USING SYSTEM DYNAMICS IN DECISION SUPPORT FOR SUSTAINABLE WASTE MANAGEMENT

LIU RONG

(B. Eng.)

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SUMMARY

The accelerating pace of technological advancement and the concern of protecting our limited natural resources are moving our society to address the issue of sustainability. Many countries have adopted the concept of sustainable development where "the needs of the present generation are met without compromising the ability of future generations to meet their own needs." (Brundtland Report, 1995).

One of the most important points of sustainable development is the interaction between the natural environment and human beings, which is most intense in rapidly urbanizing areas. Therefore, the emphasis of sustainable development should be on the urban areas. The increasing number of residents living within cities needs more and better services from infrastructure facilities and consumes more natural resources that are already scarce in some places. Among the infrastructure systems, waste management facilities have become a serious concern in most countries. It follows that the way in which we manage our resources and dispose of the waste can make an important contribution to sustainable development.

The planning of waste treatment/disposal facilities is usually addressed at the municipal level, where decision makers should plan an effective strategy, taking simultaneously into account a number of conflicting objectives, such as cost, environmental and social considerations. Finding acceptable strategies or plans involving these objectives is critical to satisfy the requirement of sustainability.

This dissertation proposes a decision support approach to aid municipal decision makers in setting their strategies about the building of waste treatment/disposal facilities. It conjointly uses two methods of SD (System Dynamics) and AHP (Analytic Hierarchy Process).

Firstly, a SD simulation model is formulated. In order to support the choice among the alternative plans, the information about the performances of the alternatives over the planning duration is required. SD is an effective method to simulate and forecast the performances of the plans. The SD model can simulate the long-term impacts of each alternative plan, on the aspects of cost, environment, recycling, and social involvement. It enables decision makers to gain better insight into the dynamic behavior inherent in the proposals.

Secondly, the AHP method is used to make a multi-criteria evaluation of each alternative based on their simulated performance, and select a preferable one among them. It takes advantage of pairwise comparisons conducted within a decision hierarchy developed through the AHP methodology. The AHP method helps to make explicit the assumptions and preferences of the decision makers with respect to desired outcomes and the impacts of the plans, and removes much of the subjectivity involved in the decision-making.

The decision support approach is targeted at macro-level planning and should be viewed as being complementary to other traditional planning tools used for more detailed planning. In the dissertation, its application is illustrated through a hypothetical case study involving selection among alternative plans for building waste management facilities under different scenarios.

Key words: *waste management facility planning, decision support, system dynamics, simulation model, AHP, sustainable development*

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CHAPTER 1

INTRODUCTION

1.1 Sustainable waste management

1.1.1 Sustainable development and sustainable infrastructure

The accelerating pace of technological advancement and concern for protecting our limited natural resources are encouraging our society to consider the issue of sustainability in the provision of basic public services. Many countries have adopted the concept of sustainable development where “the needs of the present generation are met without compromising the ability of future generations to meet their own needs.” (Brundtland Report, 1985). Sustainable development has become an important international and national approach to integrate economic, environmental, social considerations in sustainable planning to ensure that both the present and future generations can enjoy a good quality of life.

The meaning of sustainable development continues to evolve, and often contains different emphasis depending on the point of view. Environmentalists consider resource conservation as the most important issue in sustainability, insisting that economic development cannot occur at the expense of the environment, and that current utilization of resources should not compromise resource availability for subsequent generations. From the viewpoint of engineers, sustainability requires that engineering be practiced in a way that takes into consideration long-term effects and incorporates the protection of the natural environment. Fundamental changes to the mindset of engineers have been urged, and they are now exhorted “to take the lead as the managers of sustainability; to see that technological applications incorporate sustainable development concepts; to be innovative in planning so as to create projects that enhance the natural environment; and to protect natural resources; and restore natural systems." (Wright, 1996) However, pragmatism in sustainable development also requires compromise between the needs of the natural environment and that of human beings.

Sustainable development incorporates a series of actions taken in response to the trends caused by overpopulation, improved technology and overuse of natural resources. It generally includes three important aspects: a) financial sustainability, b) environmental sustainability, and c) social sustainability. It is about achieving economic growth, environmental protection, and social progress at the same time. The practice of sustainable development can help create new thinking processes and approaches to meet our needs "without conflicting the environmental health, human well-being, and the economic bottom line." (Daigger et. al, 2001). The main goal of sustainable development is to improve our quality of life. A sustainable development strategy should rest on four key elements: a) effective protection of the environment, b) prudent use of resources, c) social progress that meets the needs of all, d) high and stable levels of economic growth and employment. (UK Department of Environment, 2000).

One of the most important aspects of sustainable development is the interaction between the natural environment and human beings, and the realization that most intense interactions usually take place in urban areas. There is now heightened awareness of the need to consider the elements of sustainability in the planning and development of infrastructure systems that support life in urban settlements. (O'Neal, 1993). Engineering plays an important role in sustainable development through the planning and construction of projects that preserve natural resources, are cost-efficient, and support the human and natural environment (WFEO, 2002). Engineering contributes through the following aspects:

- Resource development and extraction: improving the engineering planning to process natural resources efficiently and with little or no waste to preserve the earth’s finite natural resources;

- Meeting consumer needs: providing clean water, energy, housing and high quality waste management that meets acceptable health standards;

- Transportation infrastructure: designing and building the transportation infrastructure to transport resources and goods efficiently with minimal negative impact on the surrounding land use and to serve the needs of consumers with little waste;

- Resource recovery and reuse: reusing and recycling resources to reduce waste, minimizing long-term impacts of waste, designing better solid waste collection and storage facilities, and improving treatment facilities for waste;

Civil engineering professionals play an important role in creating a sustainable environment through their involvement in the design, construction and maintenance of projects that affect the physical and natural environment. It has been argued that sustainable development is now absolutely central to the practice of civil engineering (Jowitt, 2004).

Civil engineering projects consume a significant amount of materials and energy. They contribute to building the infrastructure needed for our lifestyles. It affects the condition and use of land, which is one of the resources exploited. They generate a large amount of demolition wastes. Civil engineering can make significant contributions to sustainable development by improving construction and civil engineering design practices, by developing the best practice in site-based waste minimization processes, and supporting the use of recycled materials in constructed facilities.

One of the crucial roles that civil engineering plays in sustainable development is through the process of creating infrastructure. Civil infrastructure is, in many ways, a collection of systems that comprise the physical facilities in the built/constructed environment. Urbanization, the growth in urban populations, as well as changes in the life styles towards more consumerist behavior, impose heavy demands on the existing infrastructure systems in most cities, especially those located in developing countries. More and better-planned transportation, sanitation, communication, waste management and water distribution systems are needed to cope with these growing demands, improve the quality of life and relieve the pressure on the environment. The World Bank estimates that, over the next decade, as much as US$200 billion a year must be spent on urban infrastructure in Asia alone.

Infrastructure systems are both essential and a potential threat to environmental sustainability. Their use is often accompanied with emissions of harmful waste and high consumptions of energy, which present obstacles to the change towards a more sustainable society. The concept of civil infrastructure systems arises from the support services provided by the constructed facilities. Thus, civil infrastructure issues involve what it is (infrastructure) and what it does (public service). If they work well, society will have efficient transportation, safe water, a clean and attractive environment, and other essential support systems. Civil infrastructure is fundamental towards achieving progress in the physical living standards of human society. In ASCE's 1998 Strategic Plan, the linkage of civil engineering and infrastructure issues is the key topic that is given emphasis (Grigg, 2001).

Sustainable infrastructure systems planning meets society's increasing need for infrastructure through the optimal use of national resources and energy with minimal environmental impact and maximum cost-effectiveness. It comprises two parts: (1) a decision-making tool (2) a compendium of practices (planning design, construction, management, assessment, maintenance, and rehabilitation that consider local economic, environmental and social factors) (National Research Council Canada, 2001). Most of the infrastructure is planned, designed, and constructed under the lead of engineers, who are responsible for deciding where, when, and how the facilities should be built. As infrastructure systems have very long useful lives, the long-term planning of sustainable infrastructure becomes a key issue.

Among these infrastructure systems, the waste management system is one of the most important systems to have in place in the quest to achieve sustainability. Waste management has connection with public health and environmental degradation. The way that we manage our resources and the waste that we produce are important considerations in sustainable waste planning. Due to increasing trade and commercialization, all kinds of manufactured products are transported all over the world, finally ending up as waste, and therefore contributing to negative impacts on the environment if they are not handled in a proper way. A well-managed solid waste management system improves the quality of life, the standard of public health and promotes the cleanliness of the environment. This thesis concerns a new way to facilitate the decision-making in waste management planning.

Sustainability implies that a set of activities could continue to form a closed-loop system. In the context of human activities, development and resource use, it suggests actions such as conserving, maintaining, recycling and perhaps enhancing. However, there is no agreement on how one should measure the outcome of the actions, and the benchmark by which to gauge the achievement of sustainable development. (Hawkins and Shaw, 2004). Neither an economic nor an ecological indicator can by itself be a sustainability indicator, because “economic sustainability has an ecological cost and ecological sustainability has an economic cost" (Munda, 2005). It seems that an integration of the criteria is needed for sustainability measurement.

An indicator is the basis for evaluation of performance or achievement in relation to a given objective. In the engineering field, there is as yet no indicator of sustainability for the general evaluation of sustainability, but only some particular ones for certain disciplines such as environmental performance indicators. The sustainable process index (SPI) (Krotscheck and Narodoslawsky, 1996) was proposed as a measure to evaluate the viability of a process under sustainability requirements. It is an ecological evaluation system developed for the requirements of process engineering, and in operation, compares mass and energy flows induced by human activities with natural mass flows on a global as well as local scale. The UK Institution of Civil Engineering (2003) launched two indexes in the area of waste management, namely (1) the Demolition Recovery Index (DRI) which identify the potential for cost-effective recover of material from demolition, and (2) New Build Recovery Index (NBRI) which measures the potential of using recovered materials in a new building (Crudgington, 2004). However, these indicators are used to evaluate certain disciplines or only a certain aspect of waste management. They can not satisfy the requirements of this thesis to evaluate waste management planning alternatives concerning cost, environment and recycling aspects. Some evaluation indexes are proposed in this thesis and are presented in chapter three.

1.1.2 Waste and its negative influences

Waste is an unfavorable by-product of most human activities. It is defined as solid or semisolid materials resulting from human and animal activities. They are rejected because they are useless, unwanted, or hazardous (Huang, 2002). Waste is also defined as "any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations and from community activities" (CERP).

Solid waste can be classified as follows: (Huang, 2002)

a) normal domestic waste—coming from private homes,

b) bulky waste—broken furniture and appliances,

c) foliage or garden waste—often seasonal in some areas,

d) street waste—arising from street sweeping. Where collection of domestic waste is poor, street waste will include a large portion of domestic waste. Street waste will include spilled loads and dead animals,

e) market waste—generated in large quantities,

f) drain waste—from open drains is wetter than street waste,

g) commercial waste—may include large amounts of solid waste, for example, spoiled food and packaging,

h) office waste—likely to contain large quantities of recycled paper,

i) food waste—hotel and restaurants produce large quantities of food waste which can be fed to animals and

j) institutional waste—may include waste from:

    i) Hospitals that generate both domestic (from kitchens), office type of waste and more hazardous pathological and surgical waste from infected dressings, syringes, etc. The pathological and surgical waste must be disposed with great care.

    - ii) Confidential documents which need special disposal to ensure that unauthorized people cannot see them, drugs, pornography and condemned foodstuffs also require special controls.
    - iii) Schools and churches also produce waste which is mostly a mixture of office and domestic waste.
- k) industrial waste, if not managed well, may pose a variety of problems and usage such as:
    - i) Mining and mineral waste dumping on the top may cause instability and water pollution.
    - ii) Manufacturing waste can provide useful sources of stock feed for recycling industries.
    - iii) Construction waste can be used for building temporary tip-site roads, and for cover material.
    - iv) Chemical waste can pollute water sources if not properly disposed. It may also be toxic (through ingestion, inhalation or skin contact) and react together to start fires or produce dangerous product.
    - v) Agricultural waste needs careful management to minimize the breeding of insect vectors and rodents to prevent pollution of water sources.

The economic growth and urbanization in many countries have significantly increased the quantities of solid waste generated in cities. Uncontrolled, open dumping on the peripheries of many regions has caused the depletion of valuable land resources and long-term environmental and human health problems. Indiscriminate dumping has led to the contamination of surface soil and groundwater supplies, and open burning of waste contributes significantly to urban air pollution. At a global level, the uncontrolled release of methane, which is produced as a by-product of the decomposition of organic waste, contributes a significant proportion of the greenhouse effect in the region.

The increase in potentially hazardous industrial, biomedical and nuclear waste has not been accompanied by a commensurate expansion of the provision of waste treatment and management facilities. The uncontrolled dumping of biomedical waste has the potential of transporting diseases. The indiscriminate disposal of oils, used batteries, discarded paints and spent chemicals can cause significant adverse impacts on human health and the environment. Various incidents of pollution have also been reported from industrial waste or food processing plants along with biocides and toxic effluents from sawmills and timber processing areas. (Nema and Gupta, 1999).

1.1.3 Current solid waste management practices

Solid waste management is “planning, organizing, financing, and implementing programs to effect the generation, storage, collection, transporting, processing, recycling and final disposal of solid waste in a sanitary manner”. (Wisconsin statutes database, 2002). Current practices employed in the management of solid waste vary considerably between the low, middle and high-income countries. The concept of a waste management hierarchy helps to develop options for sustainable waste management. This hierarchy defines an order of practices for waste management including reduction, reuse, recycling, incineration, and sanitary landfill. The most effective combination of practices from this waste hierarchy depends on the type of material, as well as environmental and economic conditions. For example, waste paper and metal are suitable for recycling, while, some waste with a high calorific value is suitable to be incinerated.

Reduction involves reviewing processes to see how less waste can be produced. In some countries, the reduction of the amount of waste generated is promoted through regulation, education or disbursing benefits to the citizens. The current best practice in waste management is to reduce waste production in the first place by encouraging cleaner production. This is supplemented by more efficient waste collection, treatment and disposal.

(i) Collection and transfer

In many cities, MSW (municipal solid waste) is gathered in a variety of containers ranging from cans, baskets to grocery bags and plastic drums or bins. In some cities, neighborhood-dumping areas have been designated on roadsides from where bagged and loose waste is collected.

The cost of waste collection frequently constitutes the largest cost in a city's waste management. Many types of collection systems are used including door-to-door collection and indirect collection. In developed countries, collection and transfer services are capital-intensive and highly mechanized using collection vehicles, compactors and containers. These services provide a collection rate close to 90%. The remaining 10% is often disposed of in a variety of uncontrolled ways (Schnurer, 2002).

In the middle and low-income countries, waste collection and transfer tend to be labor-intensive and are undertaken by public sector personnel. Waste collection is undertaken using low-level mechanization. The collection systems are relatively inefficient, and in some cities of low and middle-income countries, the waste collection rate is only about 50 percent (Hoornweg et. al, 1999). Collection services are not extended to the poor in many of these countries. There is therefore a big difference in the level of service for waste disposal between rich and poor areas. The main constraints, to improving the collection rate and extending the same level of service to more areas, appear to be financial constraints and the lack of technical expertise.

(ii) Material recovery, reuse and recycling

In recent years, the rate of recovery of recyclable materials from MSW has improved significantly in many countries mainly due to the greater rates of recovery of paper, plastics, glass and metal. In many developed countries, recycling is promoted by government and private sector, often through legislation and regulations. In developing countries, waste recycling relies largely on the informal recovery of materials by scavengers or waste pickers.

(iii) Solid waste disposal

Open dumping: Open dumping is the most widespread method of solid waste disposal in the low and some middle-income countries. It is a kind of uncontrolled disposal method of waste without controlling leachate, dust, odor, landfill gas or vermin. The landfill gas from uncontrolled dumping sites is a hazardous factor, which may lead to outbreak of fire and adverse effects on people’s health.

Landfilling: The landfill is the site where waste is isolated from the environment until it is safe. Landfilling is the most attractive disposal option either in low-income or high-income countries. The waste is spread in thin layers. Each of the layers is compacted by a bulldozer before the next is spread. When about 3m of waste has been laid down, it is covered with a thin layer of clean earth, which is also compacted. The fill should be contoured to avoid polluting the surface soil and ground water. Gases that are generated in the landfill by the decomposition of organic solid waste are vented out and the leachate is collected and led out. (Thurgood, 1998). In low-income countries, it is often semi-engineered, and high-income countries often use full sanitary landfills. In the densely populated cities and towns, the land availability for landfill siting is a major constraint. This led to complex engineering solutions that are developed to ensure high standard operation prolonging the life span of landfill. (Johannessen et. al, 1999).

Composting: This is a natural process to dispose of the organic fraction of the municipal solid waste stream. Incineration is one of the contributors of greenhouse gases, and composting can help reduce the amount of incineration needed to dispose of municipal solid waste, as well as enhance recycling activities (Hoornweg et al.,1999). However, composting, as an alternative to other forms of waste disposal, is often neglected. This may be due to the fact that under present cost structures, composting is not a viable economic alternative. High operating and maintenance costs make the cost of large-scale production of compost higher than that of chemical fertilizers. The composting of organic waste, especially agricultural waste and sludge has been attempted in many countries. However, land scarcity, high costs of operation and maintenance and incomplete segregation are still the major constraints to the use of composting.

Incineration: It is a treatment method where waste is burnt to reduce its volume and generate energy. The waste is burnt on moving grates in refractory-lined chambers, and the combustible gases are burned in secondary chambers. Incineration produces heat, carbon dioxide, water, and some gaseous pollutants, fly ash and unburned solid residues. Incineration is an efficient way to reduce the waste volume, 80-95 percent of the original volume of combustibles can be reduced. It requires highly skilled personnel and careful maintenance. It involves heavy investments and high operating costs throughout its operation, which result in the increase of waste treatment cost thus making incineration one of the most expensive waste disposal options. Furthermore, waste incineration is only viable if the waste stream satisfies criteria on the percentage of burnable waste and its calorific value (Rand et. al, 1999). The composition of waste in developing countries is often not suitable for incineration because of its large percentage of organic and moisture content. Therefore, it will only be a good choice if other simpler and less expensive choices are not available.

1.1.4 Present waste management situation in developing regions

The following sections describe five key aspects of the present situation of waste management, particularly in developing regions.

(i) A remarkable increase in the amount of waste generated: Due to the fast population growth and urbanization, much more waste is produced in cities, especially in the developing countries. Firstly, the world population is estimated to grow significantly in the near future, to as much as 8.5 billion over the next thirty years. Out of the 8.5 billion people, it is estimated that 7.1 billion will live in developing countries. Secondly, in these countries, a large number of people have flooded towns and cities due to the high rate of economic growth in the urban areas. It is estimated that up to 90% of the newly born people will live in cities or towns, and the percentage of urban dwellers of the total population will increase from 33% in 1995 to 55% in 2025.

(ii) Variation of waste composition: People's life styles and consumption patterns will change with the increase of income expected from a rapidly developing urban economy. A large amount of inorganic, lightweight, and high-volume materials, such as paper and plastic will make up an increasing percentage of the waste stream. Moreover, more waste such as cars, that are difficult to handle, will be produced. These changes in waste composition, as well as the larger waste volume, will increase the level of difficulty for composting and even incineration.

(iii) Growing demand for formal waste disposal: In most cities of the developing countries, waste management services are inadequate. Only about 70% of the population is provided with such service and a large amount of waste remains uncollected. Furthermore, most of the waste is collected through informal systems and disposed of in open and unregulated dumps. The use of such open dumps creates several concerns (Asian Development Bank, 2002). The first is associated with the public health hazard posed by uncovered and decomposing waste. Second, leachate that is generated through the contact of solid waste with infiltrating rainwater contaminates nearby waterways and groundwater supplies. Finally, burning at such open dumps contributes greatly to air pollution. There is a great need to increase the percentage of the municipal solid waste stream handled by formal waste management systems, and to extend the services of such systems to the entire urban population (Westlake, 1997).

(iv) Poverty and budget shortages: Urban poverty is still a major urban issue in developing regions. 1.2 billion people, nearly one fourth of the world population live below the absolute poverty level and cannot afford to pay for formal waste management services. They normally live in the developing countries. However, in many of these countries, a better waste management system is terribly needed to keep pace with the waste generation and improve the sanitary condition.

(v) Shortage of land to construct new facilities or extend existing ones: As cities grow, there is greater pressure on land-use. It does not help that the nature of such facilities, which give out harmful gases and exude leachate, make them unwelcome in most communities. It is increasingly difficult to find the land suitable to build waste disposal facility in most cities. The common method is to give financial compensation or benefits to the community where the facility is built. However, the rising income level due to the economic development and increased environmental consciousness has weakened the attraction of such compensation or benefits. (Xiques, 1993).

1.2 Achieving sustainability in waste management

1.2.1 General principles towards achieving sustainability

A survey of the sustainability literature has revealed some widely held views, which are important in achieving sustainability in waste management. (ERM, 2000; Schnurer, 2002; Casanova, 2002; Peng, 2002).

(i) Alleviating the negative impact to the environment

Environmental sustainability is one of the three important aspects of sustainable development. Minimizing pollution to the environment from solid waste is important in achieving environmental sustainability. Reducing the amount of irregularly disposed waste is critical to minimize the level of pollution, followed by improving the technology of waste treatment and disposal itself to decrease the pollutants produced.

(ii) Promoting the reuse, recycling, and recovery of waste

Economic and demographic growth induces an increasing demand of goods and services, which ultimately cause a depletion of natural resources. Rational use of resources based on the recovery of energy and material is a requirement and an embodiment of sustainable development. Many countries have come to this realization and have adopted the principle of the 3Rs (reduce, reuse, recycle) in waste management.

(iii)Achieving economic sustainability

A stable level of economic growth is another key element of sustainable development besides protecting the environment and prudently using resources. The adoption of new technologies and development of new facilities should be within the affordability of the society concerned. Among other things, affordability involves rational evaluation of benefits *vs*. costs of technology adoption, plus cost-effective allocation of limited resources (budgets, land) over time during waste management planning.

(iv) Optimal planning of waste management systems

A waste management plan requires consideration of many issues, ranging from policy issues on standards of pollution, health and promotion of waste recycling, to planning issues like the location of waste facilities and the allocation of waste streams to facilities. Limited resources and long-term sustainability necessitate the use of a rational planning methodology that minimizes the use of resources and considers long-term effects.

1.2.2 Some difficulties in achieving sustainability in waste management

There are some difficulties in the practical application of the sustainability principles described above in waste management planning.

(i) Trade-offs between alternative uses of limited resources

Land and budgets are the key considerations in waste management planning. Both of these are often in short supply and their availability changes over time. Decision makers need support in making the trade-offs between alternative uses of these limited resources over time.

(ii) Accounting for long-term impacts

The waste issues such as waste generation and waste disposal usually have long-term impacts on the environment. Those impacts need to be involved in the planning of the waste management system. It is preferable that the planning methods be able to adapt the plans to changing circumstances.

(iii) Comparing planning alternatives according to sustainability

Sustainability involves environmental, economic and social aspects each of which may be expressed through a variety of factors and indicators. It is difficult to directly compare different plans according to these factors and indicators as:

(a) the factors that help to define a particular aspect will need to be identified,

(b) the relative importance of these factors has to be established, and

(c) the means by which performance or degrees of attainment of these factors are measured have to be agreed upon.

1.2.3 Proposed decision support approach

A decision support approach is proposed in the thesis to overcome the difficulties mentioned above. It conjointly uses SD (System Dynamics) as a simulation method and AHP (Analytic Hierarchy Process) as a multi-criteria decision-making tool. It can assist in the decision-making about the adoption of plans for the building of waste treatment/disposal facilities.

In the SD method, a simulation model is formulated which addresses the considerations of cost, environmental and social issues. The analysis of the consequences of different plans requires a good understanding of the main contributors to the waste problem and the responses of the solid waste system to different plans for building treatment/disposal facilities. This understanding can be achieved by exploring the interactions among relevant economic, environmental, managerial, and life style factors, which are complex and vary over time. An SD model can help in this process of exploration by simulating the process of carrying out the alternative facility plans, and projecting the long-term consequences of the plans depending on different scenarios. It is then possible to evaluate the relative attractiveness of the consequences of various plans.

The AHP method is applied for the comparison and selection of alternative plans. It is an effective approach dealing with decision problems based on the evaluation of a number of alternatives in terms of various criteria. In this study, a decision hierarchy is built up involving criteria of cost, environmental impact, level of public involvement, etc, to achieve the objective of satisfying the requirement of sustainability. The basic process of pairwise comparison helps to eliminate the influence of the decision makers' intuition regarding their desirability of the different tradeoffs between performances on the different criteria.

The SD model provides information concerning the performance of different plan proposals that might be of concern to decision makers, taking into account the system interactions and long-term effects. At the same time, the AHP methodology enables the performance of the proposals on the indicator indices to be used to identify superior proposals through a multi-level decision hierarchy.

1.3 Research objective

The objective of this research is to present an approach to support the decision-making in the planning of waste treatment/disposal facilities. Improved living conditions, increasing awareness of environmental issues, and higher health expectations require better and more advanced waste treatment/disposal facilities. The lack of proper sanitary facilities, especially in developing regions, is more serious due to poverty or a big population. With economic development and more concern for sustainable development, the employment of advanced facilities becomes more likely and even essential to maintain the quality of life.

When and where to build such facilities are the most important issues considered by the decision makers when making the plan. Several key obstacles may be encountered during planning including budget limitations, a shortage of land for waste disposal facilities, and the NIMBY (not in my backyard) attitude of the public. It is often difficult to address these issues in a way that satisfies all the stakeholders and achieve the objectives of minimizing the pressure on budget, minimizing negative impact on the environment, and minimizing opposition from the communities where the facilities will be located.

The research presents an approach for choosing desirable or acceptable plan proposals for building the facilities. The approach combines the advantages of SD (to account for dynamic interactions between plan components and elements of the plan context) and AHP (to compare the alternative plans using multiple criteria). It is envisaged that the approach will be useful in the early stages of planning when a macro and holistic view is appropriate, and can complement the use of other planning tools for more detailed planning.

1.4 Research methodology

A literature review was conducted to determine the present situation in waste management and the various solutions used to solve the problems concerned with waste management. The researches about the methodologies SD and AHP are also reviewed.

A simulation model using system dynamics methodology was developed to simulate the impacts of different alternative plans of building waste treatment/disposal facilities. It includes several indicators for the evaluation of the alternatives on various aspects of cost, environmental impact, facility service life and recycling issue.

The AHP methodology was applied as a decision making tool to compare and select the alternative plans. It makes use of the information and knowledge about the performance of the alternative plans, which are provided by SD model, in the pairwise comparisons. The main criteria included in the evaluation of the plans include cost, recycling rate, environmental impact, public involvement and the life span of waste disposal facilities.

1.5 Dissertation outline

A brief description of the subsequent chapters follows.

Chapter 2 reviews the main issues considered in waste management, and the main solutions currently in use. It also includes an introduction to the main methodologies used in this research: System Dynamics and AHP methodology and their applications in decision support.

Chapter 3 describes the formulation of the System Dynamics model and the structure of the decision-making hierarchy. It involves the establishment of the model structure, the equation formulation, the setting up of the initial values and formulation of the decision hierarchy.

Chapter 4 presents the results of the application of the method and discussion of the results. Firstly, the scenarios and alternative plans for the model are described in this chapter. The validation of the model and sensitivity analysis was also conducted. Then AHP methodology was applied on the simulation results to select the final option. Finally, the results are discussed and conclusions are presented.

Chapter 5 summarizes the main research findings and provides suggestions for future research.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the key issues involved in waste management, the current solutions and research about the application of system dynamics and the AHP methodology are reviewed.

2.1 Waste management

Waste management is the “administration of the reduction, collection, separation, storage, transportation, transfer, processing, treatment and disposal of wastes.” (WRPPN, http://www.westp2net.org). The planning of such a waste management system involves various issues, and can be conducted using a variety of methodologies. In the following sections, those issues and the methodologies in use are reviewed.

2.1.1 Issues in waste management systems

Many issues related to the different aspects or different stages of waste management should be considered. Mont these, issues of facility siting and waste generation forecast are reviewed; these are closely related to the planning for waste treatment/disposal facilities.

1) Facility siting

Shortage of land for waste disposal is an increasingly serious problem in most of large urban regions. The siting of a waste facility is a complex problem because it involves several elements:

a) facility needs, design, and operation interacting with site environmental and community characteristics;

b) facility effects and stakeholders’ background beliefs and values determine stakeholders’ beliefs, attitudes, and actions;

c) proponents siting interventions can tangibly change the facility effects and the siting process;

d) stakeholders' actions interact and result in an outcome (Zeiss and Lefsrud, 1995).

Geographical information system (GIS) is often applied in many models of waste facility siting such as the network-based system formulated in Kao et al. (1996). Facility siting generally requires processing a variety of special data. GIS can convert geo-referenced data into computerized maps. In addition, map analysis tools provided by the GIS make it easy to manipulate maps with a computer in a much more efficient way. GIS can combine various demographic, geological, land use and different criteria. GIS can also be used for preliminary site screening (Charnpratheep, et al., 1997), to exclude obviously unsuitable areas and retain potential areas for the site evaluation based on environmental impact assessment. The preliminary screening criteria and their associated priority weights that are determined using analytic hierarchy process (AHP) are included in the model; then each cell of the potential sites can be graded. The closer the grade is to one, the more suitable the grid cells are.

In waste facility siting, the actions of community and stakeholders are the main factors. Zeiss and Lefsrud (1995) constructed a comprehensive framework to combine all causal relationships between elements to explain waste-facility siting outcomes and differences between stakeholder opinions.

2) Waste generation forecast

In order to devise the most appropriate waste treatment/disposal plan, decision makers should address the problem of how to predict the amount and composition of waste that is likely to be generated in the future. Many approaches have been implemented to generate this prediction. Moreover, improved forecasts of solid waste generation lead to more reliable estimates of the capacity required for waste treatment systems and more accurate predictions about landfill site requirements (Fortin and McBean, 1983).

Bruvoll and Ibenholt (1997) projected the waste generation based on a macroeconomic model. According to their analysis, the solid waste is the difference between the mass of input and that of output. Daskalopoulos and Badr (1998) introduced another simple methodology suitable for application in the developed countries like the US and those in Western Europe. The amount of waste generated is estimated through key parameters of the methodology such as the population and mean living standard of the country.

Future waste emission can also be estimated as a percentage of the future stock or as a delayed input. The first approach is based on a static model, while the second is based on a dynamic system (Voet et. al, 2002). From the viewpoint of environmental systems analysis, materials are taken from the environment, transformed into products, discarded, and returned to the environment as emissions. The problem of estimating future emission is solved using a leaching model and a delay model. Both models are applied to calculate the outflow of disposal or emission. In the first model, the outflow is considered equal to a constant fraction of the stock, and in the second one, the outflow is equal to or a function of the inflow. After analysis, it became apparent that the leaching model could be used to predict waste flows if the driving force behind disposal is not ageing but leaching or corrosion. However, if there is significant change in the inflow function in the period of observation, or the life span of products is too long, or the period of observation is shorter than the life span of the products, the dynamic delay model must be used. In this thesis, the system dynamics model is applied with the simulation of the delayed performances.

2.1.2 Methods of planning concerned with waste management

Solid waste management has become one of the most important problems in urban policy planning and management. A solid waste management system must be based on integrated systems with a combination of many different complementary methods. The integration can take place at various levels: (1) the use of a range of different collection and treatment options; (2) the involvement and participation of all the stakeholders; and (3) the interactions between the waste system and other relevant systems (Lardinios and Klundert, 1997). With increasing demands for the saving of non-renewable resources, increased recycling, and better environmental protection, an upgraded solid waste management system should emphasize:

- Recovery and recycling of materials, involving direct action by residents and industries
- Increased and improved collection, transportation, recycling, treatment and final disposal of waste
- Utilization of the easy biodegradable fraction of organic waste for composting
- Landfilling, which will always be needed regardless of other methods utilized for non-recycled materials, residues etc

Finding acceptable plans to cope with such a problem is becoming harder because of the increasing awareness of environmental issues. It is a complex problem and includes the economic, environmental, social and technical aspects. Decision-makers have to justify the choice of location for potential disposal sites, as well as the accessorial transportation routes, taking into consideration the cost, environment, and social impacts. The decision-making is typically framed as a multi-objective and multi-criteria optimization problem with imposed constraints. Most industrial countries have adopted the "waste management hierarchy" as a guide for developing MSW management plans. According to this hierarchy, the waste should be at first reused, recycled, and recovered to reduce the amount; then the remaining waste is disposed.

As for the methodologies used, various mathematical programming techniques have been adopted, including linear programming (LP), mixed integer programming (MIP), dynamic programming (DP), non-linear programming, and network flow modeling. Recently, models based on the use of heuristic programming techniques like genetic algorithms, fuzzy logic, artificial neural networks and expert systems have begun to appear. The latter models attempt to replicate the complexity of human decision-making through processes that mimic nature or the symbolic reasoning capability of humans, rather than through a traditional mathematical representation.

Most of these models developed are formulated based on cost, typically minimizing the overall cost, which includes the cost of transportation, processing, and the capital cost of developing new sites and construction cost of the facilities. The model incorporates constraints that determine the feasibility of the solutions include constraints on the conservation of mass balance, and constraints about the capacities of various components in the waste disposal system or the carrying capacity of the environment. Chang and Lin (1997) account for a comprehensive set of costs in their model. In some research (Salvia et. al 2002), system planning was performed for a long study period, which was divided into several fixed-length periods to enable the change with the changing operational environment and the considerations of energy, social-economic and environmental constraints.

In recent research, social-economic and environmental considerations are frequently emphasized. Chang and Wang (1995) described a multi-objective mixed integer-programming model for the planning of the system incorporating such criteria as economic cost, noise pollution, air pollution, and traffic congestion.

It is probably too expensive to eliminate all risk of environmental damage. Some models recognize this by estimating the impacts and probabilities of certain risk events associated with the design choices. For example, the risk posed by hazardous waste is considered in the model described by Nema and Gupta (1999); and risk-based strategies are considered by Kavazanjian (1994).

Another approach that is popular within planning agencies is to develop solutions with the support of a suite of computer-integrated tools forming a decision support system (DSS). Such a system usually includes three main interacting components: the user interface system, the data management system, and the model management system. It contains the site risks, environmental impacts, costs, and transportation risk models for scenario evaluation, and a multi-criteria model for optimization (Fiorucci et. al, 2002, Haastrup et. al, 1998). A DSS can assist in quantifying the refuse flows that have to be sent to different treatment or disposal plants, as well as in deciding the optimal numbers and kinds of plants needed.

2.2 System dynamics and its application in waste management

As one of the main methods used in this research, system dynamics and its applications are reviewed. The contents include descriptions about its development history, advantages and its applications in waste management.

2.2.1 Overview of system dynamics

"System dynamics is a method of analyzing problems in which time is an important factor, and which involves the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world" (Coyle, 1977). SD (system dynamics) is a methodology for problem solving and simulation development with the aid of computer simulation software. It assumes a holistic view of the organization focusing on the behavioral trends of projects and relation with managerial strategy. It has experienced a sharp increase in popularity, and has attracted particular attention in recent years since computer has become readily available.

System dynamics was developed by Forrester in MIT in the 1950s (Ford, 1999). He developed the initial ideas by applying concepts from feedback control theory to the study of industrial systems, and applied it in the best-known model of urban dynamics. The origin can be traced to engineering control systems and the theory of information feedback systems. Forrester (1961) reshaped sophisticated modeling and analysis methods from control engineering into a flexible form suited to modeling and debate in the business/social fields. He offered symbols for diagramming systems and rules for connecting the symbols. The arrival of computers capable of rendering high quality interactive graphics easily has made it possible to map symbols directly onto a computer screen.

With numerous successful applications in real life projects (Rodrigues and Bowers, 1996), SD has repeatedly been demonstrated to be an effective analytical tool in a wide variety of situations, both academic and practical. As Sterman (1992) pointed out, SD models are widely used in strategy and policy assessment. SD is well suited to representing the multiple interdependencies in the assessment and this is one of the chief uses of SD.

SD is broadly used in project management (Sterman, 1992; Rodrigues and Bowers, 1996), as well as in the field of civil engineering (Jesson, 1988, Ogunlana et al., 2003). For waste management, there are also some reported applications, such as in Wager and Hilty (2002), Sudhir et al. (1996), and Mashayekhi (1992). It complements the traditional techniques.

A SD model is based on the reference mode and cause-effect relationships formulated from a situation under study. The modeling process starts with the development of qualitative influence diagrams and then moves into the development of a quantitative simulation model. These models allow for a flexible representation of complex scenarios, and the model simulation generates patterns of behavior over time.

SD describes cause-effect relationships with stocks and flows, which are the building blocks of system dynamics models. Stocks (or levels) represent accumulations within the systems, which continue to exist when all activities cease. They represent the state of the system and their values can only be changed by flows. There are two kinds of flows embedded in the feedback loops, information flows and material flows. Material flow, also called flow, represents the material flowing into, between, or out of the system boundary. Information flows are used to provide model inputs and describe the material flows.

There have been several computer softwares used in the development of system dynamics models. These include DYNAMO (the first language used to build system dynamics models); STELLA; SIMPAS; and VENSIM that is now widely used. In this research, the model is built with the use of VENSIM PLE32, software with a visual graphical user interface that helps conceptualize, build and test system dynamics models.

2.2.2 Application of system dynamics in waste management

There are not many studies on the application of system dynamics to solid waste management. A systematic model for the planning of the MSW (municipal solid waste) management system using system dynamics is described in Sudhir et. al (1996). The authors designed the model for use in developing countries, “addressing several interdependent issues such as public health, environment, present and future costs to society and the livelihood of the actors in the informal recycling sector." In the model, they divided the management system into three parts: waste generation sub-system, informal recycling sub-system, and formal sub-system. In the waste generation part, waste generation is mainly determined by population and economic activity is determined by average income. There is an important difference between the waste management situation of developing countries compared to the situation in developed countries. In developing countries, there is the existence of an informal waste recycling system consisting of waste pickers, itinerant buyers, scrap dealers, and wholesalers. The authors have used these factors as indicators to evaluate the waste management policies. The formal sub-systems that form parts of the system such as the collection, transportation and disposal of waste often depend on the municipal budgets. The authors studied two alternatives of management policy with different fund allocation and different measures to improve waste management to check the performance of the model.

Similarly, a system dynamics model used in developed countries was developed by Mashayekhi (1992). The article presented a quantitative model used for the solid waste problem in New York State in US, and applied it to examine different policies that might be adopted by the government. Compared to the model for developing countries, this model paid more attention to the financial issue within the system because of the higher cost caused by rising public awareness of environmental issues, and the fact that many landfills in use had been forced to close. The lack of appropriate sites and higher cost of developing new landfill need a much larger budget than what the government had spent on solid waste in the past. The model was also divided into several sectors such as waste generation, waste stream allocation and budget allocation. The author compared four alternative policies, their influence to the waste disposal and the improvements to the current management system, and determined the alternative giving the most cost-effective result.

Another system dynamics based simulation system is presented in Wager and Hilty (2002). The simulation system combines the advantages of a system dynamics approach with expertise from the field of Life Cycle Assessment (LCA). The integration of modeling and simulation techniques into traditional planning and decision making procedures still seems to be in its infancy. He presented an example of a simulation system that has been applied in the field of waste management and discussed it with regard to general requirements for decision support systems. The system is conceived as a system which allows simulating the ecological and economic effects of possible future developments for time periods up to 15 years. It allows the user to set input parameters such as the expected development of the waste streams. He also defined indicators for assessment of the environmental aspects as well as economic aspects, such as energy consumption and amount of waste. This model is constructed to answer the question of what will happen under the supposed scenario and with the proposed policy. It can be a general problem solver for waste management issues, or an explorative learning tool for waste management policies.

2.3 AHP and its application in decision-making

In waste management planning, the decision-making is one of the key processes. In this research, AHP (analytical hierarchy process) methodology is adopted as the decision making tool. In the following section, an introduction to the AHP methodology, its characteristics and applications are reviewed.

AHP (Analytic Hierarchy Process) is a decision analytic tool first developed by Saaty in 1977. It is a multi-criteria decision-making approach and widely used for multi-criteria evaluation activities. It can convert subjective assessments of relative importance into a set of weights (Olson, 1995). The major processes of AHP are:

1) building hierarchy structure between the top level (a comprehensive purpose) and the bottom level (alternatives),

2) constructing pair wise comparison matrix by the scales of pair wise comparison among the factors, and

3) calculating factor weights by the calculation of the eigenvector of the pair wise comparison matrix and the synthesis of the weights.

The field of multiple criteria decision making (MCDM) has expanded rapidly over the last decade and continues to do so. It involves different approaches to aid choice between discrete alternatives. They are useful in the process of narrowing down a long list of alternatives. Among them, AHP was proposed as one such approach to solve the MCDM problem and it has been widely applied (Debeljak et.al, 1986, Belton, 1986, Saaty, 1990, Mirarda, 2001, Feng, 2004). AHP is a simple and feasible multi-objective evaluation method widely used for multi-criteria evaluation activities. It is designed for subjective evaluation of a set of alternatives based on multiple criteria organized in a hierarchical structure. It provides an effective way for quantifying the data in the field of engineering (Triantaphyllou and Mann, 1995). At the higher levels, the criteria are evaluated, and at the lower levels, the alternatives are evaluated by each criterion. The decision maker does his evaluation separately for each level subjectively. By creating a pair wise comparison matrix, his subjective evaluation for every pair of items is then assessed.

AHP gives a structure and mathematical basis upon which many problem domains can be modeled. It helps people cope with the intuitive, the rational and the irrational with uncertainty in complex situations. It can be used to predict probable outcomes, plan projected and desired futures, facilitate group decision making, exercise control over changes in the decision making system, allocate resources, select alternatives, and perform cost/benefit comparisons (Mirarda, 2001). AHP also has advantages of not needing explicit decision variables, objective functions or utility functions. In particular, it is very well suited for decision problems with discrete finite alternatives, criteria, and decisions (Debeljak et.al, 1986).

On the other hand, some researchers have pointed out that AHP has a few limitations and shortcomings. Dyer (1990) pointed out that in the AHP process, the alternative ranking may reverse when adding a new alternative or a new non-significant criterion. More importantly, he pointed that all of the published examples of the use of AHP to evaluate alternatives relative to a set of criteria have assumed the principle that the weights on the higher levels of a hierarchy can be determined independently of the weights on the lower level, which leads to the arbitrary results produced by AHP. They conclude that the method must be changed to resolve the problem, and introduced a variant of the original AHP called the revised-AHP. However, the proponents of the AHP method have shown a complete disagreement with this criticism, for example in Saaty (1990), Saaty and Vargas (1984). Saaty (1990) said that the criteria can be independent of the alternatives or they can depend on them in different ways. He also argued that contrary to Dyer's criticism about rank reversal, "there is good reason for rank reversal in the relative measurement mode of the AHP," and "this is an advantage of relative measurement rather than being flawed as perceived by Professor Dyer" (Saaty, 1990). Belton (1986) also pointed out that the great weaknesses of the AHP are the ambiguous questioning procedure about criteria weights and the strong assumption of a ratio scale for the measurement of scores.

Although it is criticized in some published work, AHP is still the most widely accepted method and is considered by many as the most reliable MCDM method (Triantaphyllou, 1995). It describes the general decision operation by decomposing a complex problem into a multi-level hierarchic structure of objectives, criteria, sub-criteria and alternatives. It provides a fundamental scale of relative magnitudes expressed in dominance units to represent judgments in the form of paired comparisons. A ratio scale of relative magnitudes expressed in priority units is then synthesized to obtain a sequential ranking of the alternatives.

CHAPTER 3

THE DECISION SUPPORT APPROACH

In the beginning of this chapter, the combined use of the two methods is generalized. For SD (system dynamics) method, the characteristics and scope of the simulation model are described, and the necessity of adopting the systems concept is raised. Overall descriptions of system dynamics are provided, with mathematical expressions, causal relationships and feedback structure. The equations generated using VENSIM are presented. For AHP, the necessity of the MCDM method is presented. The choice of AHP is justified by comparing it with some other MCDM methods. Overall descriptions of the AHP are provided with mathematical expressions. Finally, the decision hierarchy is constructed.

3.1 Overview of the decision support approach

The decision support approach combines the methodology of SD (system dynamics) with AHP (analytical hierarchy process) to help in the planning of waste treatment/disposal facilities. The two methods are used together to reinforce each other. This approach is applied to choose a superior plan from a list of potential options.

Waste management planning usually involves a number of considerations such as budget allocation, environmental impact, facility siting, waste flow allocation, and adoption of technology at treatment facilities. Combinations of these factors have been addressed through different decision models at varying levels of detail; however, it is difficult to consider these factors together simultaneously. The proposed approach attempts to address this; by doing so, it is intended to help decision makers better understand the interaction between these different factors, and evaluate the performance of the alternative plans for waste treatment/disposal facilities, and compare them within a multi-criteria hierarchy.

The first part of the approach employs SD (system dynamics) as a model simulation tool to deduce the consequences of each proposal for waste treatment/disposal and facility building. The second part of the approach makes use of AHP to find the preferred choice among the available alternatives based on their simulated performance. The approach takes advantage of SD and AHP method, and uses them in a complementary way. SD simulation model provides the consequences of adopting each proposal, and enables the decision makers learn more about the interdependencies between system variables in each proposal. The judgmental process utilizes the pair wise comparisons in AHP to make the selection process clearer and simpler. The data flow within the approach is shown in Figure 3.1.

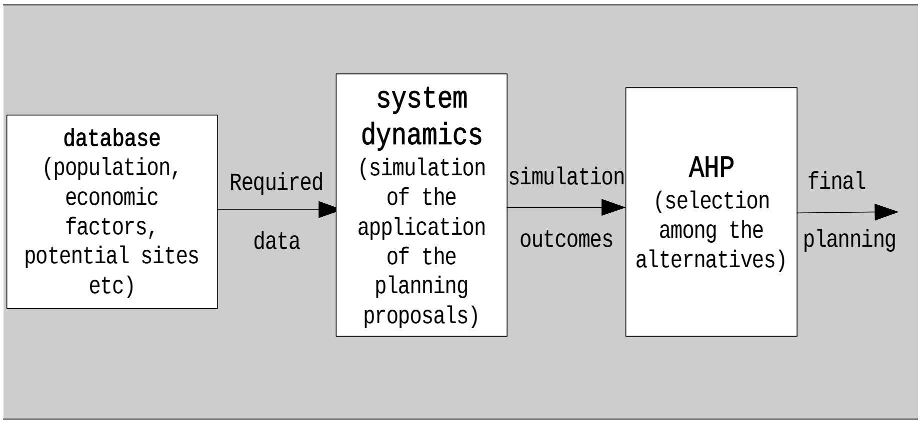


Figure 3.1 Data flow of the proposed approach

3.2 SD (system dynamics) simulation model

In the following sections, a SD (system dynamics) model is presented to assist the decision makers to better understand the long-term impacts of different planning alternatives for waste treatment/disposal facilities. It simulates the implementation of each available plan for waste treatment/disposal facilities. Several quantitative indicators are defined in the model to measure the effectiveness of each planning alternative; they also serve as a means to compare and evaluate the alternatives. It is important to note that the simulation results do not provide a single snapshot of the predicted performance; rather, the results indicate the developing trends and patterns of the variables that enable the analyst to better understand the behavior of the system as a whole.

3.2.1 Justification of the application of SD

During the past few years, the computer-oriented decision support methodologies have developed in two directions: quantitative simulation approaches and qualitative knowledge-based systems (Merten, 1991). In this thesis, the research leans more towards the former by adopting a quantitative simulation approach to obtain the anticipated performance of adopted policy, although it still incorporates a qualitative element in the assessment of these results.

In the process of planning development, an analysis of the consequences of decisions taken is usually necessary. It is customary to assess the consequences by making some kind of decision support model before actually implementing any of the plans. In this research, a SD (system dynamics) model is applied to simulate the process of the potential plans.

SD is a computer-oriented decision-support simulation approach. It can simulate the dynamic consequences of different planning strategies in a quantitative way. Therefore, it is used predominantly in the process of strategy selection and strategy testing (Merten, 1991).

SD is broadly used in project management (Sterman, 1992; Rodrigues, and Bowers, 1996), and in the field of civil engineering (Ogunlana et al., 2003). For waste management, there are also some reported applications, such as in Wager and Hilty (2002), Sudhir et al. (1996), and Mashayekhi (1992). The use of SD is complementary to traditional planning techniques.

The following points highlight the key advantages of SD, which make the method attractive for this research:

1. System dynamics is able to capture the complexity of the interdependencies that exist between the factors in the problem domain. The modeling of these interdependencies allows the causal impact of changes to be traced throughout the system. SD can also portray the rich range of nonlinear relationships occurring in real life with great fidelity. SD, more than any other formal modeling technique, stresses the importance of nonlinearity in model formulation.
2. In SD, these interrelationships can include a time-delay effect; this time delay can significantly affect the behavior of the system as revealed in the time trajectory of the system variables.
3. Furthermore, SD models can incorporate feedback between system variables; the incorporation of feedback in the model is what makes SD unique among simulation methodologies and reflects SD's origins from the field of control theory.
4. Among all the formal modeling techniques, system dynamics has the most highly evolved guidelines for the proper representation, analysis, and explanation of the dynamics of complex technical and managerial systems.
5. The SD output improves the understanding and estimation of major parameters with a very effective graphical interface, enabling a better understanding of the important influences or evolution of the plan, which are involved in the model as qualitative data.

3.2.2 Model formulation

The formulation of the SD simulation model consists of the following steps:

(a) identifying the system and its subsections;

(b) identifying the dynamic problem and generating the reference modes;

(c) determining the model components and the interrelationships among the components;

(d) constructing of the influence diagrams and the stock-flow diagrams;

(e) formulating the variables and equations; and

(f) estimating the parameter values.

The details of these steps are presented in the following sections.

3.2.2.1 Subsections of the model

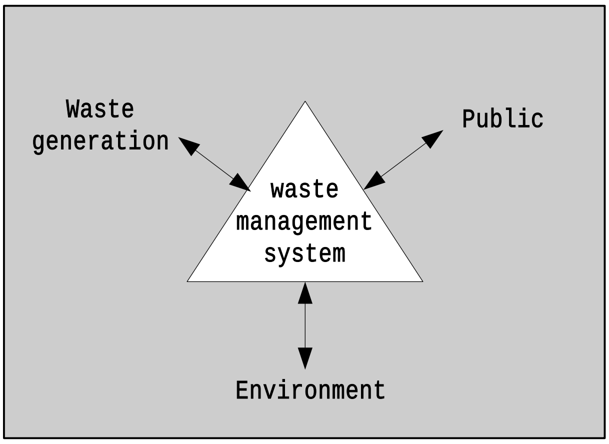


Figure 3.2 External factors affecting the waste management system

A waste management system typically has close relationships with the outside world as shown in Fig. 3.2. Generally, the system can be divided into several basic parts such as waste generation, treatment, disposal and their influences on the environment as shown in Fig. 3.3. Waste is generated from the outside of the waste management system. The measures used in waste management can inversely improve or aggravate the conditions of waste generation and the public reaction. Waste generation and its disposal can also influence the environment. The environment, public involvement, and the sources of waste comprise the main outside environment of the waste management system.

In system dynamics model, the whole system S consists of several correlated sub-systems S_i:

$$S = \{ S_i \in S \mid _{1\sim p} \} \quad (i = 1, 2, \ldots p)$$

In a waste management system, the processes of waste generation, treatment and disposal compose the main material flow. Meanwhile, all of these processes influence the environment though smell, leachate and smoke let into the environment.

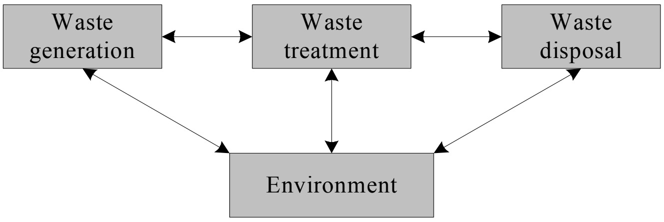


Figure 3.3 Key components of the waste management system

In this SD model, the whole system S is the waste management system. Six sub-systems are formulated, namely the sections for waste generation, waste treatment, waste disposal, finance, environment, and recycling, represented by $S_1, S_2, \ldots\ldots S_6.$

$$S = \{ S_i \in S \mid _{1\sim 6} \} \quad (i = 1, 2, \ldots 6)$$

These sections interact with each other through material and information flows as shown in Figure 3.4. Waste material flows run between the sections for waste generation, recycling, disposal and treatment. These four sections exchange information among themselves as well as with the finance and environment sections. The variables and their linkages within each sub-system are discussed in the following sections.

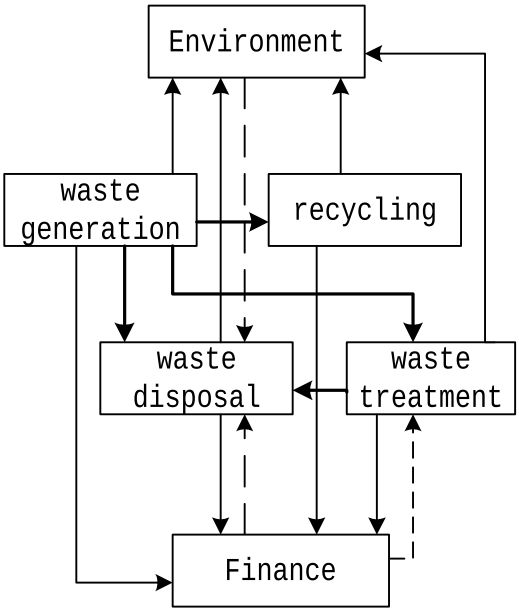


Figure 3.4 Subsections of the SD model

3.2.2.2 Reference modes

Waste management planning is a dynamic problem, which means that the situations and the considerations involved will change over time. The best way to be specific about the nature of the "dynamic problem" is to draw a reference mode, which is a graph describing how the main variables change over time (Ford, 1999). The reference mode provides a target pattern of behavior of the system. The fundamental dynamic patterns of systems include growth, decay, and oscillation. The target pattern may be one of or a combination of them. In some cases, the reference mode can be drawn from historical performance, or it can be a relatively simple extension of historical trends. In other cases, it may be necessary to draw the target pattern based on the planners' intuition and inferences from the limited available data (Ford, 1999). The target pattern is the main reference for testing the model, so it is important to analyze the system to get the reference modes.

Within the waste management system, the forecast of the waste generation is an important factor. According to historical data, the amount of waste generated keeps increasing, especially in recent years. It can be observed that in developing countries, especially those with a high rate of economic development such as China, the amount of waste is also growing rapidly. In Beijing, the capital of China, the waste is increasing at a rate of 8-10 percent per year (Beijing Business Today, 2002). It has been forecasted that in the next few years, the waste will continue to increase at a rapid rate with a trend as shown in Figure 3.5. However, from the data about the condition in developed countries (such as in the city of Osaka in Japan), it can be observed that the amount of waste is increasing but the rate of this increase is decreasing. Developed countries may even experience a trend of decreasing amounts in the total amount of waste generation (see Figure 3.6).

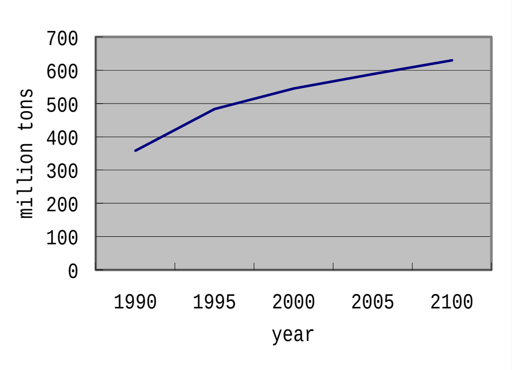


Figure 3.5 Recent trend of waste generation, Beijing China
(Source: Green Beijing environment forum)

Table 3.1 Annual amount of waste (ton) generated in the city of Osaka
(Source: official website of the city of Osaka, Japan)

1955	1965	1975	1985	1990	1991	1992	1993
314247	803462	1330099	1808023	2152412	2176218	2087239	2062351
1994	1995	1996	1997	1998	1999	2000	2001
2114137	2143899	2022265	1957926	1871320	1790947	1795118	1739974

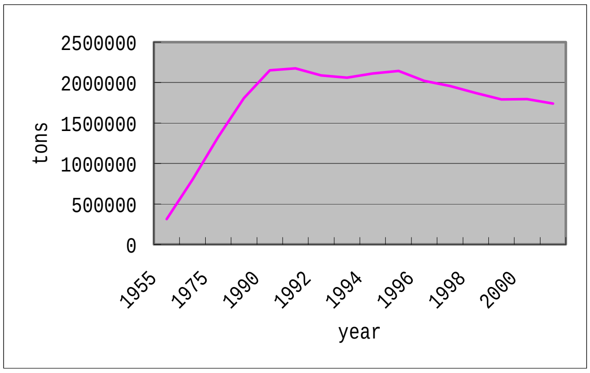


Figure 3.6 Trend of waste generation, Osaka Japan
(Generated from Table 3.1)

The developing countries are still in the stage of fast economic development with high consumption of resources and little attention paid to waste reduction. In the developed countries, the economy has developed to a level that enables them to adopt advanced technologies to reduce the consumption of resources as well as the generation of waste. Furthermore, the public is more concerned about environmental problems, which is also helpful to the alleviation of waste growth. We may conclude that in the long run, the waste generation in developing countries will grow first at a rapid speed and then at a decreasing speed. The reference mode can be drawn as shown in the graph. The curve grows with a steep slope at first and then grows flatter.

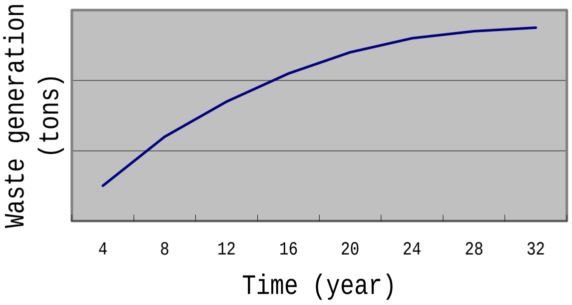


Figure 3.7 Reference mode for the variable of waste generation

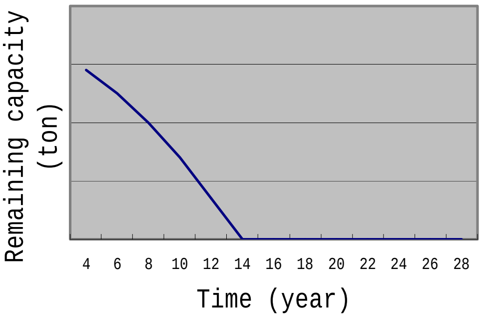


Figure 3.8 Reference mode for the variable of remaining capacity

The capacity of the landfill is another variable whose target pattern can be easily obtained. It should exhibit the pattern of decay, and reduce to zero at the end of its lifespan. Normally, with current practices of waste management the life span of a landfill is about 20 years. The reference mode of landfill life span is as shown in Figure 3.8. The curve keeps reducing until it reaches zero. The model is expected to be able to generate simulation results that follow the patterns shown in the reference mode shown above.

3.2.2.3 Influence diagrams

Influence diagrams are composed of the linkages among variables. A linkage is referred to as a cause and effect relationship between two variables. This linkage could represent either a positive relationship or a negative relationship between variables. The arrows between the variables stand for their connections. Those arrows with "+" on the tip stand for the positive connections between the two variables; this indicates that the two variables will change in the same direction. Similarly, those arrows with "-" on the tip mean the two variables that are connected will change in opposite directions. The influence diagrams for the different sections are shown in Figures 3.9 to 3.12.

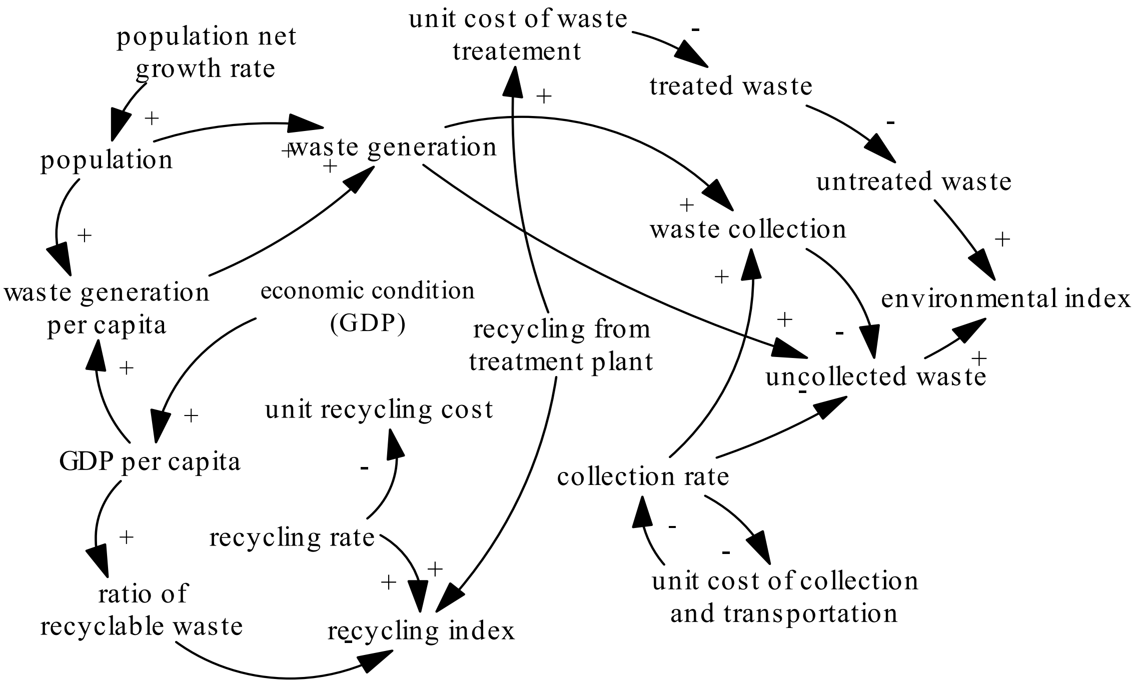


Figure 3.9 Influence diagram for the waste generation sub-section

Waste generation is influenced by the economic conditions and the size of the population. A larger population definitely leads to a higher total volume of waste generated. Sudhir (1997) described the influences as follows: economic activity and population growth affect household income, and household income in turn affects per capita waste generation. Higher income households tend to produce larger amounts of waste, and some researchers have reported a link between economic growth and an increase of the amount of waste generated (Hjorth and Bagheri, 2006). As living conditions improve, consumption grows and the waste composition changes – the waste generated becomes more bulky and lower in density, and presents more difficult for it to be composted. However, a higher standard of living increases the percentage of recyclable waste, and higher participation rates of recycling (Dyson and Chang, 2005). Schultz et al. (1995) in a review article cite numerous studies reporting a significant positive relationship between rising income and increased recycling effort.

The amount of waste collected is determined by the collection rate, which is further influenced by the cost required and the budget allocated for waste collection. Normally, in developing countries, the percentage of the budget allocated to waste collection in the total waste management budget is higher than that in developed countries (Ogawa, 1996). This is due to different conditions pertaining to waste management prevailing in these countries. A higher percentage of budgets for waste collection will help to address the problem of illegal dumping in developing countries. Developed countries pay more attention (and allocate a higher proportion of their waste management budgets) to the improvement of waste treatment and disposal to diminish the negative effects to the environment.

Waste recycling is influenced by the percentage of the recyclable waste and market conditions for recycled waste. It may also be influenced by the budget allocated to this section, because in some countries, waste recycling is still not profitable and still needs support from the government. At present, the percentage of recyclable waste in developed countries is about forty percent, which is higher than that in developing countries. However, the recycling percentage in developed countries is only around ten percent (US Environmental Protection Agency). That is to say, twenty to thirty percent of recyclable waste is incinerated or directly disposed. The recycling index variable is defined to evaluate the performance of the potential plans with regard to the recycling aspect. Increasing recycling may increase the cost incurred in recycling plants.

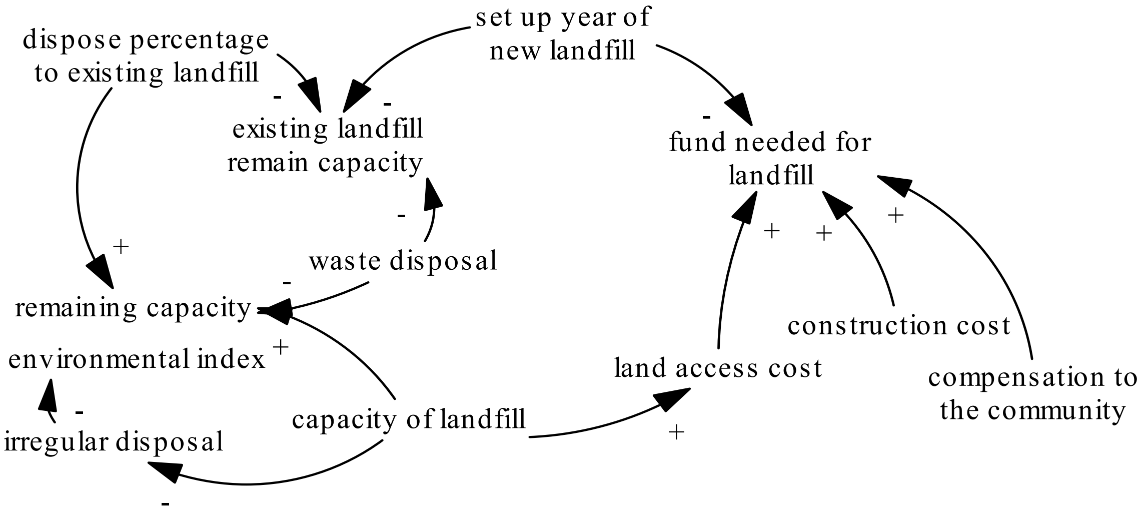


Figure 3.10 Influence diagram for the landfill sub-section

Landfill is one of the most fundamental methods of waste disposal. The process of waste disposal ends in a landfill. The waste collected, with or without treatment, should be disposed of in a landfill to meet the requirement for environment protection. A key consideration of landfill is the land availability. Landfills need considerably large spaces to contain the waste. The cost used to acquire the land for landfill should be considered. Moreover, usually the government has to give monetary compensation to get the acceptance of the community where the landfill is to be built, for the landfill may cause much unpleasant impacts. The compensation will depend on the opinion of the community (Charnpratheep, K. et. al, 1997). These opinions are classified into several levels such as acceptable, negotiable, oppose, and strongly oppose. For each level, the government may offer different levels of compensation and benefits. If some communities express strong opposition to locating the facility in their community, they may receive a higher compensation or lose the opportunity to get the compensation and benefits if the facility is not located in their communities. The compensation and benefits will increase the access cost of the site.

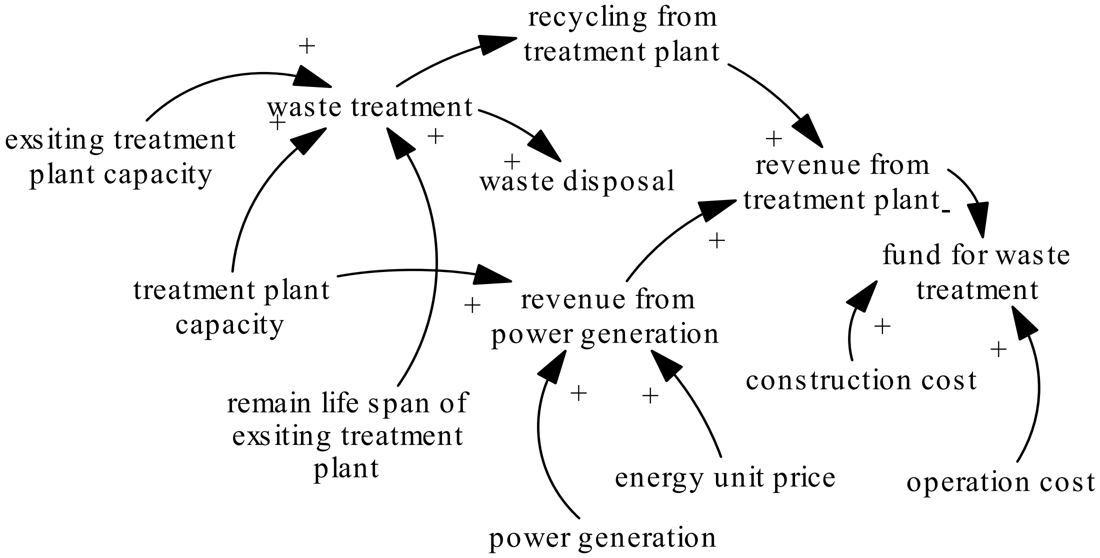


Figure 3.11 Influence diagram for the incineration sub-section

After the waste is collected, it will be transported to the treatment plant to be recycled or incinerated. Through these operations, the waste can be reused and the value can be recovered – issues to which the public is paying an increased amount of attention.

The incineration plants offer an efficient way to reduce the waste volume, reduce demand for landfill space, and recover value from waste by power generation and recycling. However, it needs a large investment of capital and incurs high operating costs. Even though the revenue from recycling and power generation can cover a part of the operational cost, it may still become a heavy burden to the government's budget. Furthermore, the communities where the incineration plant is to be built are often concerned about the environmental impacts and higher charges. Public involvement should also be considered in the plan to set up any new incineration plant.

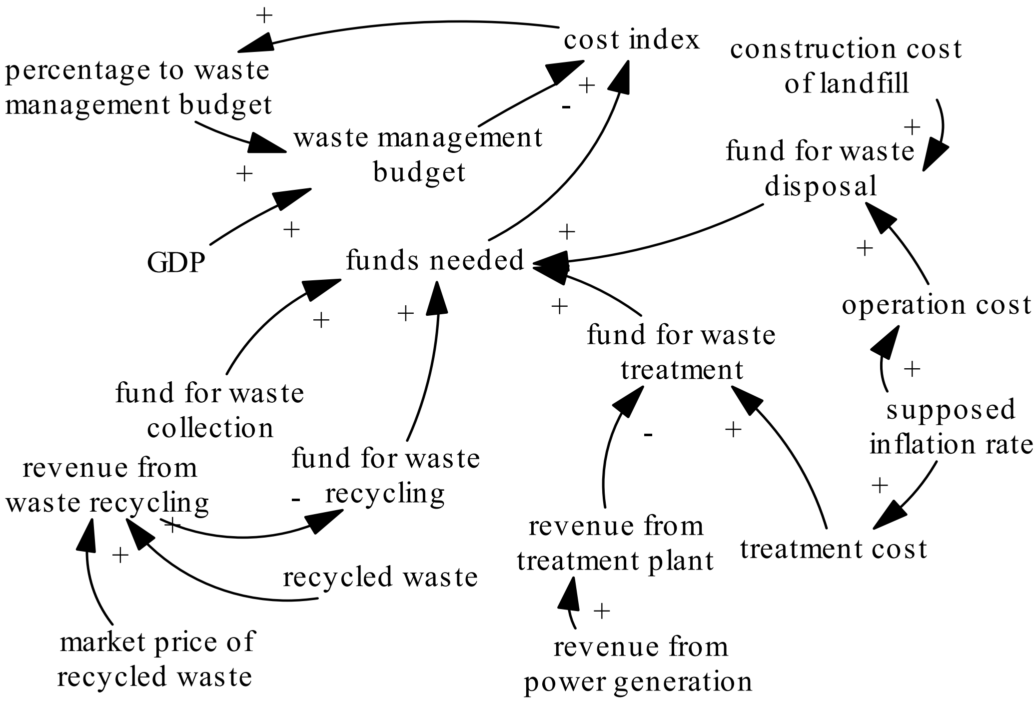


Figure 3.12 Influence diagram for the cost sub-section

Cost is an important consideration in this system. The building of all the waste management facilities needs capital investment, which will increase the funds required for waste management. Meanwhile, the waste recycled and the power generated from waste incineration can produce revenue, which will reduce the funds required for waste management. Each year the government allocates a budget for waste management. The difference between the funds required and the budget allocated should be considered by the decision maker when choosing alternative plans. This difference can be reflected by the cost index value, which is defined in the following sections. More funds required and fewer budgets allocated lead to a higher cost index value, indicating that the budget should be increased.

The stock-flow diagram is composed of the stock variables and the flows among them. Stocks (or levels) represent accumulations within the system, which continue to exist when all activities cease. They represent the state of the system and their values can only be changed by flows. There are two kinds of flows embedded in the feedback loops, information flows and material flows. Material flow, also called flow, represents the material flowing into, between, or out of the system boundary. Information flows are used to provide model inputs and describe the material flows. The structure of the stock-and-flow diagram is presented in Appendix I. Figure 3.13, which displays the major level variables of the model and the material flow of waste between them, represents the heart of the whole stock-and-flow diagram.

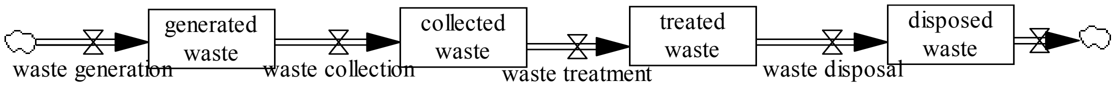


Figure 3.13 Main stocks and flows in the system dynamics model

3.2.2.4 Variables and equations of the model

In this section, the variables and equations used in the SD model are presented, together with a discussion of the choice of the simulation horizon and evaluation indicators.

A system considered by system dynamics can be represented through a series of (e.g. m) first-order differential equations:

$$dx_i/dt = f_i(x_1, x_2, \ldots\ldots, x_m; u_1, u_2, \ldots\ldots u_r; t) \quad i=1, 2, \ldots\ldots m.$$

where $x_i(t)$ are state variables, $u_1, u_2, \ldots\ldots u_r$ are the control variables.

With the vector expression: $X=\begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_m \end{bmatrix} \quad U=\begin{bmatrix} u_1 \\ u_2 \\ \cdots \\ u_r \end{bmatrix}$

And the output can be expressed through output variables y_j

$$y_j = g_j(x_1, x_2, \ldots\ldots, x_m; u_1, u_2, \ldots\ldots u_r; t) \quad j=1, 2, \ldots\ldots h.$$

The variables in the model are listed in the following table. The decision variables are used to describe alternative plans. Their values are determined according to the different alternatives chosen. The model acts as a decision support aid with regards to the building of waste treatment/disposal facilities, so the decision variables concern the starting time and size of the facilities to be built.

Decision issues	Decision variables
Time of setting up the new treatment plant	treatment plant set up year
capacity of the newly-built treatment plant	new treatment plant capacity
the capacity of the new landfill	capacity of new landfill
the opposition of the community	community reaction

The other variables are listed below. The constant variables are the parameters for constructing the simulation scenarios. The values of the level variables and auxiliary variables are determined by the values of decision variables and parameters involved in their equations.

Base year environmental index	Constant
budget allocated	Auxiliary
budget needed	Auxiliary
capacity of existing treatment facility	Constant
collected waste	Level
collection rate	Constant
community reaction LOOKUP	Lookup
compensation to the community	Auxiliary
construction cost	Constant
construction cost of landfill	Auxiliary
construction period	Constant
cost index	Auxiliary
delay allocation	Auxiliary
dispose percentage to existing	Auxiliary
population	Level
population growth	Auxiliary
power generation	Auxiliary
recyclable rate LOOKUP	Lookup
recyclable waste rate	Auxiliary
recycling	Auxiliary
recycling cost	Auxiliary
recycling from treatment	Auxiliary
recycling index	Auxiliary
recycling rate	Constant
reduce rate	Constant
remain capacity	Auxiliary
remain capacity of existing landfill	Auxiliary
remain life span of old plant	Constant

landfill			
disposed waste	Level	revenue from power generation	Auxiliary
energy unit price	Constant	revenue from treatment plant	Auxiliary
environment index	Auxiliary	SAVEPER	
FINAL TIME		supposed inflation rate	Constant
fund for waste disposal	Auxiliary	the set up year of new landfill	Constant
fund for waste treatment	Auxiliary	treatment capacity	Auxiliary
fund of collection	Auxiliary	TIME STEP	
GDP	Level	Treated waste	Level
GDP growth	Auxiliary	unit cost of collection	Auxiliary
GDP growth rate	Constant	unit operation cost of treatment	Auxiliary
GDP per capita	Auxiliary	unit recycling cost	Auxiliary
generated waste	Level		
INITIAL TIME		untreated waste	Auxiliary
interest rate	Constant	waste collection	Auxiliary
irregular disposal	Auxiliary	waste disposal	Auxiliary
land access cost	Auxiliary	waste generation	Auxiliary
net growth rate of population	Constant	waste generation per capita	Auxiliary
operation cost	Auxiliary	waste generation per capita LOOKUP	Lookup
percentage of budget to waste management	Auxiliary	waste treatment	Auxiliary
percentage of irregular disposal	Constant		

In this thesis, there are six stock variables. That means m=6, and involves 6 first-order differential equations.

$$\mathrm{X} = \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_6 \end{bmatrix}$$

The stock variable refers to a given element within a specific time interval. The rate reflects the extent of behavior of a system. The change of stock at time t is calculated from the difference between the inflow and outflow at time t. The value of stock can be represented by a first-order differential equation as follows:

$$stock_t = stock_{t-dt} + dt\ (inflow_t - outflow_t)$$

or

$$dstock(t)/dt = inflow_t - outflow_t$$

where $stock_t$ means the value of the stock variable at time t, which is calculated by adding the value of $stock_{t-dt}$ to the input and output difference during time dt.

Assume that $inflow_t - outflow_t = constant \times stock(t)$

so $dstock\ (t)\ /dt = constant \times stock(t)$

then $stock(t) = stock(0)e^{constant * t}$

where $stock(t)$ means the value of the stock variable at time t, $stock(0)$ means the initial value of the stock variable at time 0.

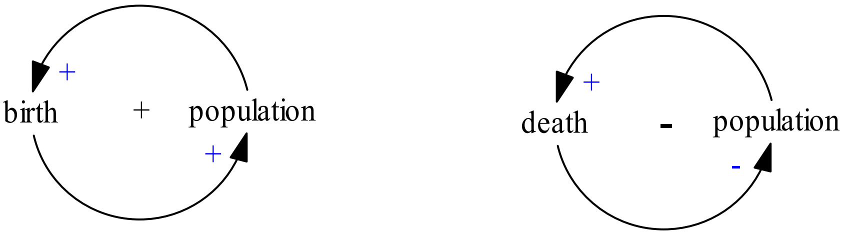
The system equations formulated as the result of a step-by-step establishment of the mathematical model needs to be solved. The solution of the system equations can be facilitated in two ways: through an analytical solution method and through computer simulation. In this thesis, the latter approach is adopted, facilitated by the ready availability of several computer packages. Numerous factors affect the formation and function of a real system, resulting in making a whole system more complex. The complexity of a system causes the inevitable adoption of a large number of system components or variables to account for the mechanism of the system. However, the derivation of a mathematical formulation for each of the system variables is accompanied by a vast amount of calculation work, which usually causes time-consuming and repeated effort. This obstacle can be resolved efficiently by utilizing simulation languages. A simulation language is a set of computer codes that implement a large amount of computations. User-friendly software that uses simulation languages enables the researcher to build a system dynamics model in an efficient and specific manner. A representative simulation software for system dynamics is VENSIM, which is used to construct the SD model in this thesis. It implements continuous simulation to solve system dynamics models. It facilitates quantifying time-dependent behaviors of any type of complex structures in a SD model. It is a useful tool for calculating a large number of system equations and various types of system structures. The equations of level, rate, and auxiliary variables are input to form the model. The results of the simulation are presented in graphical forms in an interactive manner.

The time horizon of the SD model is 30 years. Various time horizons are adopted by different scientific disciplines of management. Frederiksen (1994) et al. commented that the selected time horizon should reflect the time at least equal to the useful life of the largest commitments. Soroczynski (2002) also suggested that time horizons need to be consistent with human perception of the future. The service life of the waste treatment/disposal facility is usually 20 to 30 years. Based on the considerations mentioned, the time horizon of the SD model was selected to be 30 years.

A suitable step size is also important to the simulation. The term *dt* in the mathematical equations is represented by DT (Delta Time) in VENSIM, which represents the step size. The determination of the step size depends on the researcher. VENSIM applies the integration method based on the step size. The smaller the step size, the more accurate the results are. Because many statistics about waste management are available annually, and in order to allow a reasonable time resolution in the timing of the capital investments, the value of DT is set to be one year.

Modeling in system dynamics should involve an understanding of the feedback structure that is inherent in the complex system. A feedback loop consists of two or more linkages connecting each other. The loop starts from one variable, from which information or physical flows emanate. These flows are transmitted to a series of variables in the chain through the appropriate transformation process, and finally return to the starting variable.

The feedback relations can also be represented with (+) for positive feedback and (-) for negative feedback. A positive feedback loop is represented with '+' and a negative feedback loop is represented with '-'. Positive feedback loop, which is also called reinforcing feedback loops, contains an even number of negative relations. A negative feedback loop, which is also called balancing feedback loop, contains an odd number of negative relations. For example in Figure 3.14, Loop 1 is a positive loop and Loop2 is a negative loop.



Loop 1 **Loop 2**

Figure 3.14 Positive and negative feedback loops

The mathematical expressions of feedback are as follows:

$$(inflow_t - outflow_t)dt = dstock(t)$$

Assume that $inflow_t - outflow_t = constant \times difference(t)$

and $difference(t) = goal - stock(t)$

where *goal* means the goal value of the variable, *difference* means the difference between the goal value and the output value of the variable at time *t*.

$$dstock(t)/dt=constant\times(goal-stock(t))$$

so $$stock(t)=goal-[goal-stock(0)]e^{-constant*t}$$

In this thesis, the *budget allocated* feedback loop is a negative loop, which is shown in figure 3.15. The value of *percentage to waste management budget* affects the amount of budget allocated to waste management. The value of the variable *budget allocated* determines the value of *cost index*, which influences the *percentage to waste management budget* successively.

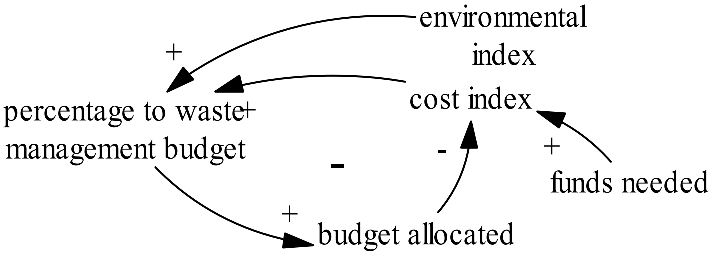


Figure 3.15 Budget allocated negative feedback loop

The following sections present the equations of the SD model. The VENSIM equations refer to some utility functions from the software, which are described and explained in Appendix II.

i) The waste flow

The equations in this section mainly describe the flow of waste. The amount of waste transported to the incineration plant is equal to the amount of waste generated minus that recycled and that irregularly disposed. The waste finally disposed into the landfill includes two parts. One part is the collected waste that is neither recycled nor incinerated; the other part is the cinder from the incineration.

```
WD=WC-WR-WT + RAI                                    (3.1a)
WG=WGC*population                                    (3.1b)
WR=WC*RIR+RIT                                        (3.1c)
```

WUC=WG-WC (3.1d)
WUT=WC-WT-WC*RIR (3.1e)
EI= (WUC+WUT)/population (3.1f)
EIB= (WUC+WUT)/population
(with the data of the first year) (3.1g)
Environmental index=EI/EIB (3.1h)
Recycling index=WR/(WG*RAR) (3.1i)

WC- the amount of waste collected in each year
WG- the amount of waste generated in each year
WT- the amount of waste treated in treatment plants in each year
WD- the amount of waste disposed in landfills in each year
WR- the amount of waste recycled in each year
WUC- the amount of waste uncollected in each year
WUT- the amount of waste untreated in each year
RAI- remainder after incineration in each year
WGC- waste generated per capita in each year
RIT-waste recycling in treatment plant in each year
RIR-waste recycling rate
RAR-waste recyclable rate in each year
EI-environmental indicator in each year
EIB-environmental indicator in the first year of simulation

These equations are expressed using VENSIM terminology as:

```
waste generation = population * waste generation per capita * 365
      /1000
      Units: ton/Year
```

The waste generated each year is calculated as the product of the waste generation per capita per day and the size of the population, with some unit conversion factors to account for the fact that the unit of waste generation per capita is kg/day.

The waste generation per capita is influenced by the GDP per capita, and is calculated through a LOOKUP function. For various range of GDP per capita, the waste generation per capita takes on the corresponding value shown in the following table.

Waste generation per capita	0	0.4	0.8	1.5
GDP per capita	<2000	2000-5000	5000-20000	>20000

```
waste generation per capita = waste generation per capita LOOKUP(GDP
      per capita)
Units: kg/day
waste generation per capita LOOKUP((0,0), (2000,0.4), (5000,0.8),
      (20000,1.5))
      Units: dimensionless
GDP per capita = GDP/population
      Units: $
GDP = INTEG (GDP+GDP growth)
      Units: $
GDP growth = GDP * GDP growth rate
      Units: $/Year
```

In the model, it is assumed that in different simulation scenarios, the GDP grows at different rates; but within the same scenario, the rate is a fixed. The value of GDP for each year is equal to the integer part of the sum of GDP growth and GDP of last year.

```
population = INTEG (population growth)
      Units: person
population growth = population * net growth rate of population
      Units: person/Year
```

The rationale behind the equations about population is the same as those for GDP.

```
waste treatment = MIN( treatment plant capacity, (waste collection-
      waste recycled))
      Units: ton/Year
```

The amount of waste treated in the treatment plant is the smaller one between the plant capacity and the amount of waste collected but not recycled.

```
waste disposal = waste collection-recycling-waste treatment + waste
      treatment * (1-reduce rate)
      Units: ton/Year
```

The amount of waste disposed in the landfill is the amount of waste that is not recycled and not treated, plus the residue after incineration.

```
untreated waste = waste collection-waste treatment- recycling
      Units: ton/Year
environment index = (irregular disposal + generated waste * (1-
      collection rate)+untreated waste)/population/base year
      environmental index
```

```
      Units: dimensionless
```

The environmental index is one of the evaluation indicators of the model; its value is determined by the sum of the uncollected waste, untreated waste and irregular disposed waste divided by the value of the population size. The reasons behind the definition of the environment index are presented in detail in Chapter 4.

```
recycling = waste collection*recycling rate
      Units: ton
recycling from treatment = IF THEN ELSE(unit operation cost of
      treatment>=0.0005, 0.05, 0)
      Units: dimensionless
recyclable rate LOOKUP((0,0), (2000,0.2), (5000, 0.4), (20000,0.5))
      Units: dimensionless
recyclable waste rate = recyclable rate LOOKUP(GDP per capita)
      Units: dimensionless
```

The recycling rate in the incineration plant (`recycling from treatment`) is influenced by the unit cost of the recycling cost in the plant, which is presented through an `IF THEN ELSE` function. If the cost is larger than or equal to $0.5 per ton, the recycling rate is 5%; otherwise, the rate is zero. The parameter value is assumed based on the references presented in the above contexts.

The percentage of waste that can be recycled is influenced by the quality of life, which is represented by the GDP per capita in this model. It is calculated through another LOOKUP function. Values used for GDP per capita are shown in the following table (the reasons behind the boundary values are discussed in the following section).

GDP per capita	<2000	2000-5000	5000-20000	>20000
Recyclable waste rate	0	0.2	0.4	0.5

```
recycling index = (recycling from treatment + recycling
      rate)/recyclable waste rate
      Units: dimensionless
```

The recycling index is another evaluation indicator. It is obtained by dividing the sum of recycled waste by the amount of recyclable waste. The rationale behind its definition is also presented in Chapter 4.

ii) Treatment and disposal facilities

$$TC=OC \tag{3.2a}$$

(Before the adoption of new treatment plant, the capacity of waste treatment TC is the capacity of the old plant OC)

$$TC=NC+OC \tag{3.2b}$$

(After the adoption of a new plant and before the closing of the old plant, the treatment capacity TC is the sum of the capacity of new plant NC and that of old plant OC.)

$$TC=NC \tag{3.2c}$$

(After the closing of the old plant, the treatment capacity TC is the new plant capacity NC.)

$$RNL=NL-DNL \tag{3.2d}$$

$$ROL=OL-DOL \tag{3.2e}$$

The remaining capacity of the landfill is equal to the total capacity of the landfill minus the amount of waste that has been disposed in the landfill, which is applicable to both the new and old landfills (3.2d, 3.2e). The service lives of the landfills end when `RNL/ROL` turns zero.

TC-waste treatment capacity
OC-old plant capacity
NC-new plant capacity
NL- total capacity of new landfill
OL- total capacity of old landfill
DNL-waste disposed in new landfill in each year
DOL-waste disposed in old landfill in each year
RNL-remaining capacity of new landfill at the end of each year
ROL-remaining capacity of old landfill at the end of each year

The corresponding VENSIM equations are:

```
treatment capacity = capacity of existing treatment facility +
      STEP(new treatment plant capacity, treatment plant set up
```

```
      year)-STEP(capacity of existing treatment facility, remain life
      span of old plant)
      Units: ton/Year
```

The treatment capacity is defined as the sum of the capacity of the existing plant and that of the new one. A STEP function is used to integrate the three equations together, namely “TC=OC”, “TC=NC+OC”, and “TC=NC”. Before the new treatment plant is set up, the first STEP function returns zero. The value of “treatment capacity” equals to “capacity of existing treatment”. When time goes to the set up year of the new plant, and before the end year of the old plant, the first STEP function returns the value of “new treatment plant capacity”, and the second STEP function returns zero. The value of “treatment capacity” equals to “capacity of existing treatment” plus “new treatment plant capacity”. When time goes to the end of the life span of the old plant, the second STEP function returns the value of “capacity of existing treatment”. The value of “treatment capacity” equals to “capacity of existing treatment” plus “new treatment plant capacity” and minus “capacity of existing treatment”, which is finally the “new treatment plant capacity”.

```
remaining capacity of existing landfill = IF THEN ELSE( existing
      landfill capacity-disposed waste*dispose percentage to existing
      landfill>0, existing landfill capacity-disposed waste*dispose
      percentage to existing landfill, 0)
      Units: ton
dispose percentage to existing landfill = 1-STEP(dispose percentage
      to new landfill, (construction period + the set up year of new
      landfill))
      Units: dimensionless
remaining capacity of new landfill= MAX( capacity of new landfill-
      disposed waste*(1-dispose percentage to existing landfill), 0)
      Units: ton
```

The IF THEN ELSE function is used in the equation for the remaining capacity of the existing landfill. If the value of “existing landfill capacity” minus the amount of waste disposed in it is larger than zero, that value is returned as the remaining capacity;

otherwise, it is zero. The equation for the remaining capacity of the new landfill is formulated in the same way, except that the MAX function is used. The value of the remaining capacity is the larger of zero and the difference between the "capacity of new landfill" and the amount of waste disposed in it. When the remaining capacity turns to zero, the landfill is considered to have reached its capacity.

iii) Financial flows

FC=CC*WC (3.3a)
FR=RC*WR (3.3b)
FT=OTC*TC-RT and
FT=OTC*TC-RT+CT*NC (during the construction period) (3.3c)
FD=OLC*(RNL+ROL) and
FD= OLC*(RNL+ROL) +CL*NL+CCL+LA*NL (3.3d)
(during the building period of new landfill)
BN=FC+FD+FR+FT (3.3e)
BA=GDP*PB (3.3f)
Cost index= BN/ BA (3.3g)

The basic idea of this sub-section is that the cost incurred is the sum of the funds needed for waste collection, waste disposal, waste incineration, and waste recycling (3.3e). The budget allocated to waste management is assumed a certain percentage of the GDP each year (3.3f). The cost index, which is used to evaluate the financial issue, is obtained by dividing the value of the budget needed by the value of budget allocated (3.3g). The definition of the cost index is presented in Chapter 4.

FC-fund for waste collection in each year
FD-fund for waste disposal in each year
FR-fund for waste recycling in each year
FT-fund for waste treatment in each year
RT-revenue from treatment plant in each year
CT-unit construction cost of new treatment plant
CL-unit construction cost of new landfill
OTC- unit operation cost of treatment
OLC-unit operation cost of landfill
CC- unit cost of collecting waste
RC-unit cost of recycling waste

CCL- compensation cost for new landfill to the community
LA- unit land access cost for new landfill
BN- Budget needed for waste management in each year
BA- Budget allocated to waste management in each year
PB-percentage of budget allocated to waste management

The corresponding VENSIM equations are:

```
unit cost of collection = IF THEN ELSE(collection rate>=0.9,
      16*(1+assumed inflation rate)^Time, 10*(1+assumed inflation
      rate)^Time)
      Units: $/ton
fund of collection = unit cost of collection and transportation*waste
      collection
      Units: $
```

The cost for waste recycling is influenced by the collection rate. It is assumed that if the collection rate is above 90%, the unit collection cost is a particular value; while, if the rate is under 90%, the unit collection cost adopted is a higher value.

```
fund for waste disposal = IF THEN ELSE(remain capacity of existing
      landfill>0, operation cost of the existing landfill + cost
      needed for the new landfill, cost needed for the new landfill)
      Units: $
```

The fund for waste disposal includes two parts - the operational cost of the existing landfill and the cost needed for the construction and operation of the new landfill.

```
cost needed for new landfill=STEP(annuity of the investment during
      the construction period, set up year of new landfill)-
      STEP(annuity of the investment during the construction period,
      (set up year of new landfill+ construction
      period))+STEP(operation cost, (set up year of new landfill+
      construction period))
      Units: $
annuity of the investment during the construction period= present
      value of the investment for new landfill*interest
      rate*(1+interest rate)^construction period/((1+interest
      rate)^t-1)
      Units: $
```

The cost needed by the new landfill includes the initial investment and the operational cost. The initial investment, which is mainly the construction cost, is usually not totally paid at one time, but several times during the construction period. It is calculated taking into consideration the time value of money, and is annualized over the construction period.

```
present value of the investment for new landfill=land access cost +
      compensation cost to the community + construction cost of
      landfill
      Units: $
```

The initial investment includes the land access cost, construction cost and the compensation cost to the community.

```
construction cost of landfill = capacity of new landfill*10
      Units: $
community reaction LOOKUP((0,0), (1,1e+005), (2,2e+005), (3,4e+005),
      (4, 5e+005))
      Units: dimensionless
compensation to the community=community reaction LOOKUP(community
      reaction)
      Units: $
land access cost = capacity of new landfill * unit land access cost
      Units: $
```

The compensation cost is defined according to the reactions of the community where the site is located. A LOOK UP function is used to make sure the appropriate level of compensation will be given based on the community reaction.

```
operation cost = IF THEN ELSE(remain capacity>0, 1.5e+008 *
      (1+supposed inflation rate)^Time, 0)
      Units: $/ton
unit operation cost of treatment = (50+STEP(50,treatment plant set up
      year)-STEP(50, remain life span of old plant))*(1+supposed
      inflation rate)^Time
      Units: $/ton
```

The operational cost includes the cost to operate the existing landfill as well as the new one. It is calculated through product of the unit operation cost and the remaining capacity of the landfills.

```
revenue from power generation = energy unit price*power generation
```

```
      Units: $
revenue from treatment plant = revenue from power generation +
      recycling from treatment
      Units: $
fund for waste treatment = unit operation cost of treatment*treatment
      plant capacity-revenue from treatment plant + construction
      cost*treatment plant capacity
      Units: $
```

The operation of the incineration plant also generates revenue through the incineration of the waste to generate power and the recycling of waste. The total fund needed by the incineration plant is obtained by subtracting the revenue from the cost.

```
budget needed = fund for waste disposal + fund for waste treatment +
      fund of collection + recycling cost
      Units: $
budget allocated = GDP*percentage of budget to waste management
      Units: $
delay allocation = DELAY FIXED( budget allocated, 1, 2.3e+009)
      Units: $
cost index = budget needed/delay allocation
      Units: dimensionless
```

Budget allocated to the waste management normally cannot be used immediately, and the plan is usually made one financial year in advance. The DELAY function is used to deal with the delay of the budget allocation.

3.2.2.5 Estimation of the parameter values

Owing to the absence of data from a real case, the parameters are set based on reference data from different resources and a hypothetical project. They are chosen to be as realistic as possible. The application of the model with such parameters and variables is only for demonstration purposes. The referenced data include those from developing countries as well as developed countries because the planning methodology is proposed for use in developing countries with the initial condition similar to that of a developing economy. As the economy develops and the raising of environmental hygiene standards, advanced facilities are planned in these countries; then, the operating standards for the new facilities will be based on the data from developed countries.

Waste generation

In the section on waste generation, the required data are GDP growth rate, population growth rate, percentage of budget allocated to waste management, and waste generation per capita. As the research focuses on big cities in developing countries, the GDP growth rate of China, which is around 8% per year (http://www.nationmaster.com), is taken as a reference. Likewise, the population growth rate is also estimated based on the condition of major cities in China, which is about 0.7% per year (http://www.nationmaster.com). Data on the waste generation per capita and the GDP per capita from several developed and developing countries in Asia is compiled from separate sources (see Table 3.2).

Table 3.2 Per capita waste generation and GDP (selected Asia cities)

City/country	Waste generation per capita (kg/cap/day)	GDP per capita (US$/cap) (9)
Beijing/China	0.88 (1)	4,671
Tokyo/Japan	1.5 (2)	27,033
Hong Kong/China	1.17 (3)	24,649
Bandung/Indonesia	0.71 (4)	2,969
Khanthabouri/Lao PDR	0.37 (5)	1,592
Pattaya/Thailand	1.63 (6)	6,575
Barisal/Bangladesh	0.4 (7)	1724
Yangon/Myanmar	0.45 (8)	1491

Data sources:
(1) Beijing Environmental Sanitation Administration, 1996
(2) Japan Waste Management Association, 1996
(3) Planning, Environment and Lands Bureau, 1994
(4) UNDP/World Bank Water and Sanitation Program, 1993
(5) Personal communication with UNDP/World Bank Water and Sanitation program, RWSG-EAP, Lao PDR and Cambodia office, 1998
(6) Pollution Control Department of Thailand, 1998
(7) World Bank, 1998
(8) Cleaning Department, Yangon City Development Committee cited in Tin et al., 1995
(9) www.nationmaster.com

Adopted from 'what a waste: solid waste management in Asia' (Hoornweg et. al, 1999)

Based on the data presented in Table 3.3, four ranges of per capita GDP were recognized, namely below $2000, $2000 to $5000, $5000 to $20000, and above $20000. The relationship between GDP per capita and the waste generation per capita (waste generation per capita LOOKUP) is specified by the following pairs of values.

GDP per capita	0	2000	5000	20000
Waste generation per capita	0	0.4	0.8	1.5

Based on a survey of the data from three regions (see Table 3.2), it is found that the percentage of recyclable waste increases with per capita GDP. The recycling rate can be influenced by government policy, which also influences the recycling cost. One study has found that the unit recycling cost first grows with the recycling rate but then decreases beyond a certain level (12%) (DEPPA, 1997). In the model, the following pairs of values specify the relationship between GDP per capita and recyclable waste rate (recyclable rate LOOKUP).

GDP per capita	0	2000	5000	20000
Recyclable waste rate	0	0.2	0.4	0.5

Table 3.3 Waste recycling rate and GDP (selected countries)

	Thailand	Hong Kong	U.S.
Percentage of recyclable waste (%)	40	60	50
Percentage of recycled waste (%)	15	8	28
GDP per capita ($)	6575	24646	35935

Data sources:
Environment Protection Department of Hong Kong, 1994
U.S. Environmental Protection Agency, 2001
Institute for Global Environmental Strategies, 2002
www.nationmaster.com

Data about the waste treatment/disposal facilities

The main data required in the planning of the incineration plant are those about its construction and operation. In this model, it is assumed that the new incineration plant is not built immediately but only after the lapse of a number of years within the study period. It is also assumed that a relatively advanced plant will be built to meet the waste treatment requirements.

Table 3.4 Process capacities of incineration plants

	Denmark	Singapore
Incineration capacity	46284ton/year	18250ton/stoker/year
Power generation capacity	22373MWh/year	Generation rate 60MW

Data sources:
Tuas South Incineration Plant, Singapore
Waste incinerator and gas engine produces heat and electricity in Denmark

To estimate the construction and operational characteristics of this plant, data from two developed countries (Singapore and Denmark) are taken as reference (see Table 3.3). These two plants are on different scales - the plant in Singapore is bigger with six stokers. In the study, two alternative plant capacities were considered. The first was a larger plant with a capacity of one million tons per year whilst the second plant was half as small, having a capacity of only half million tons per year. The power generation capacity is related to the plant capacity. The Denmark plant is taken as a reference since it reports the total power generated per year. It was not possible to check this against a similar figure for the Singapore plant since there was no information on the number of days on which maintenance of the stokers was carried out at that plant. The following empirical relationship was established between the waste disposal capacity per year and the power generation capacity per year based on the data of the Denmark plant:

Power generation (kw) = 480 (kw/ton)* incineration plant capacity (ton)

The data about the landfill include the costs of construction and operation, the capacity of the new landfill, and the level of public opposition. One of the main issues that should be addressed at this stage is the site selection. Data such as maps of the municipality showing land use, the network and depth of groundwater, the road network system, topography, geology, the network of electric/gas transmission lines, and the location of other public services is needed to help in site selection. Selecting a site to address public concerns is important as strong public objection may lead to failure in the operation of the new landfill.

The capacity of the new landfill is another key consideration. In order to minimize the transaction costs associated with design, permission, closure and post-closure requirements, the new landfill should ideally have the capacity to be operated for ten to twenty years. The major evaluation criteria used for site selection are as follows:

i) The conditions of the site itself

The area needs to be large enough to provide services during for the design life of the project. The depth of the ground water and the permeability of the soils should also be considered because if the level of ground water is too high or the soil is permeable, the leachate of the landfill may pollute nearby sources of potable water. Furthermore, the direction of the wind is also a consideration. It is not suitable to locate the facility upwind of the city with respect to prevailing winds.

ii) The relationship with other buildings around

It is not pleasant to locate a museum or an opera house near a waste disposal plant, neither is it pleasing for people to see vehicles full of garbage while shopping. Therefore, the waste disposal facilities or transfer stations should be located considerably far away from downtown and avoid being near the places of public interest. Because some facilities such as incineration plants and transfer stations emit undesirable smells and have a negative impact on aesthetics, they should also be a certain distance away from residences.

iii) Relationship with other infrastructure

When considering the building of new waste management facilities, engineers should not ignore the impact to other service infrastructure. For example, landfills need considerable amount of deep excavation to prepare the site. Buried electric transportation and telecommunication cables, and pipelines transporting water or gas may be affected. There should be a certain distance between the new site and these lines. Landfills should also be kept far away from potable water wells. On the other hand, the new site selected ought to be near existing roads to minimize the travel time and transportation cost.

iv) After use and future development

It is at the beginning of the planning that the planner should consider the after use of the facilities' sites, especially the landfills. Because of the weak foundation, the landfill sites after closure cannot be used for heavy industries or tall buildings. They are neither suitable to be used for residence, hospital, schools, where the population density are high, for fear of the leak of polluted gas or liquids. Normally, these sites can be used as greenbelts, or for recreation and light industries. The planner should also consider the future development of the city over the course of the service life of the disposal facilities (usually 20 to 30 years). If the area to be occupied by the new landfill has the potential to be developed into a high-tech industry area, it might not make economic sense to site the facility there.

The data of suitable potential sites for the new landfill can be input into the model for comparison.

To ally public concerns, potential sites should be evaluated to make sure they can meet all the environmental and safety standards. The analyst should also solicit feedback from the community residents through surveys and dialogue sessions. The reactions of the community can be characterized qualitatively into several levels, such as strong opponent, opponent, negotiable and acceptable. The level of compensation is tied to the degree of opposition in the community. The level of community reaction and the compensation costs for the potential sites are input into the model.

Table 3.5 Capital costs of incineration plants

Incineration plant	Year	Construction Cost (million S$)	Capacity (Tons/Day)
Ulu Pandan	1979	130	1100
Tuas	1986	200	1700
Senoko	1992	560	2400
Tuas South	2000	900	3000

Data source: National Environmental Agency of Singapore

Table 3.6 Data about landfills

	(1)	(2)
Landfill area	350 hectare	100 hectare
Landfill capacity	63 Mm^3	43 Mm^3
Capital cost	300mil US$	330mil US$
Operation cost	-	23 M$/year
Weight reduction rate	80%	-

Data sources:
(1) Semakau Landfill in Singapore
(2) South East New Territories Landfill in Hong Kong

The capacity of the new landfill will be determined by the area of the site. The capital cost and operation cost will be influenced by the quality of construction and services to be achieved. In this model, it is assumed that a fairly advanced sanitary landfill and incineration plant will be built. The data of such facilities in some developed regions are taken as a reference. It can be observed from Table 3.5 that the construction cost of a landfill and the capacity increase with time because of the increasing requirement of the facility. Ignoring inflation, and in view of the data presented in Tables 3.5 and 3.6, it is supposed that the construction cost of the facility is decided by its capacity, which is calculated as the product of the unit construction cost and its capacity.

Table 3.7 Percentage of GNP allocated to waste budgets

City, country	Year	% GNP on waste management
New York, US	1991	0.48
Toronto, Canada	1991	0.33
London, UK	1991	0.28
Kuala Lumpur, Malaysia	1994	0.38
Budapest, Hungary	1995	0.33
Madras, India	1995	0.51
Lahore, Pakistan	1995	0.45
Dhaka, Bangladesh	1995	0.54

Data source:
What a waste: solid waste management in Asia, 1999

In the model, cost is an important consideration. The budget for waste management often determines the service level provided. From the research in some countries, it is found that the budget allocated for waste management is usually about 0.5 percent of the GNP (Hoornweg et. al, 1999). The figures in Table 3.7 show that in most developed and developing countries the percentage of the GNP spent on waste management is below 0.5%. The value of 0.5 percent of GDP is used in the hypothetical case study to determine the waste management budgets in this thesis.

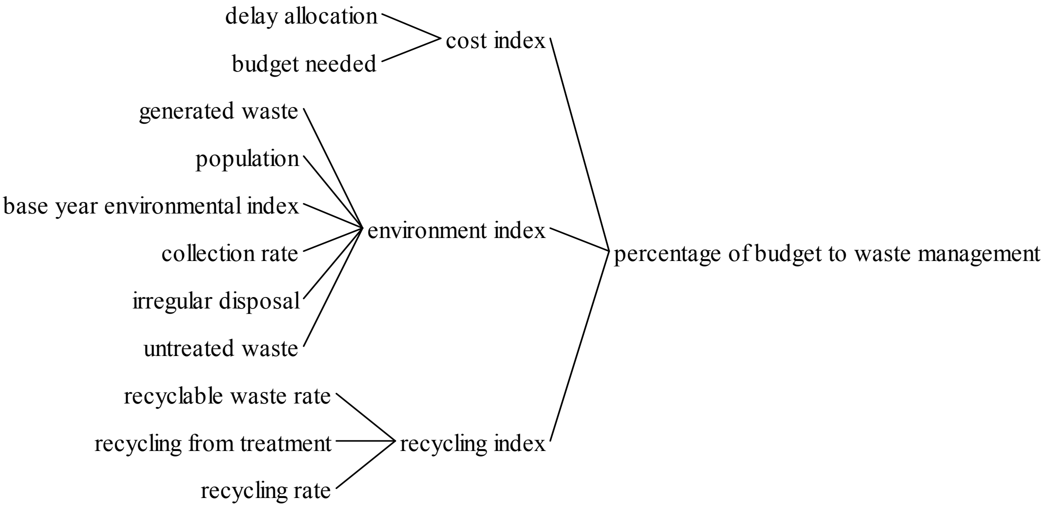


Figure 3.16 Cause tree of percentage of waste management budget

From the cause tree, it can be found that the percentage of the budget allocated to waste management is also affected by the feedback through the environmental index, cost index and recycling index. It means that when these indexes exceed threshold values, more budget may be needed to improve the conditions of environment or recycling operation. Then the percentage will be increased. In the hypothetical case, the value of 0.5% is the original value of the percentage of budget allocated to waste management.

3.3 AHP hierarchy for the selection of alternatives

An AHP decision hierarchy with its structure of objectives, criteria, sub-criteria and alternatives is constructed for the comparison and selection of alternative plans. Pair wise comparisons, based on the information provided by the SD model, are carried out within the hierarchy to measure the relative performance of each of the alternatives in terms of the individual decision criterion.

3.3.1 Justification of the application of AHP

The problem of selecting the most suitable alternative from the various combinations of decision alternatives involves a variety of criteria of cost, environment, etc., making it a multi-criteria decision making problem. Multiple criteria decision-making (MCDM) involves making preference decisions over a finite number of alternatives that are characterized by multiple, usually conflicting attributes. It can work with mixed data and allows the incorporation of both qualitative and quantitative information. (Mendoza and Prabhu, 1999). In this thesis, the analytic hierarchy process (AHP) is applied as the decision-making method. Compared to other methodologies, AHP offers a more intuitive and easier method of determining the importance of a fact or an attribute with respect to the decision at hand especially if the decision process is not easily quantified.

Other traditional methods that have been employed to aid the decision-making process include probability theory, certainty factors, fuzzy logic and utility functions.

Each of these methods offers a way of combining the different criteria and selecting a preferred alternative.

Probability theory measures the extent to which one set of propositions stands apart, out of logical necessity, from the rest. The advantage of probability theory is that it is firmly based on the mathematics of logic. P(E) is the probability that event E will occur or that it is true. It requires that probabilities of truth be assigned to each fact, criteria and the relationships among them. The determination of these probabilities is often quite difficult and sometimes artificial. There is no methodology for determining the values of these probabilities. Therefore, probability theory suffers from the problem that the probabilities required for the application are hard to acquire, even for experts. (Hanratty, 1992).

Fuzzy logic is an implementation of fuzzy set theory, which is an analogy to set theory where the “edge” of the set is fuzzy. The practical application of fuzzy set theory can be difficult because the coding of relationships and quantification of membership sets and fuzzy relationships becomes a much more intricate process. Fuzzy logic increases the difficulty of implementation and the complexity of the system. Ironically, fuzzy theory also requires the expert to express his choice in precise quantitative terms even though membership and relationships are defined over fuzzy sets.

A Utility function is based on derived equations that represent the utility of a given property. It requires an empirical and theoretical equation that rates the performance of each choice. However, for many problem domains, there is no proof that the functions are accurate, and sometimes the decision-making is based on subjective criteria that cannot be quantified in the utility functions.

Table 3.8 Comparison of four MCDM methods

Method	Preference educing mode	Decision output	Nature of input information	Availability of software package
TOPSIS	Direct rating	Choice	Cardinal & deterministic	No
SMART	Tradeoff & rating	Choice	Cardinal & deterministic	Yes
AHP	Pairwise comparison	Ranking & choice	Cardinal& either deterministic or non-deterministic	Yes
ELECTRE	Pairwise comparison	Choice	Either cardinal or ordinal & deterministic	Yes

There are also some MCDM methods analogues to AHP, such as ELECTRE, SMART and technique for preference by similarity to the ideal solution (TOPSIS). Most of these approaches consist of the stages of aggregation of the judgments with respect to all criteria for every alternative, and ranking of the alternatives according to the aggregated judgments (Zanakis et al., 1998). In table 3.8, the four methods are compared with regard to four aspects that are key issues in choosing a MCDM method. (Guirouni and Martel, 1998; Hanratty and Joseph, 1992).

Preference educing mode. The way to educe the outcome can be direct rating, tradeoffs or pairwise comparison, the choice of which can be according to the preference of the decision maker. In this thesis, the simulation outputs of the SD model show the differences between the performance of the alternatives, and make it easy to obtain the relative weights of the alternatives through pairwise comparison. It is easier to evaluate each alternative through relative weights than through absolute weights (Salmeron and Herrero, 2005).

Decision output. In TOPSIS, SMART and ELECTRE, the output is the choice of the most favorable alternative, while AHP can generate a ranking of all alternatives. In this regard, AHP can be said to provide more information to the decision maker rather than just simply reporting the "best" alternative.

Nature of input information. The requirement of the input information is another important issue in selection of the methods. In the application of AHP, some non-deterministic information that is not very accurate can be involved. Another advantage of the AHP is that it can educe a relative ordering of immeasurable subjective preferences by pair-wise comparison.

Software package. The availability of computer software greatly enhances the application of the methods. Aid of computer can reinforce the performance of the methods. The availability of software enhances the usability of AHP.

AHP has widespread application in solving MCDM problems. It is based on relative instead of absolute ratings. The strongest features of AHP are that it generates numerical priorities from subjective knowledge expressed in the estimates of paired comparison matrices (Liu and Hai, 2004). The multi-criteria aspect of decision analysis appears because outcomes must be evaluated in terms of several objectives. The purpose of the valuation model is to take the outcomes of the system model, determine the degree to which they satisfy each of the objectives, and then make the trade-offs to arrive at a ranking of the alternatives that express the preferences of the decision maker. AHP provides a simple but theoretically sound multiple-criteria methodology for evaluating alternatives. The strength of the AHP lies in its ability to structure a complex, and multi-attribute problem hierarchically, and then to investigate each level of the hierarchy separately. The pertinent data are derived from a set of pairwise comparisons. Using AHP, the priorities of the alternatives are scaled independently for every criterion at each level. The weight of each criterion is defined by the same procedure. Accordingly, the overall priority of alternatives is yielded. (Liu and Hai, 2005). AHP can help people cope with the intuitive, judgments in complex situations. Some researchers have criticized AHP (Dyer, 1990, Schoner, 1989). AHP is still an attractive tool because of its simplicity of use and its ability to translate subjective judgments into quantitative ratios (Stewart, 1991).

In engineering, AHP has been widely applied as a MCDM (Hanratty, 1992). Such as in civil engineering, it is used to evaluate the use of various structural materials (Mikawi and Mosalla, 1996). In biochemical engineering, it is used to evaluate the tissue engineering reactors (Omasa et.al, 2004). In transportation engineering, it is used in the evaluation of comprehensive highway transportation system (Wan and Kang, 1994). In chemical engineering, it is implemented into the expert system for laboratory reactor selection (Hanratty, 1992). It is also used in computer system selection (Vellore and Olson, 1991), and in engineering assessment and evaluation (Hwang, 2004; Tummala et. al, 1997).

3.3.2 Overview and the mathematical description of the methodology

The application of AHP method involves four steps:

i) Set up a decision hierarchy by breaking down the decision problem into a hierarchy of interrelated elements.

ii) Collect the input data of pairwise comparisons of the decision elements.

iii) Use the eigenvalue method to estimate the relative weights of the decision elements, and determine the consistency of the judgments.

iv) Aggregate the relative weights of the decision elements to arrive at a set of ratings for the decision alternatives.

In the first step, the decision hierarchy for the process is developed. The problem is broken down into a hierarchy of decision elements of different levels. Each level corresponds to a common characteristic of the elements in that level. The top level represented the main goal of the problem. The intermediate levels correspond to the criteria and sub-criteria, and the lowest level contains the decision alternatives.

Table 3.9 Scale used in pair wise comparisons

Intensity of Importance on an Absolute Scale	Definition	Explanation
1	Equal Importance	Two criteria contribute to the objective
3	Moderate Importance of A over B	Experience and judgment favor one criterion over the other
5	Essential or Strong Importance of A over B	Experience and judgment strongly favor one criterion over the other
7	Very Strong Importance of A over B	A criterion's dominance is strongly demonstrated in practice
9	Extreme Importance of A over B	The evidence favoring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	
Reciprocals	If criteria i has one of the above numbers assigned to it when compared with criteria j, then j has the reciprocal value when compared with i	

In the second step, the elements of a particular level are compared pair-wise with respect to a specific element in the immediate upper level. A judgmental matrix is formed and used for computing the priorities of the corresponding elements. The judgmental matrix is denoted as A. Each element a_{ij} of the matrix is a number which indicates the relative preference of criteria i over criteria j.

A= (a_{ij}) $(i, j = 1,2,\ldots,$ the number of criteria)

The matrix has important characteristics that

1) the diagonal elements are all equal to one, because they represent comparison of a criterion with itself:

$a_{ii}=1$

2) the lower triangle elements are the reciprocal of the upper triangular elements:

a_{ij}=1/ a_{ij}.

3) all the numbers are positive:

a_{ij}>0

The scales in Satty (1977) provide a valuable guide in assessing the strength of preferences when making the pair wise comparisons between element *i* and element *j*. (Table 3.9)

After constructing the matrix of comparison, the next step is to obtain the relative weights *w* of the decision elements from the pairwise comparison matrix developed in the first step.

$$A=\begin{bmatrix} w_1/w_1 & w_2/w_1 & .... & w_1/w_n \\ : & : & : & : \\ : & : & : & : \\ w_n/w_1 & w_n/w_2 & .... & w_n/w_n \end{bmatrix}$$

Consider $W= (w_1, w_2,..., w_n)^T$, where *W* is the vector of the weights and *n* is the number of decision elements. It is agreed that the relative weights of the criteria can be estimated by finding the principal eigenvector *W*, that is

$$AW = \lambda_{max} W$$

where λ_{max} is the maximum eigenvalue. Saaty (1994) proposed a simple way to obtain an estimate of λ_{max} when the exact value of w_i is available in normalized form.

$$\sum_j a_{ij} w_j = \lambda_{max} w_i$$

$$\Sigma\, \Sigma a_{ij} w_j = \Sigma [\sum_j a_{ij}] w_j = \sum_i \lambda_{max} w_i = \lambda_{max}$$

It has been proven (Satty, 1977) that λ_{max} is always greater or equal to *n*, and the closer λ_{max} is to *n*, the more consistent are the pariwise comparisons of matrix A. Consistency of the judgments a_{ij} is one of the most important issues of AHP.

Consistency means that if *i* is preferred than *j* and *j* is preferred than *k*, then *i* is preferred than *k*, and

$a_{ij}a_{jk} = a_{ik}.$

The consistency condition can be measured using the C.I. (Consistency Index) and C.R. (Consistency Ratio). C.I. is a function of the maximum eigenvalue $\lambda_{\max}$ and the number of elements *n*. C.R. can be calculated through C.I. and R.I., where the latter is an average random consistency index. The R.I. values are also given in Saaty (1977).

n	1	2	3	4	5	6	7	8	9	10	…
R.I.	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	…

$C.I. = (\lambda_{max} - n)/(n-1)$

$C.R. = C.I./R.I.$

Normally, a smaller C.I. or C.R. means better consistency of pair wise comparison. When $\lambda_{max} = n$, C.I. and C.R. become zero, which means the pair wise matrix is completely consistent, and the comparison matrix is called a consistent matrix. A general rule is that a CR<=0.1 is considered to be acceptable. For CR>0.1, it is suggested that the matrix of pairwise comparisons be revised to eliminate inconsistencies.

In the final step, the weight vectors determined in step 3 are used to produce a vector of composite weights which serve as the ratings of the decision alternatives. Using a very similar procedure, the local priorities of alternatives with respect to each criterion can be calculated. For example, the local priority of alternative 1 with respect of criteria c1 and the local priority of criteria c1 are aggregated to calculate the final priority of alternative 1. The vector of the composite weights of all the possible alternatives W_a is calculated through:

$$W_a = \prod_{i=1}^{k} B_i$$

where B_i is the matrix with rows consisting of W vectors, k is the number of alternatives. W_a is the vector of the final priority of all alternatives. The largest weight in this vector represents the best choice.

3.3.3 Structure of the decision hierarchy

The four level decision hierarchy built in this thesis is shown in Figure 3.17. The objective is to satisfy the requirement of sustainability. The hierarchy is composed of four criteria and two sub-criteria presented in the following paragraphs.

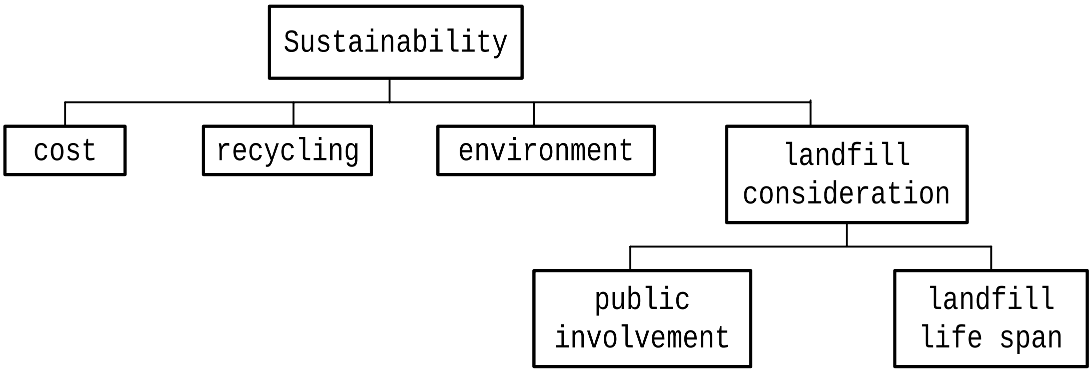


Figure 3.17 Top-level goal and criteria of the decision hierarchy

Criteria 1- Cost. Cost is a key consideration in the planning of waste treatment/disposal facilities, and is also a major obstacle to adopting technologically advanced facilities. In this research, it is assigned the highest weight for importance among all the criteria (details of the calculations involving the weights are shown in the next chapter). Comparisons between the alternatives on this criterion are based on the performance of the “cost index” indicator in the SD simulations.

Criteria 2- Environment. Reducing the negative impact of the waste on the environment is a must to achieve sustainability. Comparisons between the alternatives on this criterion are based on the performance of the “environmental index” indicator in the SD simulations.

Criteria 3- Recycling. Recycling is an essential issue in waste management, and is therefore an important evaluation criterion for the selection of facility building plans. Comparisons between the alternatives on this criterion are based on the performance of the "recycling index" indicator in the SD simulation.

Criteria 4- Landfill consideration. The criteria about landfill include two sub-criteria: public involvement and the life span of the landfill. To overcome the natural opposition of the community where the facility will be located is a prerequisite to the eventual construction of the facility. One way to overcome opposition is to offer compensation to the community, and this will inevitably increase the investment cost of the facility. This issue is tracked by the values of the variable "community reaction". The life-span of the landfill is an important consideration in determining the cost-effectiveness of the plan. In this approach, the life span of the landfill is deduced from the simulation through the variable "remaining capacity of landfill". The year that the landfill capacity turns to zero stands for the end of its service life.

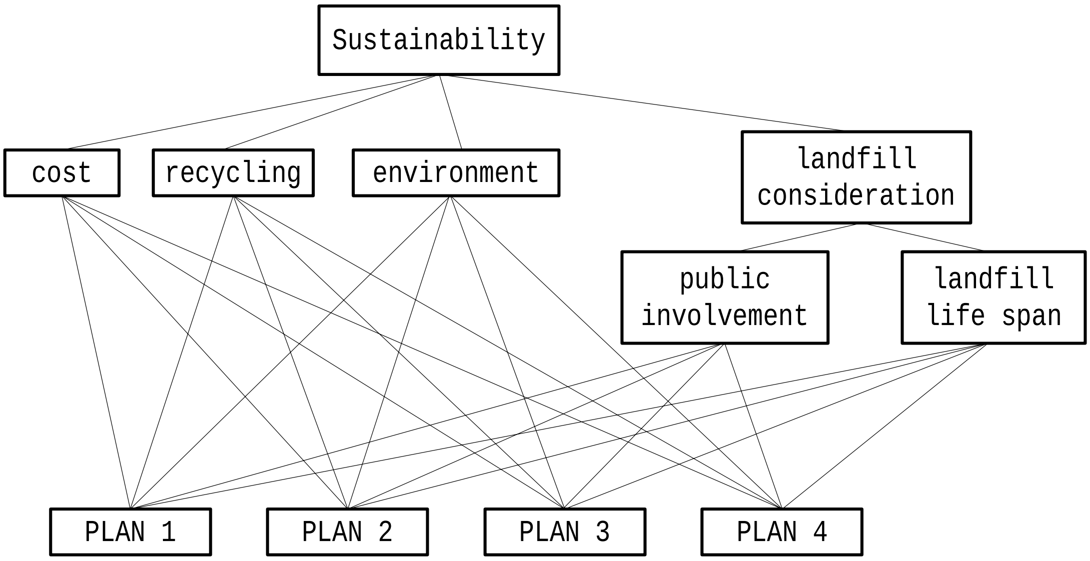


Figure 3.18 AHP hierarchy for the alternative selection

CHAPTER 4

DEMONSTRATION OF THE APPROACH

In this chapter, the decision support approach is demonstrated using a hypothetical case. Several hypothetical alternative plans for waste treatment/disposal facilities are simulated in the SD (system dynamics) model under different scenarios, and compared in the AHP hierarchy based on their simulated performances. Discussions about the results are presented in the second part of this chapter.

4.1 Identifying feasible alternatives and scenarios

It is usually difficult to predict future conditions, such as the economic development and the population growth accurately. Thus, the decision makers need to consider a range of scenarios involving possible developments. Alternative plans, which meet the planning requirements, are evaluated on their performance under several possible scenarios.

4.1.1 Hypothetical scenarios

The scenarios for the simulation are constructed by changing the parameters that are beyond the control of the decision maker. Two hypothetical scenarios in this model are constructed concerning the condition of the economy. The economic development cannot be determined by the decision makers, but it does exert an influence on the budget allocated to waste treatment/disposal facility building and waste generation as well. In this hypothetical case, different conditions of economic development are introduced in the different scenarios of the simulation as shown in Table 4.1.

Table 4.1 Hypothetic scenarios

Scenario 1	Scenario 2
Relatively high rate of GDP growth and high inflation rate	Relatively low GDP growth speed and low inflation rate

GDP is one of the main indexes of economic condition. Under the first scenario, the hypothetical GDP growth rate is supposed to be seven percent, which is a high rate of growth compared to the three percent assumed in scenario 2. The Inflation rate is another important parameter affecting costs in the model. Thus, the scenarios consider different settings for these two factors. Some economists have shown that the output gap (the difference between the actual GDP and potential GDP) of a country has a positive correlation with the inflation rate although there are some who take the contrary position there is not a very strong correlation between the growth rate of GDP and the inflation rate. However, in most cases, a higher GDP growth rate is often accompanied by a higher inflation rate. In running the model, we adopt the first view and suppose that the two factors change in the same direction.

4.1.2 Alternatives under consideration

The alternatives are constructed by changing the parameters of the problem at hand. In this research, four alternatives are simulated to examine their outcomes. It is believed that the start of construction of the waste treatment facility and the site selected for the landfill are two important issues in the planning of waste treatment/disposal facilities. As the capital and operating costs of an incineration plant are relatively high, it is normally difficult for developing countries to afford the building and operation of an advanced plant. However, higher public expectations on environmental quality standards make it necessary to construct one in due course. With economic development, being able to afford such advanced treatment facilities becomes easier. Therefore, it is assumed that the decision maker plans to begin the building of an advanced incineration plant either in the tenth year of the planning period or in the twentieth year, after significant economic development has occurred. Foreseeable consequences of the difference in timing for the construction of advanced facilities are that there may be a significant difference not only between the costs incurred but also between the different impacts on the environment.

Another consideration involved in the alternatives is the selection of the site for a new landfill. The decision maker needs to consider the size of each potential site, as well as the levels of public acceptance in the surrounding communities.

The following four plans, PL1 – PL4 are the alternatives adopted in the hypothetical case.

PL1: The incineration plant is to be put into use in the 10th year of the planning period. The new landfill (of a small capacity) is to be built on a small site; community opposition is moderate (low community reaction level). Its construction begins at the start of the planning period (with a certain construction period).

PL2: The incineration plant is to be put into use in the 20th year of the planning period. The new landfill (of a small capacity) is to be built on a small site; community opposition is moderate (lower community reaction level). Its construction begins at the start of the planning period (with a certain construction period).

PL3: The incineration plant is to be put into use in the 10th year of the planning period. The new landfill (of a large capacity) is to be built on a big site; community opposition is intensified (higher community reaction level). Its construction begins at the start of the planning period (with a certain construction period).

PL4: The incineration plant is to be put into use in the 20th year of the beginning of the planning period. The new landfill (of large capacity) is to be built on a big site; the community opposition is intensified (higher community reaction level). Its construction begins at the start of the planning period (with a certain construction period).

Table 4.2 Linguistic description of planning alternatives

	PL1	PL2	PL3	PL4
Incineration plant start up year	10th year	20th year	10th year	20th year
Site area	Small	Small	Big	Big
Community opposition	Tempered	Tempered	Intensified	Intensified

The formulation of the alternative plans can be easily implemented in the model by changing the initial values of the decision variables in the equations. The initial values of the relative decision variables in each alternative plan are shown in Table 4.3.

Table 4.3 Values of decision variables assigned to alternative plans

	PL1	PL2	PL3	PL4
Capacity of new landfill (million tons)	20	20	40	40
Community reaction (dimensionless)	2	2	4	4
Incineration plant set up year (dimensionless)	10	20	10	20

4.2 Validation and sensitivity analysis

4.2.1 Validation of the model

The model should be checked for validity by using the reference modes drawn in the last chapter. For validation, the model is run using the PL1 alternative under the first scenario. To recall, the PL1 alternative constructs a small landfill together with the early development of the incineration plant. The first scenario postulates high GDP and inflation growth rates. Fig. 4.1 depicts the simulation results for generated waste, irregular disposal and cost index variables. It can be seen that the levels of generated waste and irregular disposal increase with time indicating that the equations are properly constructed. The value of the cost index should be around one, which means that there will not be a huge gap between the cost needed for the plan and the government budgets.

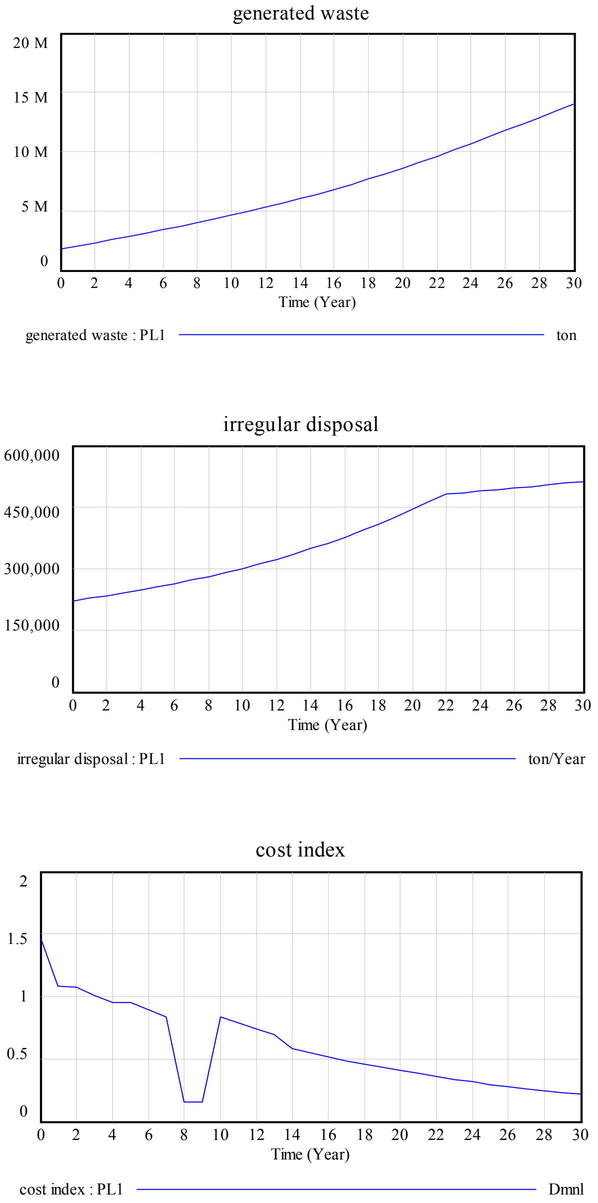


Figure 4.1 Results from validation run

The calibration of SD model is based on previous knowledge, which is represented using reference modes. In this model, two reference modes are applied, which have been presented in the sections above. The behavior of the model is expected to match the anticipated curves. That means the simulation results of the two variables should match the target pattern established.

On comparing the simulation result of waste generation generated by the model and the reference mode drawn previously, we find that they are generally similar in shape and have the same tendency. In the simulation, about twenty years into the planning period, the level of waste generation begins to increase at a lower rate, similar to the situation envisioned in the reference mode.

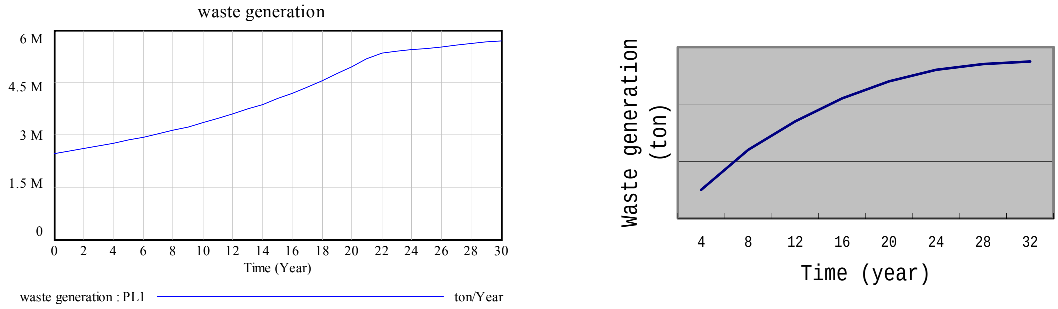


Figure 4.2 Comparison of SD result and reference mode for waste generation

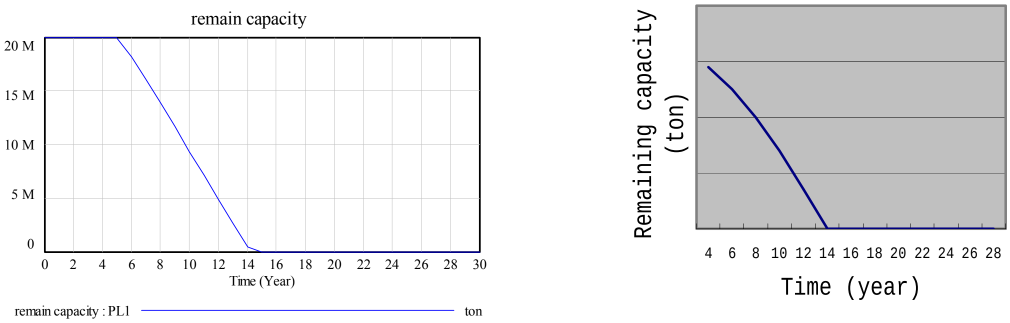


Figure 4.3 Comparison of SD result and reference mode for remaining capacity

The comparison between the simulation results of the variable representing the remaining capacity of the landfill and its reference mode can also provide evidence that the structure of the model is valid. In the simulation, the landfill is put into use in the fourth year and then the capacity drops to zero around the fourteenth year. It shows a trend similar to that of the reference mode of the previous chapter.

In model formulation, it is assumed that the waste generated grows with the increases of population and the GDP. In the simulation results, it can be found in Figure 4.4 that this assumption is also matched.

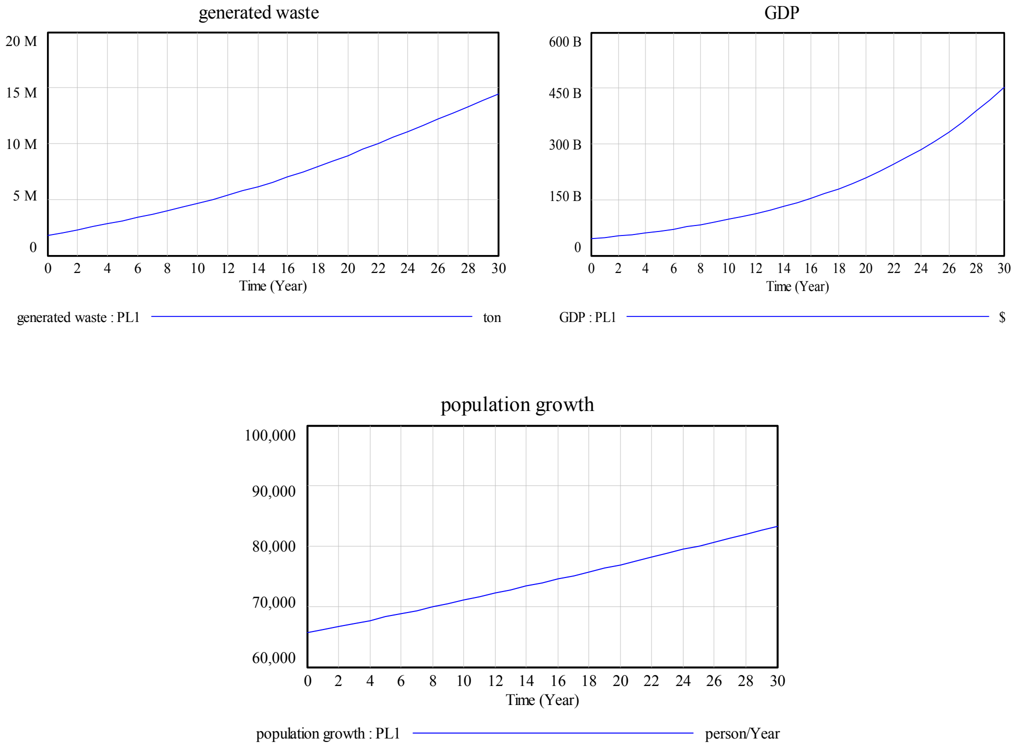
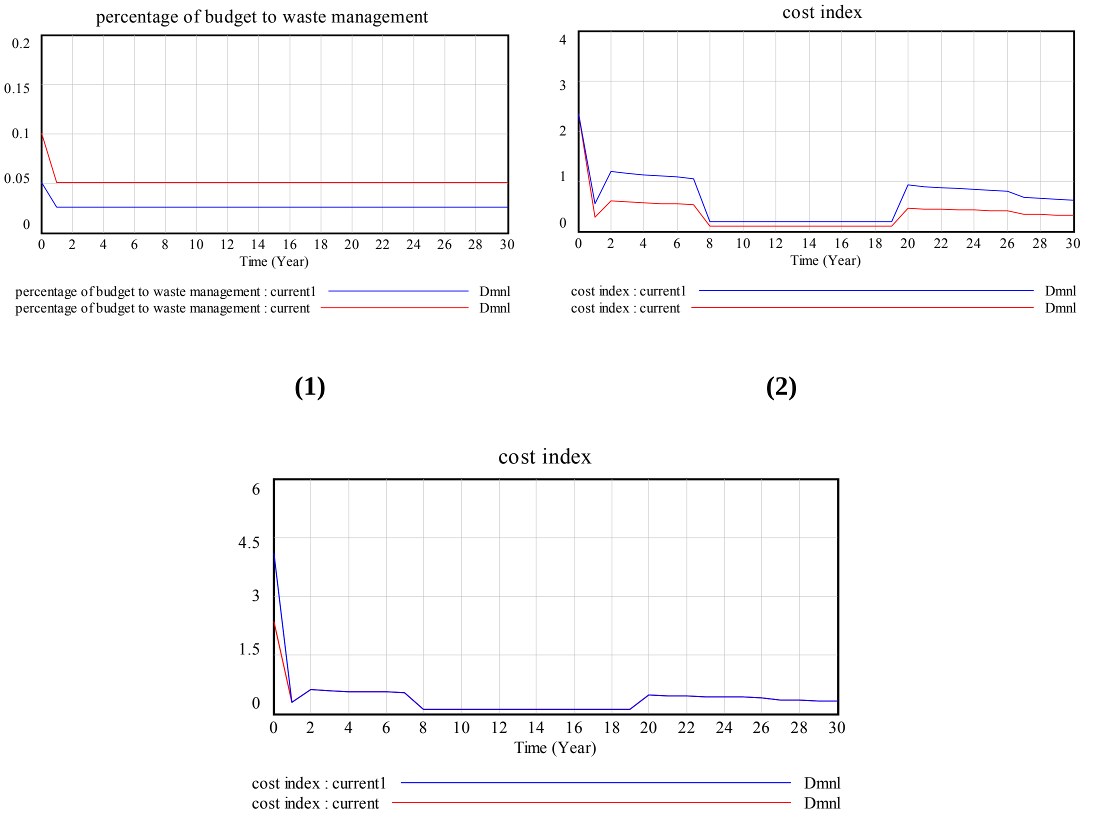


Figure 4.4 Simulation results to match the assumption

4.2.2 Sensitivity analysis

In the model formulation and application, there is some uncertainty about the value of some of the parameters. It is necessary to test these uncertain parameters through sensitivity analysis. Experienced researchers have learned that "a well-structured model will generate the same general pattern despite the great uncertainty in parameter values" (Ford, 2000). VENSIM software provides the function to perform this sensitivity analysis in an automatic way, but unfortunately, this function is not included in the VENSIM PLE version used in this research. Instead, sensitivity analysis is carried out using a traditional but more laborious approach by manually changing each uncertain parameter one-at-a-time and keeping the others constant. It includes a high and a low value for each important factor around a baseline case.

In this research, two parameters were chosen to be included in the sensitivity analysis: a) the percentage of budget allocated to waste management and b) the land access cost. The results of the sensitivity analysis plotted in Fig. 4.4 (2) indicate that when the percentage of budget allocated to waste management is doubled, the cost index responds in the opposite direction as expected. In Fig 4.4 (2)-(3), the changes of cost index are shown respectively corresponding to the change of those two parameters.



(1) **(2)**

(3)

Figure 4.5 Results of the sensitivity analysis

The analysis of land access cost is conducted in the same way. Because this cost is incurred only when the landfill is constructed, the cost index curves are different only in the year that the landfill is constructed. (see Fig.4.4 (3)) A check of the curves for the other variables was performed and did not reveal any unusual growth or decay pattern, indicating that both the formulation of the model and the values for the parameters adopted are reasonable.

4.3 Performance of alternatives under different scenarios

All the alternative plans are simulated under the different scenarios. In the simulation outputs, the numbers marked on them differentiates the curves presenting the results of the different runs. Eight runs of the model were made corresponding to the simulation of four alternatives under two different scenarios. The legend of the simulation outputs and the corresponding alternatives are shown in the following table.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Scenario 1	PL1	PL2	PL3	PL4
Scenario 2	PL1’	PL2’	PL3’	PL4’

The performance of the different alternatives can be evaluated through the indicator variables. The simulation results of the key indicator variables are shown in Fig. 4.5. In the thesis, several indicators are defined for the evaluation of the alternative plans.

The evaluation of sustainability impacts of policies or plans is often not satisfactory because the standards for evaluation are difficult to determine, and to evaluate any aspect of sustainable development is to try to measure the immeasurable (Bell and Morse, 1999). However, wherever possible, it is preferable to use quantitative indicators rather than subjective assessments to evaluate the impact of the various plans on sustainability.

An indicator is a variable that points to the significant outcomes of the planning process and which can be used for management purposes. Indicators make it easier to define aims and to measure the effectiveness of the implementation of plans. They can translate physical and social science knowledge into manageable units of information, and then provide crucial guidance for decision-making (Masakazu, 2003).

Indicators which have been adopted (UNCSD, 2001) in the field of waste management include:

a) rate of waste recycling and reuse, which is the percentage of waste reused or recycled in the waste actually generated on a per capita basis;

b) generation of solid waste, which is the amount of industrial and municipal solid waste, derived from the production of waste per person on a weight basis at the point of production; and

c) level of public participation.

In this thesis, the evaluation indicators used are the environmental index, cost index, and recycling index. For the evaluation of sustainable development, the three aspects of cost, environment, and social involvement are the most important. The cost index needs to be formulated to evaluate the utilization of the budget for waste management. The traditional indicators on the cost aspect only focused on the investments on the waste facilities. The cost index in this thesis considers both the capital investment on the facility and affordability to the government. It is assumed that there is no private investment and all investment is from the government. With economic development, the government budget that can be allocated to waste management grows. It is important to make full use of the budget to make the standard of waste management as high as possible on the premise that other public services will not be compromised. The cost index is formulated based on the above considerations.

As for the environmental aspect, the generation of waste per person is a commonly used indicator. Although it can reflect the change in the amount of waste generated, it does not reflect the negative influence of the waste on the environment. In this thesis, the environmental index is defined to evaluate the negative influence of the waste, due mainly to the uncollected and untreated waste. The amount of uncollected and untreated waste per person per year acts as an indicator of the negative influence of waste for that year. A comparison of the quantity of uncollected and untreated waste each year with that in the base year reveals whether this negative influence to the environment is aggravated or reduced. The environment index is thus constructed, with the "amount of the uncollected and untreated waste per person per year" as the numerator and the "amount of the uncollected and untreated waste per person in the base year" as the denominator.

Recycling is an important issue in waste management as it contributes to a reduction of resource usage and environment protection. It should be included when comparing the alternatives. Traditionally, the indicator used is the recycling ratio - defined as the percentage of the total amount of waste that is recycled. However, it has been observed that the composition of the waste changes over time, and in developed economies, the percentage of the recyclable waste increases as well as the percentage of waste that is recycled. Unfortunately, this change is usually not captured in traditional indicators. In this thesis, the recycling index based on the traditional recycling ratio is modified to reflect changes in the amount of recyclable waste. The numerator is the percentage of waste that is recycled, where this waste is the sum of the waste recycled in the recycling plant and that recycled at the incineration plant. The denominator is the percentage of the recyclable waste. It reflects the degree to which waste that can be recycled has actually been recycled.

i) The Cost index is defined as:

$$\text{cost index} = \frac{\text{budget needed by waste management}}{\text{budget allocated to waste management}} \tag{4.1}$$

Cost is an important issue involved in waste management planning. The cost index defined in this thesis shows the ratio between the budget needed and the actual amount allocated. If the index value is one, the budget allocated is enough to meet the requirement. Cost index with smaller values mean that less budget is required. Sudden increases in the curves should be avoided because they indicate a sudden and heavy increase in the burden on public funds. On the other hand, the curves with values much smaller than one indicate that the available budget is not fully spent – this situation is also not desirable.

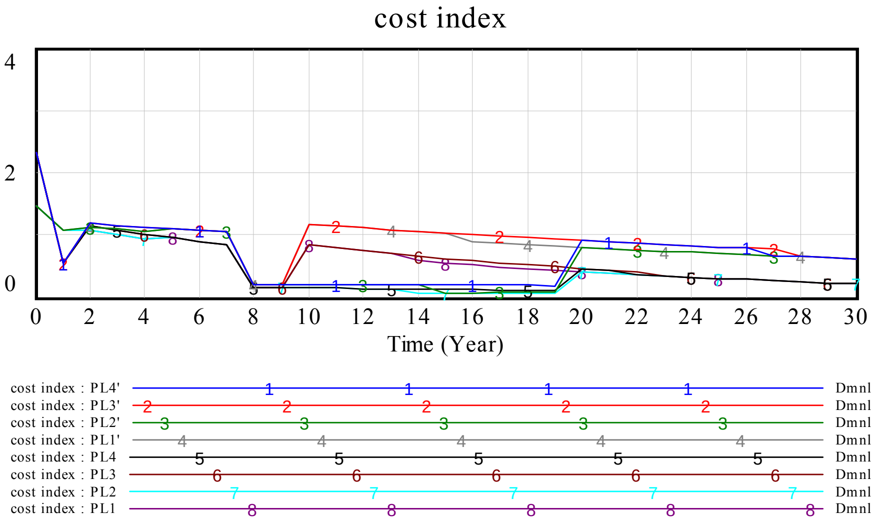


Figure 4.6 Simulation output of cost index

In the hypothetical example in this thesis, the sudden decline of the cost index curves in year 8 is caused by the closure of the old incineration plant. The sharp increases in year 9 or 19 are due to the adoption of a new plant. It is observed that the increase caused by a later adoption of incineration plant is more moderate than that caused by an earlier adoption. In the situation where the aim is to have the least amount of impact on the public budget, alternatives 2 and 4 are preferable to 1 and 3.

ii) The Environmental index is calculated as follows:

$$\text{environmental index} = \frac{\text{uncollected waste+irregularly disposed waste}}{\text{population}} \Bigg/ \frac{\text{base year uncollected waste + base year irregular disposed waste}}{\text{base year population}} \qquad (4.2)$$

The negative environmental influences of the waste are mainly ascribed to the uncollected waste, irregularly disposed waste, and untreated waste. The sum of these wastes is normalized by the size of the population. The index value of each year is compared with that of the base year, to reflect the annual changes of this negative influence. Thus, if the index is one, the negative influence of the waste to the environment is same to that of the first year. If the index is larger than one, that means the uncollected or irregular disposed waste per person grows, and thus, the negative influence is intensified.

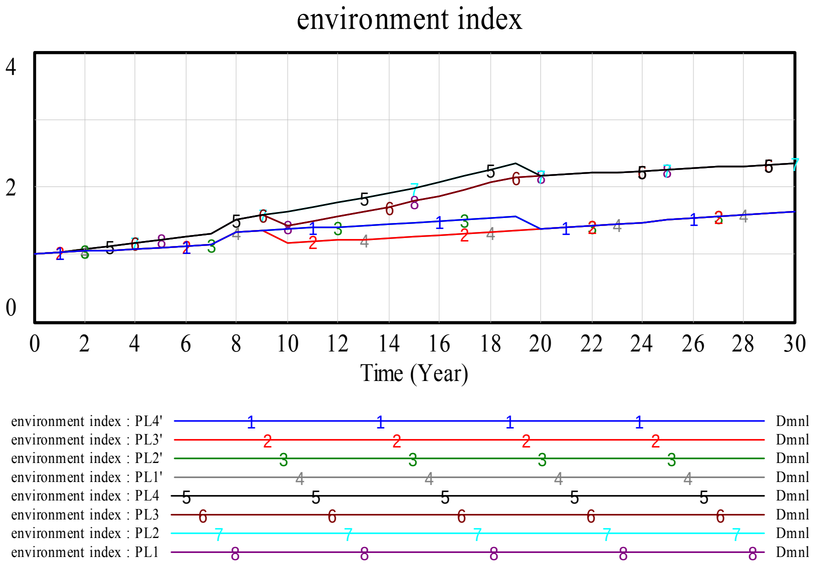


Figure 4.7 Simulation output of environmental index

From the simulation outputs of environmental index, it is observed that under the hypothetical scenario of faster economic development, the negative impact on the environment diminishes, with smaller environmental index values. Under scenario 1, all of the alternatives' environmental indexes are smaller than those under scenario 2.

They perform better and have less impact on the environment than under scenario 2, under which the environmental indexes are larger representing a deteriorating condition. Under each scenario, the values of environmental index of alternative 1 and 3 are both smaller than that of alternative 2 or 4. Thus, alternatives 1 and 3 are more favorable to the environment than the other two.

iii) Recycling index is calculated as follows:

$$\text{Recycling index} = \frac{\text{The percentage of the recycled waste}}{\text{The percentage of the recyclable waste}}$$

$$= \frac{\text{recycled waste in treatment plant} + \text{recycled waste in recycling plant}}{\text{waste generated}} \Bigg/ \frac{\text{recyclable waste}}{\text{waste generated}} \qquad (4.3)$$

A larger index value indicates that more of the recyclable waste is recycled, and this reflects better performance from the waste recycling effort.

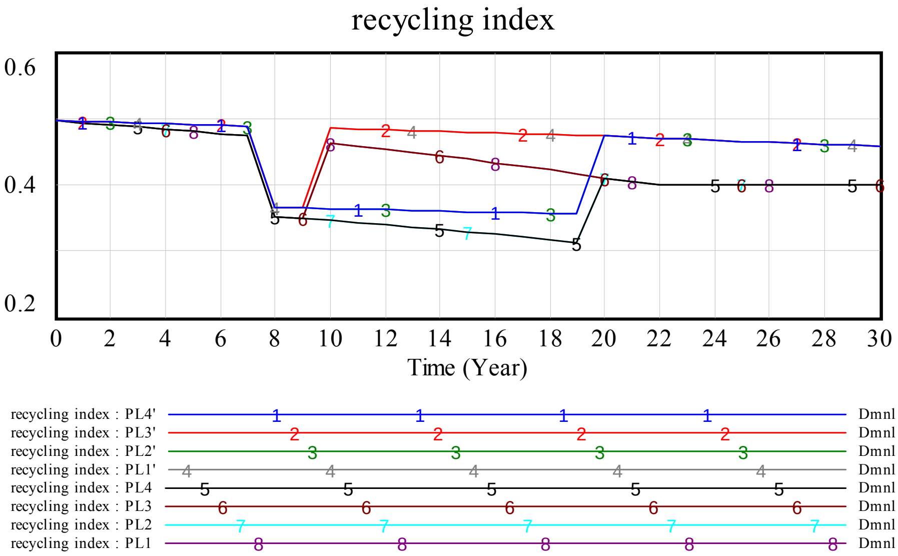


Figure 4.8 Simulation output of recycling index

From the simulation, outputs of recycling index show that under scenario 1, the recycling state is better than that under scenario 2. The sudden change of the curves may arise from the changes of the operating conditions of the treatment plant, as it is assumed that the recycling actions in a treatment plant contribute significantly to the amount of recycled waste. The adoption of a new incineration plant will improve the recycling situation. Similarly, the closure of the old incineration plant will reduce the amount of recycled waste. It is observed that alternatives 2 and 4 have a larger recycling index value than the other two alternatives under both scenarios. That means alternative 2 and 4 have better performances with regard to recycling.

The service life span of the landfill can be determined by observing the simulation outputs of the values of "the remaining capacity of the landfill", which is shown in Figure 4.8. When it becomes zero, the landfill is at the end of its life span. For example, under scenario 1, alternative 3 provides the longest service life of a landfill, and under scenario 2 alternative 4 can make the landfill have the longest service life.

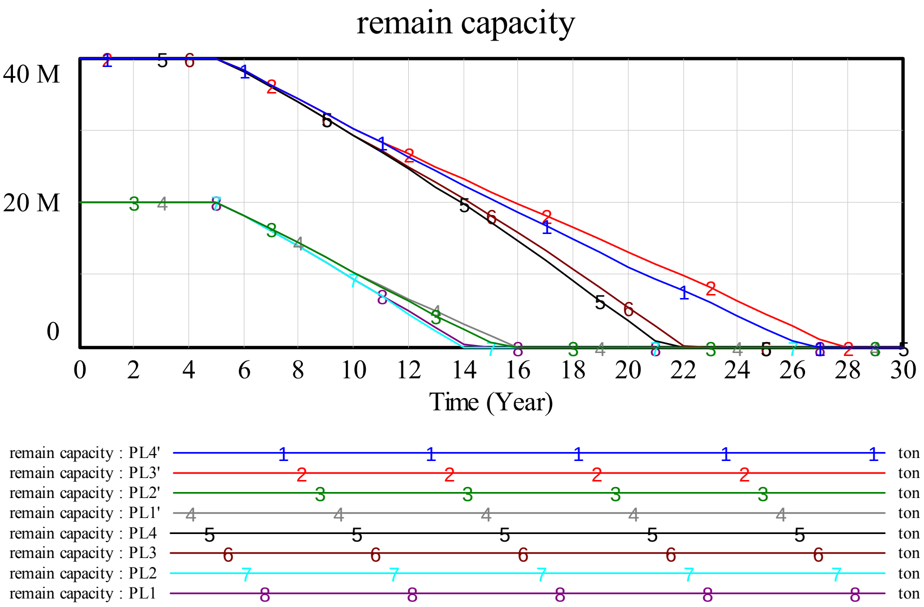


Figure 4.9 Simulation output of remain capacity of landfill

4.4 Selection of preferred alternative using AHP methodology

In this section, the application of the AHP is presented following the steps discussed in the previous chapter. The alternatives are compared using the hierarchy and their simulated performance under the different scenarios.

(i) Subjective pair wise comparison

Selection using the AHP methodology utilizes the relative importance of factors within each hierarchical level. The basic approach for deriving relative weights is by way of pairwise comparison. The criteria of each category are compared in terms of their importance within the given category. A rate a_{ij} is chosen by the decision maker, regarding the importance of an criterion i, in comparison to the importance of another criterion j of the same category. Then, in the reciprocal comparison, the rate of the importance of criterion j over i is 1/ a_{ij}. Table 4.4 shows the pairwise comparison rates of all the criteria. The methodology of pairwise has been presented in last chapter.

Table 4.4 Pair wise comparison scales of the criteria

Goal	Cost	Environment	Recycling	Landfill consideration
Cost	1	2	5	5
Environment	1/2	1	4	4
Recycling	1/5	1/4	1	1/2
Landfill consideration	1/5	1/4	2	1

Landfill consideration	Public involvement	Landfill life span
Public involvement	1	1/2
Landfill life span	2	1

The preference of the decision criteria is based on the decision purpose and the decision maker. The comparison of the criteria follows the most widely accepted nine-point scale, which was presented in the last chapter. For example in the comparison between cost and environment criteria, the *a* value is 2, which means the cost criteria is moderately (more) important than the environment criteria. For the comparison between cost criteria and recycling criteria, the *a* value is 5, which means the cost criteria is essentially more important than the recycling criteria. In the next step, the relative weights of these criteria will be calculated based on these pairwise comparison matrixes.

Table 4.5 Pair wise comparison scales of the alternatives under each criterion

Cost	PL1	PL2	PL3	PL4
PL1	1	1/5	2	1/4
PL2	5	1	6	2
PL3	1/2	1/6	1	1/5
PL4	4	1/2	5	1

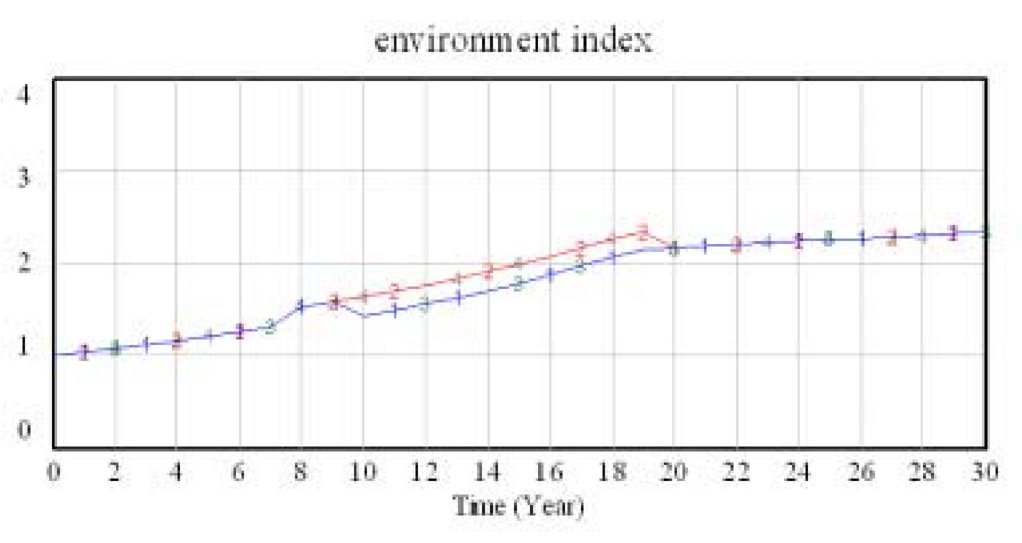
Environment	PL1	PL2	PL3	PL4
PL1	1	4	1	4
PL2	1/4	1	1/4	1
PL3	1	4	1	4
PL4	1/4	1	1/4	1

Recycling	PL1	PL2	PL3	PL4
PL1	1	5	1	5
PL2	1/5	1	1/5	1
PL3	1	5	1	5
PL4	1/5	1	1/5	1

Landfill life span	PL1	PL2	PL3	PL4
PL1	1	2	1/6	1/5
PL2	1/2	1	1/7	1/6
PL3	6	7	1	2
PL4	5	6	1/2	1

Public involvement	PL1	PL2	PL3	PL4
PL1	1	1	4	4
PL2	1	1	4	4
PL3	1/4	1/4	1	1
PL4	1/4	1/4	1	1

The procedure for the pairwise comparisons of the alternatives is the same as that for the criteria. The comparison between each alternative is based on the trends observed for the evaluation indicators obtained from the SD simulation. However, this evaluation is not based on any particular value of the simulation trace. Rather, the whole simulation trajectory is evaluated subjectively. Table 4.5 shows the pairwise comparison rates based on their simulated performance under scenario 1, as shown in Figure 4.10.


environment index
4
3
2
1
0
0
2
4
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8
10
12
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16
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20
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24
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28
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Time (Year)
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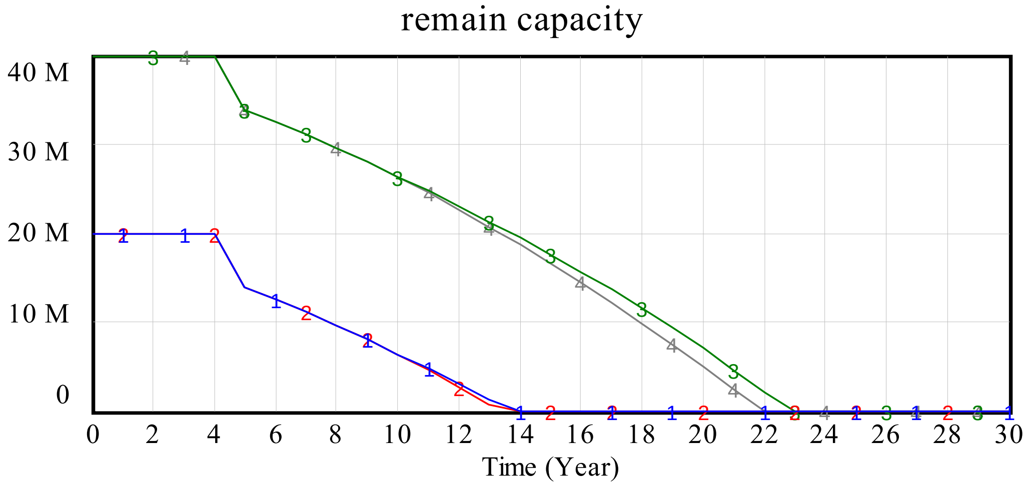
3
4


remain capacity
40 M
30 M
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10 M
0
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2
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Time (Year)
1
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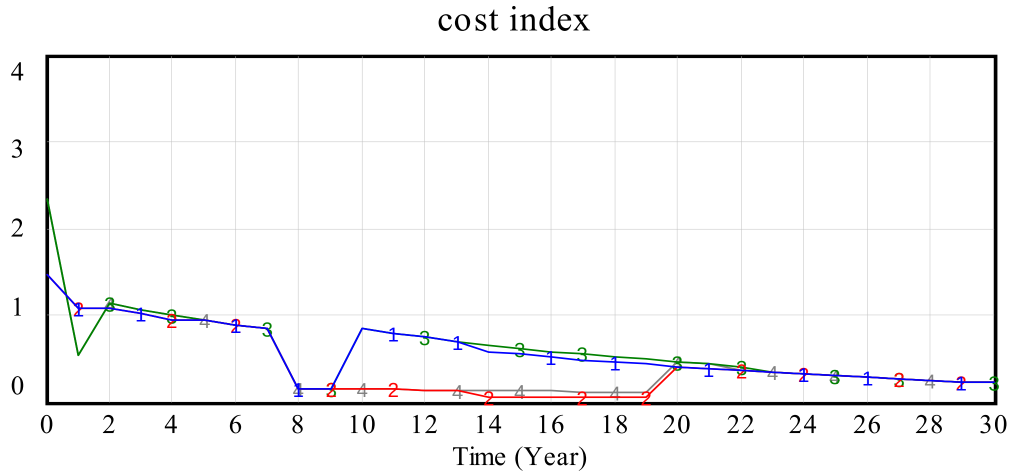
cost index
4
3
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1
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Time (Year)
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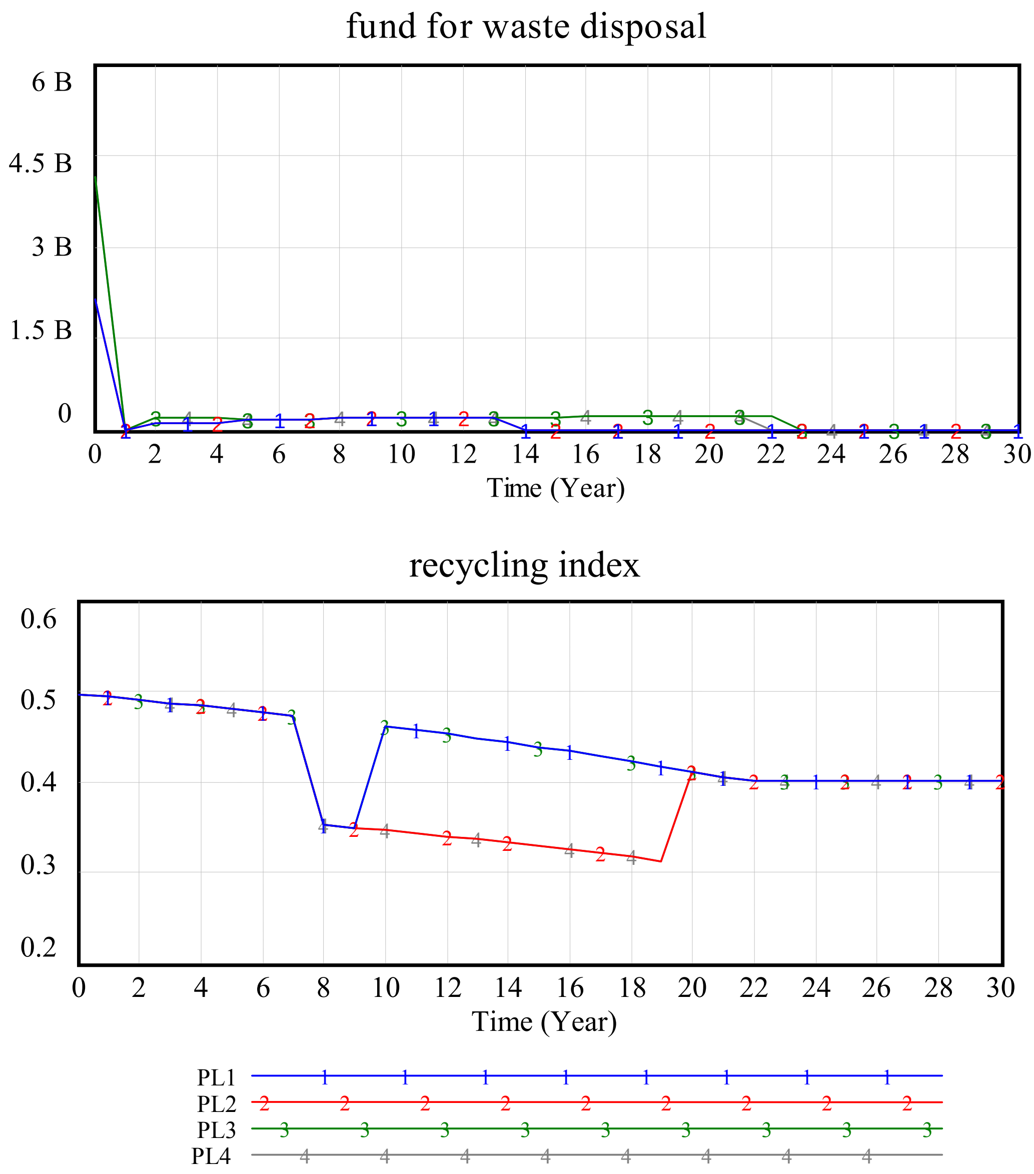

Figure 4.10 Performance of planning alternatives under the first scenario

(ii) Calculation of the weights

The comparison rates elicited from the decision maker are converted into relative scales to enable the alternatives to be ranked. In this research, the relative scales of importance are obtained by normalizing the columns of the pairwise matrixes. The methodology and equations have been presented in section 3.3.2. The calculated results of the relative weights of the criteria are shown in Table 4.6 and Figure 4.9.

Table 4.6 Priorities of the criteria

Goal	Cost	Environment	Recycling	Landfill consideration	Priorities
Cost	1	2	5	5	0.4977
Environment	1/2	1	4	4	0.3158
Recycling	1/5	1/4	1	1/2	0.0769
Landfill consideration	1/5	1/4	2	1	0.1096

Landfill consideration	Public involvement	Landfill life span	Priorities
Public involvement	0.33	0.33	0.33
Landfill life span	0.67	0.67	0.67

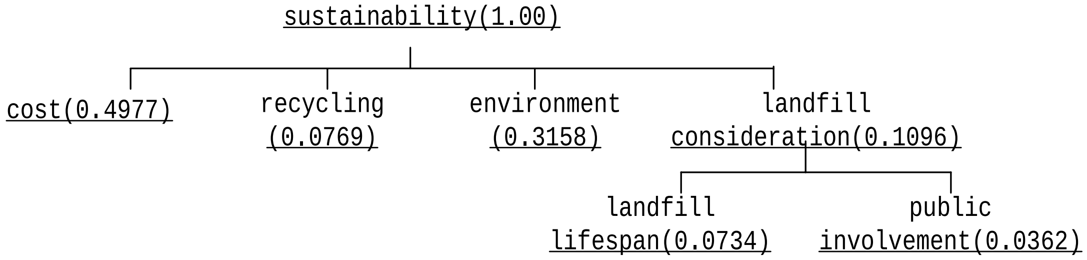

Figure 4.11 Weights of the criteria

The calculated results of the final local priorities of the alternatives are shown in Table 4.7. The relative weights are shown in Fig. 4.11. (The values in brackets against the different PL alternatives represent the normalized evaluation of the performance of each alternative under the conditions of scenario 1).

Table 4.7 Priorities of the alternatives

Cost	PL1	PL2	PL3	PL4	Priorities
PL1	1	1/5	2	1/4	0.1044
PL2	5	1	6	2	0.5051
PL3	1/2	1/6	1	1/5	0.0666
PL4	4	1/2	5	1	0.3240

Environment	PL1	PL2	PL3	PL4	Priorities
PL1	1	4	1	4	0.4
PL2	1/4	1	1/4	1	0.1
PL3	1	4	1	4	0.4
PL4	1/4	1	1/4	1	0.1

Recycling	PL1	PL2	PL3	PL4	Priorities
PL1	1	5	1	5	0.4167
PL2	1/5	1	1/5	1	0.0833
PL3	1	5	1	5	0.4167
PL4	1/5	1	1/5	1	0.0833

Landfill life span	PL1	PL2	PL3	PL4	Priorities
PL1	1	2	1/6	1/5	0.0891
PL2	1/2	1	1/7	1/6	0.0577
PL3	6	7	1	2	0.5161
PL4	5	6	1/2	1	0.3371

Public involvement	PL1	PL2	PL3	PL4	Priorities
PL1	1	1	4	4	0.4
PL2	1	1	4	4	0.4
PL3	1/4	1/4	1	1	0.1
PL4	1/4	1/4	1	1	0.1

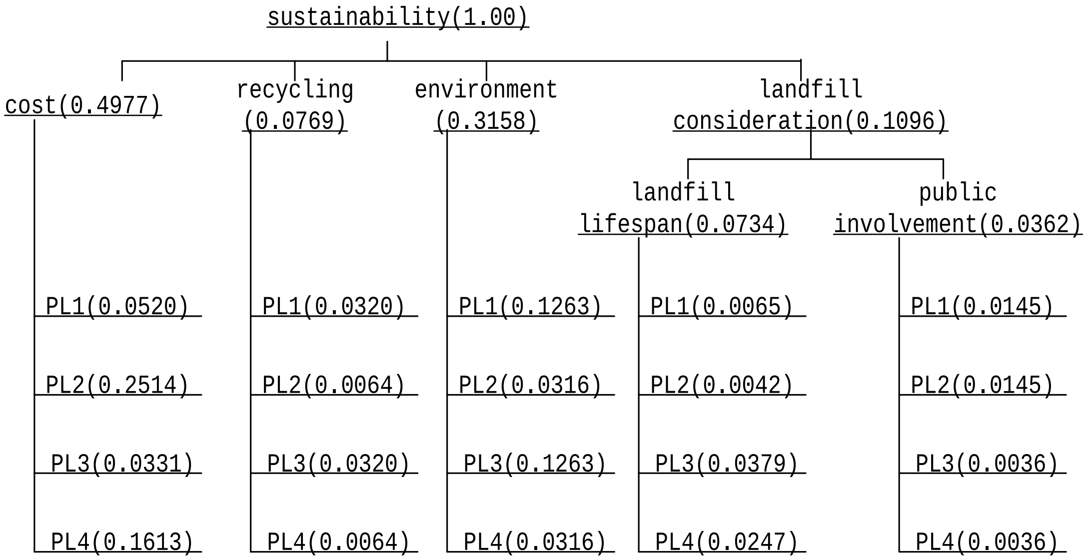

Figure 4.12 Weights of the alternatives

(iii) Consistency measure

One of the most important features of the AHP is the ability to determine the degree of consistency of the judgments a_{ij}, which are the pair wise comparison scales between factors. These judgments are required to be transitive and consistent. This means that if i is preferred than j and j is preferred than k, i is preferred than k, $a_{ik} > 1$ as well as $a_{ij}a_{jk} = a_{ik,}$ as discussed in the previous chapter. However, the consistency of judgments is often not easy to achieve owing to subjective nature of the judgment. In making pair wise comparisons, errors arising out of inconsistency in judgments affect the final answer. C.I. (Consistency Index) and C.R. (Consistency Ratio) can measure the consistency condition. These terms, together with the relevant mathematical expressions were presented in the previous chapter. The calculation of CI and CR for the cost sector of the hypothetical case is illustrated by equations 4.4 and 4.5. The calculation for the other sectors is not shown here (for brevity) but only the final values for all the sectors are given in Table 4.4.

$$\lambda_{\max} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} * \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} 1 & 1/5 & 2 & 1/4 \\ 5 & 1 & 6 & 2 \\ 1/2 & 1/6 & 1 & 1/5 \\ 4 & 1/2 & 5 & 1 \end{bmatrix} * \begin{bmatrix} 0.1044 \\ 0.5251 \\ 0.0666 \\ 0.3240 \end{bmatrix} = 4.0893 \quad (4.4)$$

$$\textit{Consistency Index} = (\lambda_{\max} - 4)/3 = 0.0298 \qquad (4.5)$$

Table 4. 8 Weights and consistency index of the alternatives

	Cost	Environment	Recycling	Public involvement	Landfill life span
PL1	0.1044	0.4	0.4167	0.4	0.0891
PL2	0.5051	0.1	0.0833	0.4	0.0577
PL3	0.0666	0.4	0.4167	0.1	0.5161
PL4	0.3240	0.1	0.0833	0.1	0.3371
$\lambda_{\max}$	4.0893	4	4.0001	4	1.1795
C.I.	0.0298	0	0	0	0.0598

A cutoff limit of 0.1 has been proposed. That means the consistency index should not be larger than 0.1, or the pair wise comparisons should be revised (Saaty, 1977). From the above table, it is observed that the consistency indexes are all below 0.1, which means that the ratios of pair wise comparisons can be accepted. When the CR is calculated , the value obtained indicates that the pair wise comparisons obtained for the hypothetical example are acceptable .

Table 4.9 Consistency Ratios of the criteria

	Cost	Environment	Recycling	Public involvement	Landfill life span
C.R.	0.0335	0	0	0	0.0672

The C.R. is required to be no larger than 8% for n=4, and 10% for all values of n>=5. Since 0.0335<=0.08 and 0.0672<=0.08, the ratios of pair wise comparison are acceptable.

(iv) Hierarchical synthesis

The ranking of the alternatives needs the synthesized scores of the alternatives as the final scores. Here, synthesis involves multiplying the priority weight / performance rating of each alternative under each criteria with the weight of that criteria down the hierarchy and adding the products to get the final score of each alternative. The weights of the alternatives and the criteria are shown in Figure 4.11 above.

The results of the synthesis (for the various alternatives evaluated under the first scenario) are:

PL1	0.231344
PL2	0.308089
PL3	0.233013
PL4	0.227604

The alternative with the highest score is chosen as the final decision. In this case, the second alternative PL2 has the highest score, under the first scenario and is selected as favorable alternative. The performance of the alternatives under the second scenario is similar to what was observed under the first scenario (see Figure 4.5-4.8). Therefore, the pair wise comparisons in this situation are likely to be the same as that discussed earlier, leading again to the choice of PL2 as the preferred alternative. If the evaluation criteria or their rates are different from those under scenario 1, another alternative might be selected as the best choice. The decision makers then have to find a means of resolving what might be the best overall alternative. This will necessarily involve taking into consideration their assessment of the likelihood of the different scenarios envisaged, together with the attitudes of the decision makers themselves about choosing an alternative that might prove to be less than ideal under particular circumstances. This situation is not considered in this thesis and could be taken up in future studies.

4.5 Discussion of the results

A discussion of the SD simulation results (from the SD model) and the evaluation of the performance of the different alternatives using the AHP hierarchy is presented in the following paragraphs.

(i) Simulation results from the SD model

1. Adopting different scenarios

The different GDP growth rates and inflation rates under different scenarios have not significantly influenced the final selection of the plans. Under each scenario, the simulated performances of the alternatives are different, but the differences are not big enough to change relative preferences in the AHP pairwise comparison among the different alternatives. Furthermore, in the hypothetical example used in the study, it is supposed that the cost issue is considered to be the most important by the decision maker, and in the evaluation used AHP, the criteria of cost assumes a weight of 0.5 (equal to the sum of the other three). The alternative PL2 is the alternative that causes the least burden on the budget. Even under the scenario of faster GDP growth, this alternative is still the favorite choice. If the weights of the criteria change, the ranking of the alternatives will change accordingly, and then the final choice will change. Another possible reason for the dominance of the second alternative is that the impact of the economic changes assumed is weak compared with the large costs involved in the construction and operation of the facilities.

2. Impact on cost

The capital costs of the incineration plant and the landfill account for a considerable proportion of the budget required for waste management. This may cause sharp increases of the cost index curve and become a heavy burden on the government budget. Moreover, the increase is considerably greater when the incineration plant is set up earlier. A deferred investment with regard to the incineration plant can lighten the burden on the budget. The operating cost of the facilities is much lower than the capital cost, and this is reflected by flat cost index curves during the operation period.

3. Impact on the environment

The value of environmental index shows an overall growth pattern, indicating the accumulating impact to the environment. However, the slope of the curve is becoming lesser with time, which means that the growth rate is decreasing. This reflects the impact of measures like increased landfill capacity, with a consequent reduction of the amount of irregularly disposed waste. This helps to alleviate the accumulated pollution to the environment as reflected in the environmental index.

4. Impact on landfills

The simulation results reveal the contribution of the advanced incineration plant in extending the service life of the landfill. The adoption of the proposal to build an incineration plant helps to extend the life span of the landfill by reducing the amount and volume of waste ending up in the landfill. Earlier adoption and a larger capacity of the incineration plant lead to a longer life span of the landfill.

5. Impact on recycling

The simulation trajectory of the recycling index reveals that the adoption of the incineration plant significantly increases the value of the recycling index due to the recycling conducted in the plant, thus improving the amount of recycled waste.

(ii) Alternative selection using AHP

In the example presented, the alternative PL2 was selected. This alternative involves the decision not to build the incineration plant until economic conditions warrant it in order to avoid a heavy burden on the government budget. In addition, the landfill will be located on a relatively small site, in order to reduce community opposition. The PL2 alternative may have been preferred because cost is considered the most important criterion, and PL2 is the alternative with the lowest cost. The alternative chosen would depend on the weights assigned to the different criteria.

In the long run, the adoption of advanced incineration plants will contribute greatly to alleviating environment degradation, improve waste recycling and prolong the life span of the landfill. The incineration plant in the PL2 alternative has a small treatment capacity. In addition, it is assumed that only one new plant is to be built. If more incineration plants are put into use, the effect on extending the life span of landfill and the improvement of waste recycling will become more obvious, although the cost of the additional incineration plants is expected to be high. The decision maker should balance the considerations within the system and consider adopting the advanced facilities early to get the benefits of alleviating the degradation of the environment. However, this involves a tradeoff with the cost factor since early adoption leads to a higher burden on government budgets.

CHAPTER 5

CONCLUSION

5.1 Need for an alternative DS approach

Increasingly, waste management is becoming an important environmental issue. The huge amount of waste generated and its negative impact on the environment, caused by rapid urbanization, population growth, and a changing life style, become significant obstacles towards sustainable development. Besides encouraging the reduction of waste generation and the recycling of waste, the adoption of advanced waste treatment/disposal facilities will make an important contribution to the achievement of sustainability in waste management. However, the planning of such facilities involves other considerations beyond that of the cost involved. A number of conflicting objectives and public aspirations are presented. For example, the high cost required for waste collection, transportation and treatment must be balanced against the limited public budget for waste management. The increasingly large amounts of waste generated must be reconciled with the diminishing land available to dispose of the waste. Finally, there is also the divergence between the public desire for environmental protection and the NIMBY (not in my backyard) attitude, usually expressed as the opposition of the community to build the disposal facilities in their own neighborhoods. All of these conflicts lead to the increasing pressure on waste managers, planners and regulators to develop an acceptable approach for planning the facilities.

The adoption of advanced waste treatment/disposal facilities is an effective means of achieving sustainability in waste management. In the decision-making for the facility building, it is very important to make good use of limited resources, minimize the possible harmful effects of waste, and balance the needs of various stakeholders.

When the decision makers are faced with several proposals, they need to evaluate these proposals and choose the one, which reflects the best tradeoffs between the various considerations highlighted. Adopting an approach of comparing the alternatives based on an understanding of the long-term performance of these alternatives is more convincing than relying purely on intuition and comparisons at a fixed point in time.

5.2 Suitability of the proposed decision support approach

In this thesis, a decision support approach, which combines the use of the system dynamics (SD) method with the AHP method, is proposed. In combining the use of two distinct methods, the proposal takes advantage of the strengths of each during the different stages of the decision making process. SD is used to formulate a model that can simulate the consequences of different alternative plans under various scenarios. The analytic hierarchy process (AHP) method is then applied to compare the different alternatives based on their performance as revealed by the SD simulation.

The SD model consists of six sections; together, these cover the major issues involved in waste management - waste generation, waste treatment, waste disposal, waste recycling, financing, and environmental impact. These sections are connected by both the material flow of waste from generation to final disposal, and the information flow among the influencing factors. The model is illustrated with a hypothetical case study that involves alternative plans to address the waste treatment/disposal facility issue in a developing region over a planning period of thirty years. The performance of each plan under different scenarios is simulated in the model, and evaluated through the trajectory of indicator variables / indices such as the cost index, recycling index, and the environmental index.

The AHP hierarchy integrates a multitude of pairwise comparisons between criteria and between alternatives into a consistent set of scaled scores that help decision makers choose the final plan. The decision hierarchy in this study includes four criteria and two sub-criteria organized into two levels. The criteria include the significant considerations involved in the waste management such as cost, environmental impact, waste recycling, and public involvement. The ratios of the pairwise comparisons between these criteria are assigned according to the decision makers' preference. Although specific numbers, in the form of pair wise comparison ratios, are presented in the hypothetical example, it should be noted that these are only meant as an illustration of the proposed method. Should these ratios change, the priorities of the criteria will alter accordingly, and will consequently result in a change in the priority sequence of the alternative plans.

The joint use of these two methods has some notable advantages. Firstly, the SD model is able to capture the most important cause-and-effect dependencies between the key decision variables and parameters in the model, and shed insight as to the time trajectory of the system as a result of these dependencies. Secondly, the proposal takes advantage of the AHP comparison matrix in the judgment process, simplifying the process of arriving at an outcome for the decision maker.

The main weakness of the approach is the complex model structure of the SD model, as well as the large number of parameters involved in the model. This makes the identification and communication of the underlying concepts and assumptions difficult. This is not a shortcoming of the SD paradigm *per se* but more of the way in which SD models are structured.

The main shortcomings of the present study include:

a) systematic assessment of the uncertainty and sensitivity of the model parameters has not been attempted;

b) the proposed methodology has not been validated with a real-life case study because of the difficulty of obtaining access to such data; as such, the methodology could only be tested on hypothetical values based on data from different reference sources.

The approach advocated in this research is not intended to replace more detailed planning and engineering analysis. It can be complementary to the more traditional methodologies and techniques employed in waste management facility planning.

5.3 Suggestions for future work

To-date there has not been many studies that combine the use of SD and AHP methodology to address waste management issues. This study has contributed in this respect by illustrating how such a combination might work, thereby illustrating the strengths and weaknesses of such an approach. Future studies along the same lines could address the following points:

- Adding more influence factors. The impacts of some policies and the feedback of the policies could be included in the waste generation section as they may influence the growth rate of waste generation. Factors pertaining to recycling, such as market supply and demand, and market prices of the goods made from recycled waste could also be added. Furthermore, private investment through various public-private partnership arrangements could be considered to provide another source of funding for waste management facilities and thus help alleviate the cost pressure on government budgets.
- Validation can be made more effective. In the thesis, a hypothetical case is used to demonstrate the methodology. The validation is made based on the hypothetical data. In future work, data from real-life project can be input into the model to generate the simulation outputs of some variables, such as the amount of waste

generated, treated, and disposed, the fund needed by waste management. Thus, the model is verified by checking the consistency of the simulation outputs and the real-life records of these variables.

- More research could be done to validate the relationships among the model parameters.
- More indicator variables and evaluation criteria could be identified and included in the decision-making hierarchy.
- Risk associated with the adoption of the different scenarios could be taken into account, as decision makers may not consider all scenarios as being equally probable.
- The proposed DS approach could be developed into a waste management policy planning tool with a good user interface linking model assumptions, scenarios, decision variables (as planning alternatives), outcomes and trade-off comparisons between planning alternatives.

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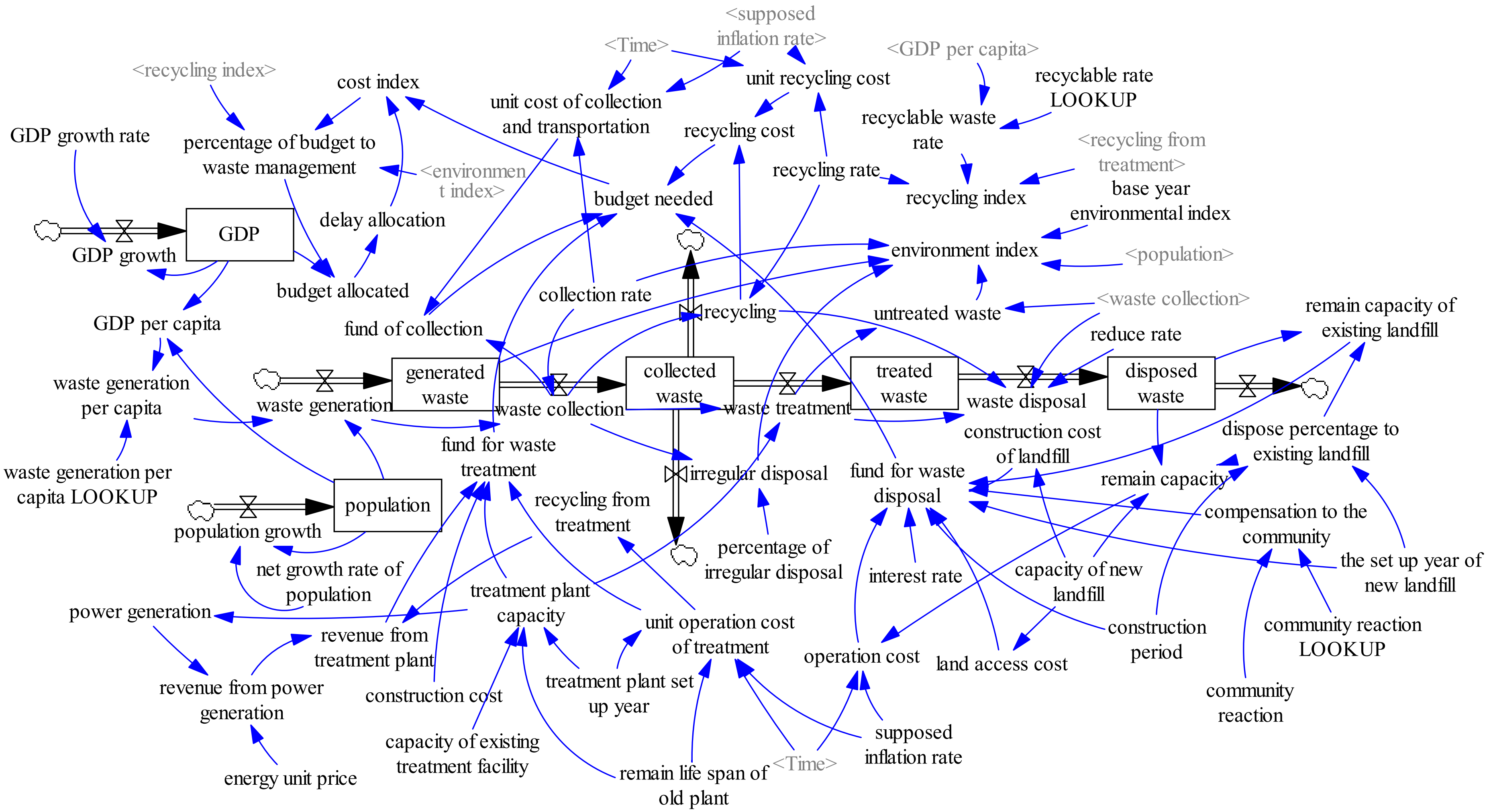
Appendix Ⅰ

Flow diagram of the system dynamics simulation model


<supposed inflation rate>
<Time>
unit recycling cost
<GDP per capita>
recyclable rate LOOKUP
<recycling index>
cost index
unit cost of collection and transportation
recycling cost
recyclable waste rate
GDP growth rate
percentage of budget to waste management
<environment index>
recycling rate
<recycling from treatment>
budget needed
recycling index
base year environmental index
GDP
GDP growth
delay allocation
environment index
<population>
budget allocated
collection rate
recycling
untreated waste
<waste collection>
GDP per capita
fund of collection
reduce rate
remain capacity of existing landfill
waste generation per capita
generated waste
waste generation
waste collection
collected waste
waste treatment
treated waste
waste disposal
disposed waste
fund for waste treatment
construction cost of landfill
dispose percentage to existing landfill
waste generation per capita LOOKUP
irregular disposal
fund for waste disposal
remain capacity
population
recycling from treatment
population growth
compensation to the community
net growth rate of population
percentage of irregular disposal
interest rate
capacity of new landfill
the set up year of new landfill
treatment plant capacity
power generation
revenue from treatment plant
unit operation cost of treatment
construction period
community reaction LOOKUP
operation cost
land access cost
revenue from power generation
construction cost
treatment plant set up year
supposed inflation rate
community reaction
capacity of existing treatment facility
remain life span of old plant
<Time>
energy unit price

Appendix II

FUNCTIONS APPLIED IN SD MODEL FORMULATION

`1)INTEGER: target variable=INTEG( {x} )`

This function returns the integral part of value X to the target variable.

`2)IF THEN ELSE: target variable=IF THEN ELSE( {cond} , {ontrue} , {onfalse} )`

When the description of `{cond}` is true, the function returns the value of`{ontrue}`, otherwise, the function returns the value of `{onfalse}.`

`3)MAX: target variable= MAX ( {x1} , {x2} )`

The function returns the larger one between values `{x1}` and `{x2}` to the target variable.

`4)MIN: target variable= MIN ( {x1} , {x2} )`

The function returns the smaller one between values `{x1}` and `{x2}` to the target variable.

5)LOOK UP: Variable A LOOK UP [(a_1,b_1), (a_2,b_2), (a_3,b_3)…]

`Variable A= Variable A LOOK UP (Variable B)`

A LOOKUP variable should be formulated when the function is used, which is `Variable A LOOK UP` in the above example. The function returns value to variable A according to the value of Variable B as shown in the flowing table.

Variable B	$< b_1$	$< b_2$ and $> b_1$	$< b_3$ and $> b_2$	…
Variable A	a_1	a_2	a_3	…

`6)STEP: target variable=Initial value + STEP ( {height} , {stime} )`

The function returns zero until `Time` reaches `{stime}`, and then it returns the value of `{height}`. The target variable equals to `Initial value` until `Time` reaches `{stime}`, and then equals to `Initial value + {height}`.

`7)DELAY FIXED: target value= DELAY FIXED ( {in} , {dtime} , {init} )`

The function returns the value of `{init}`, until `Time` reaches `{dtime}`, and then it returns the value of `{in}`