namely historic inspection, display model behaviors better represent the conditions of the real system and may be used for trend simulation and policy regulation analysis.

The basic thinking for the simulation analysis are as follows: the simulation discussion is carried out according to the current state to observe the consequences of the current policy so as to decide whether the regulation is necessary; after the adjustment of the population and economic growth rate, the simulation discussion is carried out so as to form relatively normal socioeconomic development posture; and then the collection rate and disposal rate are adjusted to observe the waste discharge loss. According to the criteria of minimum waste discharge and pollution loss, better policy mix is strived for.

(1) Simulation analysis on current constant policy

China conducted the fifth census in 2000 and the first economic census in 2004. Both of them can correct the relevant data of socioeconomic statistics in 2000. Therefore, simulation and analysis of current trend should be based on the data in 2000.

1) Changes of economic aggregate

Economic development is the key to promote sustainable development of cities. Beijing's continuously increasing capital investment makes its technological progress notable and labor productivity gradually raise. Over the years, the GDP growth rate has mainly remained above 10% and the economic aggregate has been growing. Under the assumption of 10% economic growth rate, Beijing's economic aggregate will reach RMB 2,653.35 billion until 2025 and RMB 28,539.7 billion until 2050. With the economic development, the total waste discharge loss also has a massive growth. (Figure-8)

It may be possible to achieve 10% economic growth rate in the first 25 years for Beijing's economic growth rate was 12.3% in 2007, 9% in 2008 and 10.2% in 2010. However, it should have a certain difficulty in continuing to maintain the 10% economic growth rate and make economic growth reach rapid growth after 2025.

The reason is that Beijing is a city with water shortage. Its energy resources basically rely on foreign supply and the reserved land resources are very limited. Therefore, the economic growth rate will continue to fall because of its water resource, energy resources, and land resources et al constraints.

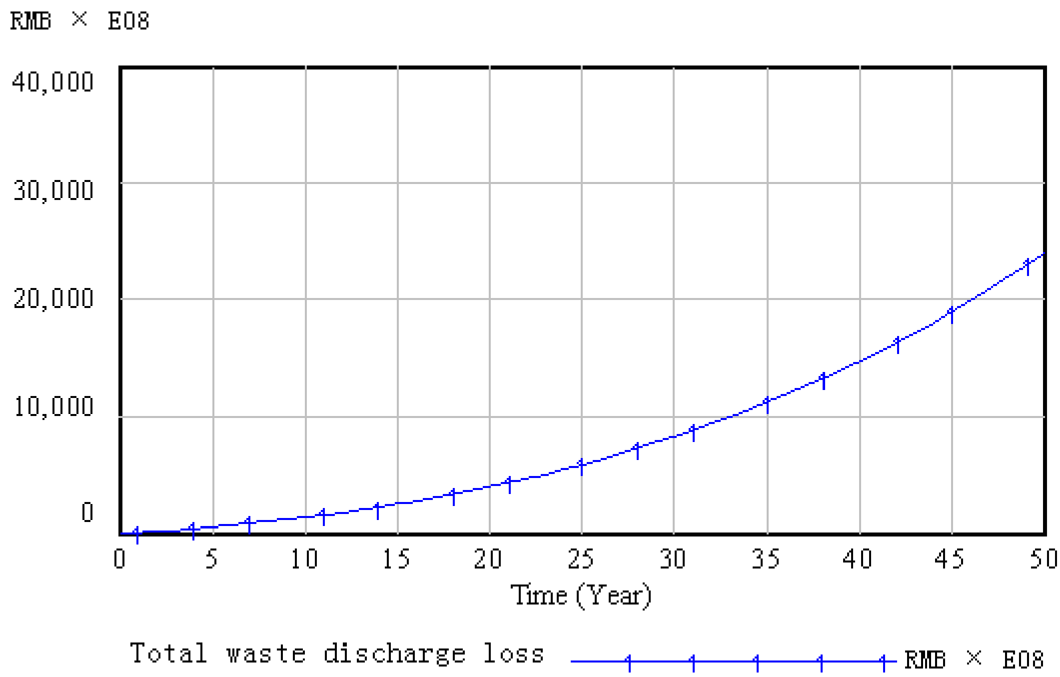

Figure-8 Total Waste Discharge Loss in Beijing

2) Changes of population

The simulation results of Figure-9 show that the total population in 2010 would reach 18,140,000. It began to exceed Beijing's certain capacity of 18,000,000. Until 2025, the permanent population will have been more than Beijing's certain population capacity when the population is 18,636,000. And by 2050, the permanent population will reach 22,439,000 and be 4,439,000 more than the population capacity.

In the population growth of 2010, the growth of permanent population is 125,000, occupying about 35% of total population growth. The growth of floating population is the major factor of Beijing's population growth. And the conclusion is the same with the fifth census in 2010.

Currently, Beijing is working out various measures to control the growth of floating population.

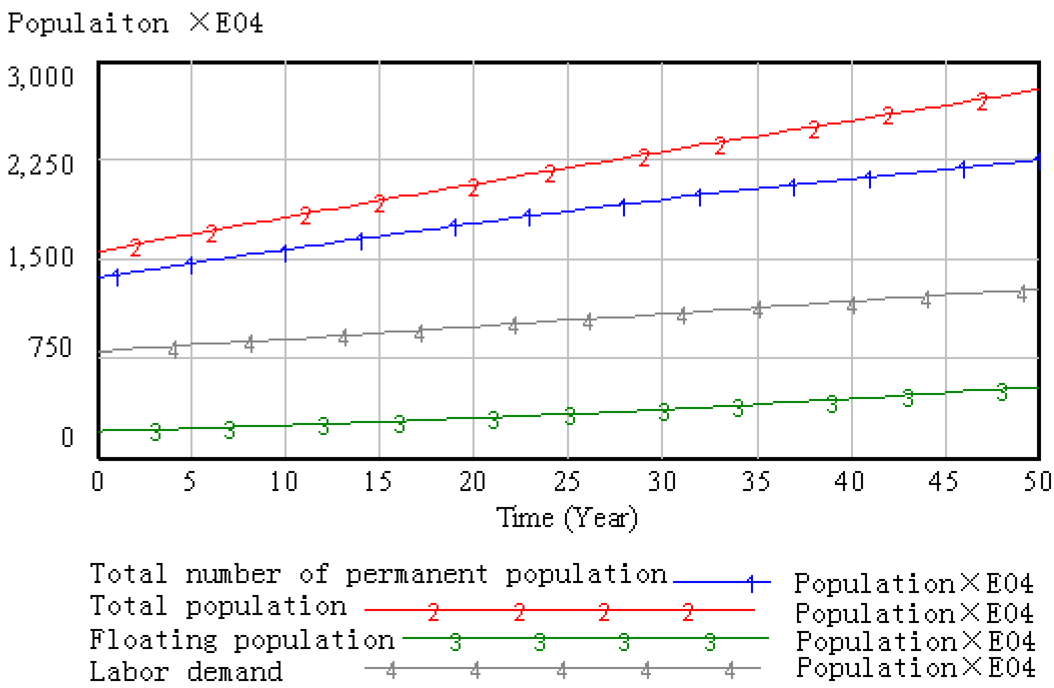

Figure-9 Changes of Population and Labor Demand in Beijing

3) Changes of waste charging, investment and pollution loss

Figure-10 shows the changes of Beijing's accumulated waste charging, accumulated financial investment and accumulated total pollution loss. From the trend, accumulated waste charging is continuously increasing while the accumulated financial investment is continuously decreasing; in addition, the accumulated total pollution loss caused by waste discharge is surging.

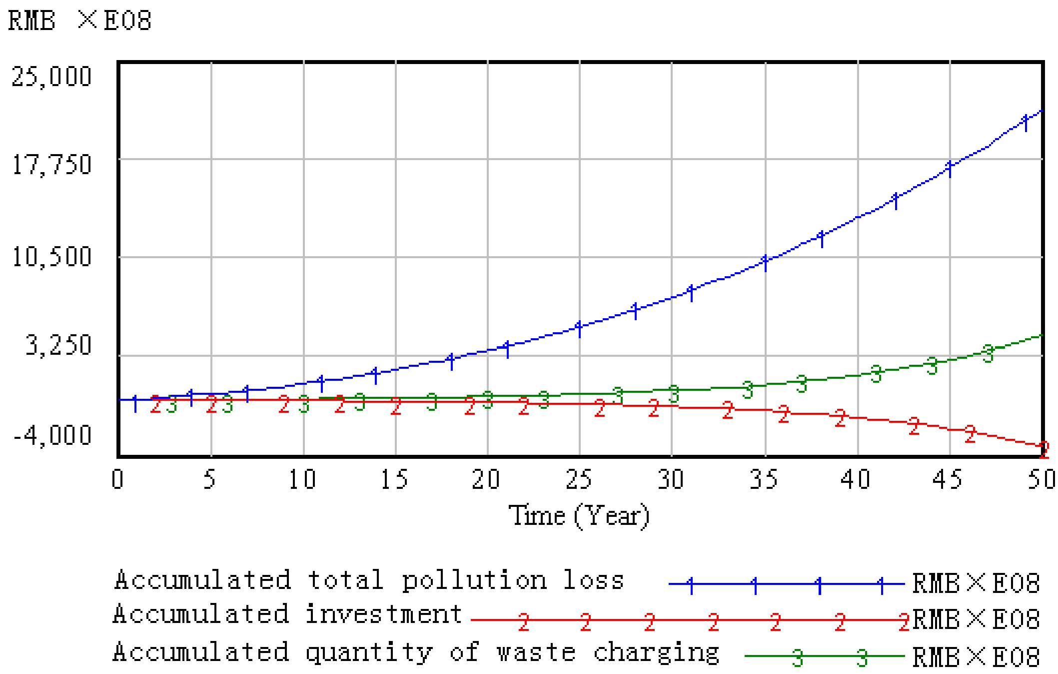

Figure-10 Accumulated Waste Charging, Accumulated Financial Investment and Total Waste Discharge Loss

The reason for the surging of accumulated total pollution loss is that the economy is growing at a rate of 10%, resulting in large population into Beijing, continuous growth of total population and rapid rise of waste output. The waste pollution will get worse and the waste pollution loss will increase under the condition of maintaining the current collection rate and disposal rate of domestic waste.

The reason for the increasingly decreasing accumulated financial investment and even surplus is that the accumulated financial investment is accumulated by the difference between waste charging (domestic waste charging + construction waste charging) and waste disposal expenses (domestic waste disposal expenses + construction waste disposal expenses). The output of construction waste grows at a rate of 10% and the charge of construction waste is high (the charge for waste-cleaning per ton is RMB 16), while the disposal expenses of construction waste are low (the land-use fees per mu is just RMB 86,700). Therefore, construction waste disposal has surplus. Such surplus exceeds domestic waste disposal expenses under the low collection rate and domestic waste disposal rate so that accumulated financial investment continuously falls and even has surplus. That is, in fact, financial investment is negative. Finance is actually profitable if the waste collection rate and disposal rate won't be improved.

Obviously, such conditions are unsustainable; relevant policies must be changed, collection rate and bio-safety disposal rate of domestic waste must be increased and total environmental pollution loss caused by domestic waste discharge must be minimized.

(2) Simulation analysis of policy mix

1) Result of adjusted economic and construction waste growth rates

Provided that the economic and construction waste growth rates both are 10% in the 50 years to come, the above-mentioned simulation result with a stable trend is achieved, which is absolutely improbable to be true.

The law of world economic development indicates that thanks to the comparative advantages, the economy always develops faster at the early stage, and when the economic growth reaches a certain level, the economic growth rate begins to decline and takes on "inverted S-type" growth feature with weakening comparative advantages and diminishing marginal return (effect). For many years, the economic growth rate in Beijing has been maintaining at 10%, for one reason of a smaller economic scale and for the other of the driving role of the Olympic economy. After the 2008 Olympics, the economic growth rate shall takes on gradual decline trend. By around 2025, the economic growth rate shall be about 6%; after 2035, the economic development level in Beijing will basically reach that of the world's moderately developed countries in 2000 and the economic growth rate shall be about 4.5%.

The construction waste increase has a close relation with the economic development scale and level. Since the reform and opening-up especially the 1990s, due to the economic development demands, accumulated citizens' housing problems in the past decades as well as the driving role of Olympic economy, the architecture industry in Beijing develops by leaps and bounds, which in turn leads to the construction waste output at a higher level. However, the total output of construction waste will also gradually decrease as the economic development speed slows down, the urban redevelopment scale diminishes, the internal population in urban areas moves outward and the Olympics came to an end. And its growth rate takes on a basically similar change trend with the economic growth rate.

According to the above-mentioned trend analysis about the economic and construction waste economic growth rates in Beijing, the economic and construction waste economic growth rates are set through the table functions so as to observe changes of the economic aggregate and total population.

After the economic and construction waste economic growth rates are adjusted, the simulation prediction results of the economic aggregate, population change and waste charging & investment indicate that the economic aggregate in Beijing will drop from RMB 28539.7 billion in 2050 to RMB 3219.62 billion. The main difference in changes of economic aggregate growth takes place in years after 2025; and before 2025 the economic aggregates of the two economic growth rates show little change 2025 later on the gap gradually becomes wider.

Before 2025 the total population is almost the same and 2025 later on takes on a slight drop. By 2050 the total population after the adjustment of economic growth rate is 25.028 million and drops by 8.94% or 2.458 million compared to 27.486 million with the economic growth rate of 10%; but it exceeds the limit of the certain population capacity (18 million) in Beijing. At present, effective measures for controlling population growth have not already been available.

Seen from Figure-11, after the economic and construction waste economic growth rates are adjusted, the accumulated quantity of waste charging falls down and the fiscal surplus is also reduced mainly owing to the reduced construction waste output.

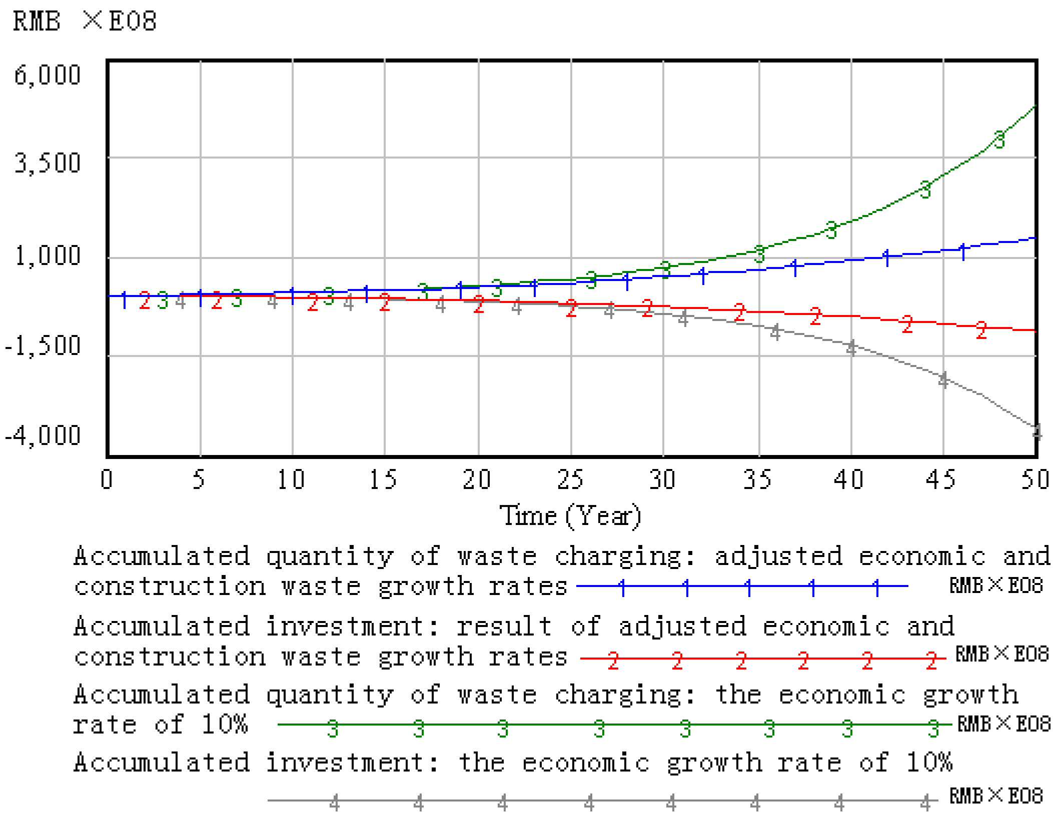

Figure-11 Waste Charging & Pollution Loss Result Comparison of Adjusted Economic and Construction Waste Growth Rates

In a word, by adjusting the economic and construction waste growth rates, the population, economic development and waste disposal system in Beijing are basically at a relatively reasonable state.

On the basis of the determined state above, changes of total population, economic aggregate, green GDP, accumulated total pollution loss and accumulated financial investment/ subsidy of waste disposal can be studies under different waste collection rates, waste disposal rates as well as disposal methods.

2) Simulation analysis of policy mix under different states

A. Setting of relative parameters

The relative parameters that may be adjusted include waste collection rate, bio-safety waste disposal rate, proportion of waste disposal methods and land-occupation cost index of construction waste et al. And all the above-mentioned parameters will be adjusted according to relevant programming in Beijing.

- Waste collection rate. It is adjusted from approximately 50% in 2000 to 100% in 2010.
- Bio-safety waste disposal rate. It is adjusted from 81.5% in 2000 to 100% in 2010.
- Proportion of waste disposal methods (including incineration, landfilling, comprehensive disposal, composting and source separation). It is adjusted from 0:95%:3%:2%:0 in 2000 to 40%:30%:30%:0:0 in 2010 and to 40%:10%:30%:0:20% in 2025.
- Land-occupation cost index of construction waste. The land used in the previous simulation costs RMB 1,300,500 per hectare. However, as far as the actual growth conditions for the eight kinds of land acquisition costs in Beijing from 2000 to 2003 is concerned, the annual growth rate of land cost is about 3%; therefore, the landfill cost of construction waste should also go up along accordingly.
  Land-occupation cost index of construction waste is $8.67 * (1 + 0.03)^{T}$.

The above-mentioned parameters are input to the model for simulation and calculation and the simulation results will be defined as overall adjusted results.

B. Results of overall adjusted parameters

a. Total population

After the parameters are overall adjusted, the population change trend from 2000 to 2050 in Beijing is detailed in Figure-12, from which a fact is indicated that growth of the total population is slowdown but the total population are still increasing since 2025.

The total population is 18.222 million in 2012 which starts to exceed the population capacity in Beijing; 20.106 million in 2020 which starts to exceed 20 million; 25.028 million in 2502.8 which increases by 64.3% compared with that in 2000.

The simulation results also show that growth of the total number of permanent population will basically reach the balanced state around 2035 and will remain about 20 million. The main reason bringing the continuous growth of total population is the sustained growth of floating population.

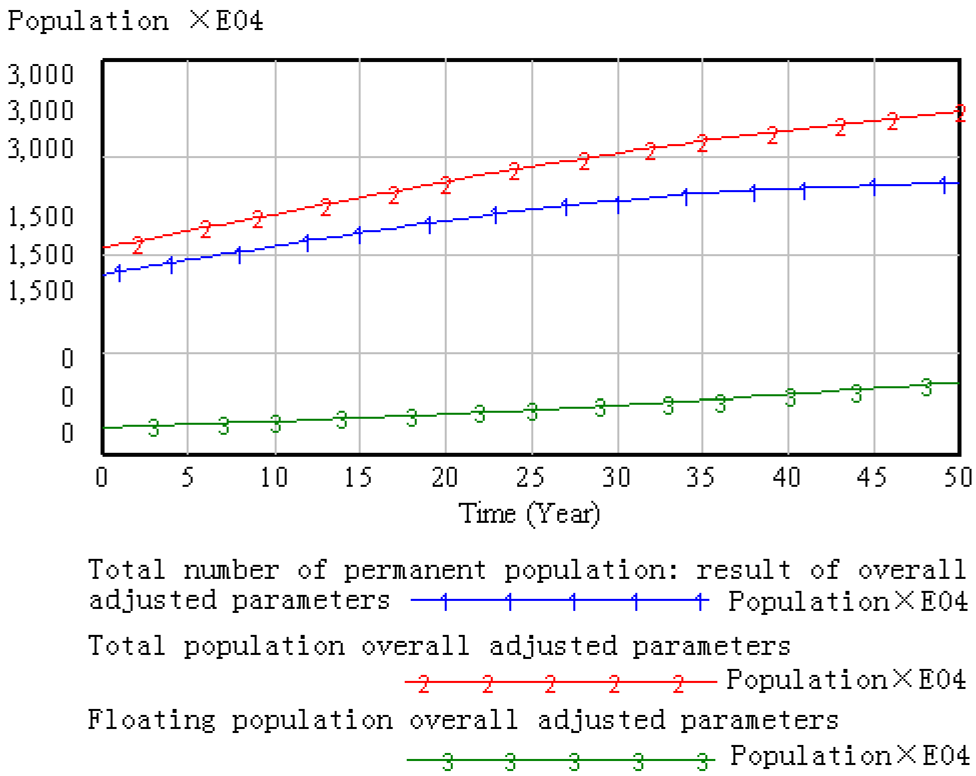

Figure-12 Population Change of Overall Adjusted Parameters

b. Economic aggregate and green GDP

The simulation results in Figure-13 show the economic aggregate takes on S-type growth trend. The economy grows relatively fast before 2025 and trends to slow down 2025 later on with basically reaching a balanced state in 2050. The green GDP basically keeps up with growth of the economic aggregate before 2025 and trends to slow down after 2025 with achieving the peak point around 2035 and then begins to decline at an increasing speed. As a result, the gap between green GDP and economic aggregate gets wider.

Changes of the green GDP are closely bound up with the total loss of waste discharge. The total loss of waste discharge clearly takes on index-rising feature in Figure-13, which is the main reason causing the sharp decline of green GDP after 2035.

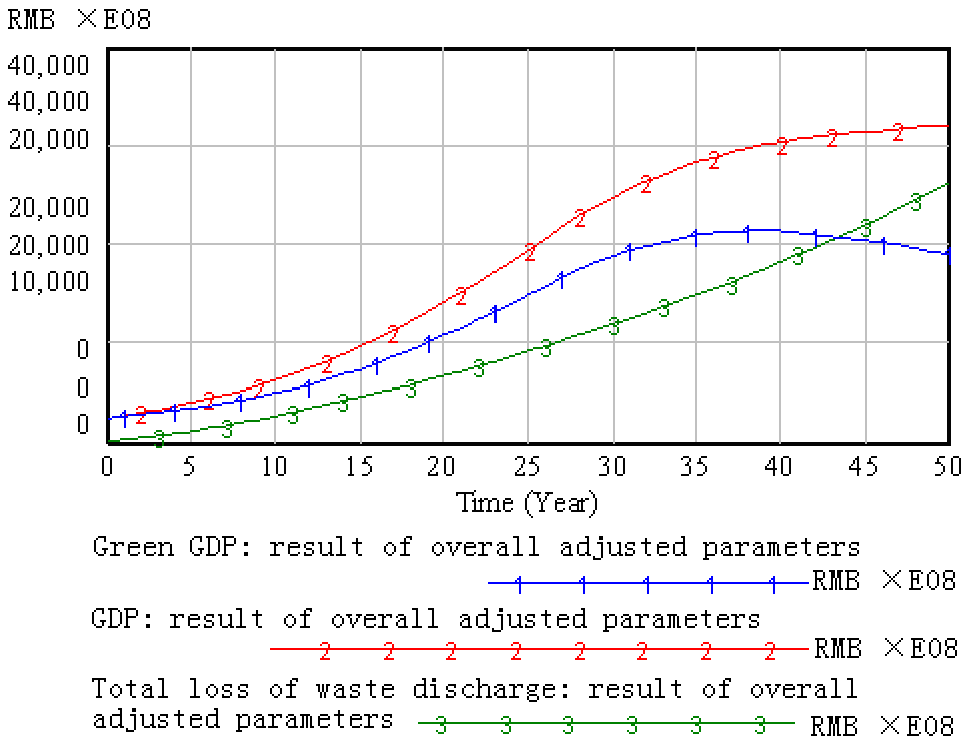

Figure-13 Changes of Economic Aggregate, Green GDP and Total Loss of Waste Discharge

c. Accumulated total pollution loss

Seen from Figure-14, after relative parameters are adjusted, the total loss of waste discharge has a significant drop especially after 2025 and takes on a more apparent dropping trend. This proves that there are close relations among total loss of waste discharge, economic scale & economic development speed and construction waste discharge.

The accumulated total pollution loss accounts for a great share in the total loss of waste discharge but continuously drops, which shows as the waste disposal is strengthened, the accumulated loss caused by waste pollution is reduced continuously. On the contrary, landfill loss caused by landfill of waste is quickly increasing.

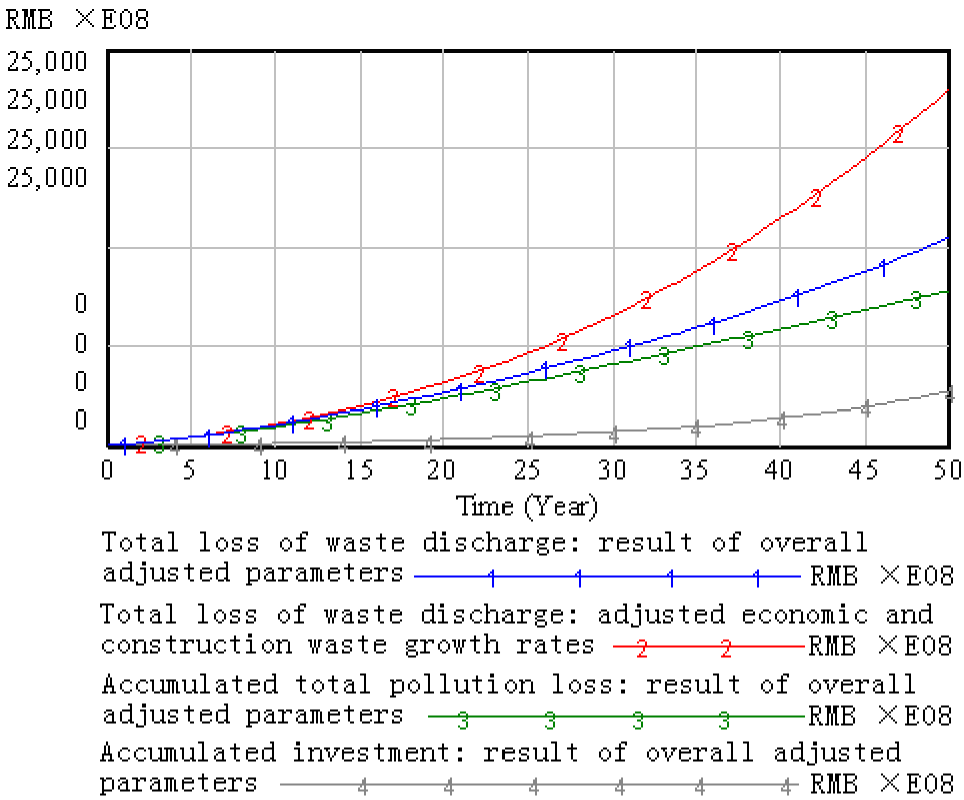

Figure-14 Changes of Waste Discharge Loss

d. Change of accumulated investment (fiscal subsidy)

The simulation results after the waste disposal plan is overall adjusted indicate that according to the current charging standard of construction waste cleaning of RMB 16 per ton, fiscal accumulated the waste disposal investment is continuously rising (see Figure-15) with reaching RMB 4.563 billion in 2025 and RMB 39.409 billion in 2050 respectively. And this year the waste disposal investment occupies 0.12% of the economic aggregate's GDP.

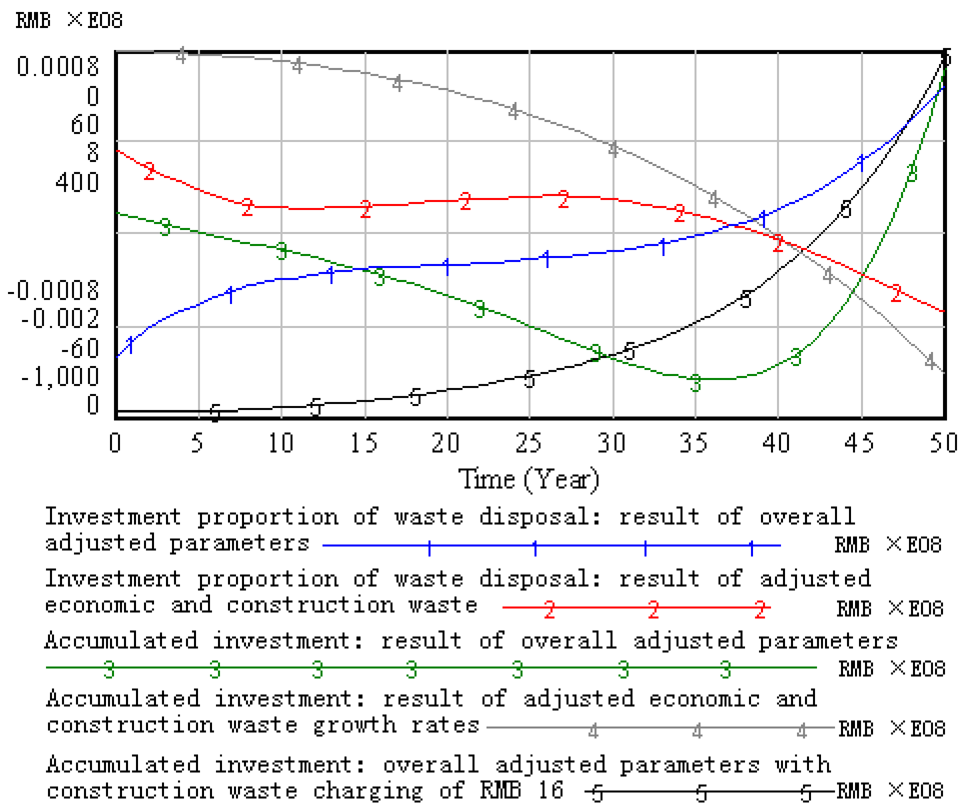

Figure-15 Changes of Accumulated Waste Disposal Investment & Investment Proportion

If the charge of construction waste cleaning is RMB 20 per ton, the waste disposal investment will have balance, which will reach RMB 3.006 billion in 2025. And around 2035 the accumulated investment balance from waste charging begins to decrease and the investment proportion of waste disposal begins to turn to positive from the original negative. By 2046, the previous balance from waste charging will be totally put into the waste disposal; every year the fund expenditure from the fiscal revenue will be used for waste disposal with a very rapid growth trend and its gross amount will reach RMB 5.473 billion in 2050.

3.4 Preliminary conclusions

The study on the management system is sponsored by the Beijing Municipal Commission of City Administration and environment. Because the model is still under expansion and adjustment, only a small part of the simulation analysis is displayed above. However, by means of various policy mix simulations, the following preliminary conclusions may be obtained.

(1) The system dynamics is focused on studying the relationship among municipal waste, population and economic development. The flexibly adjusted management system (referred to the model built in this study) boasts of special advantages. It can put various relevant factors into one system to be considered; possessed of a great many policy adjustment port, it can be used not only to carry out various policy mix simulations but also to make and evaluate the charging policy of domestic waste as well as to carry out the green GDP accounting for waste discharge and disposal system. Therefore, this model is a favorable municipal waste management strategy and provides a favorable platform for regulating the strategy simulation.

(2) The operation mode of domestic waste management system in Beijing has a relatively

small effect on its population size, while change of the population size affects the waste disposal and management greatly, especially for waste disposal investment. So controlling the population size in Beijing will contribute significantly to the stable operation of the domestic waste management system.

(3) Because the birth rate in Beijing is very low, the number of births grows slowly. The growth of permanent population in Beijing mainly results from the sustained growth of floating population and the economic development demand serves as the very drive for the sustained growth of floating population. Under the current economic development model, for the purpose of maintaining higher economic development speed as well as reducing the population immigration rate, the labor productivity must continue to be improved and the employment elasticity to be reduced, namely, the labor demand quantity of unit GDP value added shall continue to be reduced.

(4) The theories and methods of the green GDP accounting are introduced to the municipal waste management system, so the effects municipal waste disposal and management may be observed from a macroscopic viewpoint, thus helping to provide a new benchmark for the evaluation of municipal waste management system.

(5) The total loss caused by waste discharge in Beijing takes on index-rising feature. Therefore, although the green GDP grows along with the economic aggregate, if the domestic waste disposal investment cannot be gradually increased and the bio-safety disposal rate cannot be improved, the gap between green GDP and economic aggregate will become more wider and even they are likely to decline rapidly.

(6) The loss caused by waste pollution accounts for a great share in the total loss of waste discharge. Therefore, the waste collection rate and bio-safety disposal rate must be rapidly improved so as to decrease the environmental pollution loss caused by domestic waste discharge.

(7) In the current waste-charging management system, the main source of waste charging is the disposal charge of construction waste which as a sensitive factor has a great effect on fiscal subsidy for waste disposal and the disposal charge for the residents is lower while disposal charge for organizations' domestic waste discharge has not be collected yet. Therefore, the waste charging standard needs to be improved and the waste charging system to be perfected by means of establishing a combined charging method for residents' domestic waste discharge and construction waste discharge as well as organizations' domestic waste discharge so as to realize the balance among waste disposal investment, waste discharge charge and government's fiscal subsidy and to guarantee the persistent and stable operation of the municipal waste disposal and management system.

4 Future Prospect

(1) At present, with a relatively small number of studies focusing on system dynamics in municipal waste management system in China, the system dynamics study is still in its infancy. And the available studies still mainly focus on the model building and simulation while less attention is paid to the dynamic behavior analysis and sensitive factor determination in the model, so a large amount of work still needs to be done. In addition, as the urbanization process in China speeds up and number of big cities continuously increases, there will be more users in favor of system dynamics in municipal waste management system.

(2) Possessing of a good many advantage, the system dynamics wins universal preference

from the publics. However, currently in China, simulation results of studies that use system dynamics to investigate the urban domestic waste issue are generally one-dimensional and the suggested combination of policies is non-optimized, so how to obtain data from the space system to automatically display the simulation results at the two-dimensional and three-dimensional spaces and how to combine with optimization techniques to achieve the optimized policy mix still need to be further explored.

1) Combination of SD model and "3S" technologies

For the present, in the municipal waste management system, management statistics on various sanitary facilities basically relies upon manpower, which not only results in lots of work for the managers but also leads to great difficulty with regard to programming, decision-making and management because the management departments have great difficulty in carrying out real-time supervision for decades-long sanitation facilities, new and rebuilt sanitation facilities as well as the operating efficiency. Therefore, carrying out scientific and information management for municipal waste by adopting modern space simulation technology becomes more and more important. If the remote sensing (RS), geographic information system (GIS) and global positioning System (GPS) are combined together with the powerful data prediction ability of the system dynamics, a "live" system will be achieved which is dynamic, visible and continuously updated as well as three-dimensional and which is transmitted through computer network and can be adopted in different regions and levels. In particular it is suitable ,on the one hand for optimizing and managing the arrangements on municipal waste collection point, transfer station and disposal site; on the other for predicting and forecasting waste discharge and pollution as well as evaluating the management system.

2) Combination of SD model and optimization techniques

If the SD model could be combined with system optimization methods such as multi-objective programming (MOP), fuzzy pattern recognition (FPR) and inexact fuzzy multi-objective programming (IFMOP), then it will be able to obtain optimized policy mix and improve the efficiency of municipal waste management.

3) Safety and early-warning of municipal waste management system

The social economy develops towards high-level and complicated direction and climatic changes will result in more sudden disasters, more and more attention shall be attached to the safety and early-warning problems. Therefore, in order to guarantee the safety with respect to population, resources, environment and social economy and to realize the sustainable development in urban areas by discovering and solve problems in advance during the process of municipal waste disposal and management, not only prediction but also a set of monitoring, early-warning and emergency-response mechanism is required.

Studies of system dynamics with regard to municipal waste management can be greatly advanced if the system dynamics can be combined with emergency judgment methods, utilize its advantages predict the behaviors of complex dynamic feedback systems, and monitor the municipal waste management system with early alert.

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