SURMAT
decision support tool to select municipal solid waste treatment technologies

Case study in Ho Chi Minh City, Vietnam

Le Thi Kim Oanh

Thesis committee

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Wageningen University

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Professor of Logistics and Operations Research
Wageningen University

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Le Thi Kim Oanh

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Le Thi Kim Oanh

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Chapter 1
Introduction

1.1 Introduction to the research problem

The rapid economic development and population growth of Viet Nam has led to serious environmental problems (Mol and Van Buuren 2003, p.11,40). Outstanding among these problems is the production of huge and increasing amounts of municipal solid waste (MSW). Annually, Viet Nam discharges more than 15 million tons of solid waste, of which about 12.8 million tons are MSW (85%) (Liem 2007; MONREd Viet Nam 2009). Progress in collection, reuse, recycling and treatment of solid waste has been made, but further improvement is considered as urgent. As a consequence, the government has issued decisions and regulations to encourage or improve the activities related to solid waste reduction, collection, transport and treatment. A recent one is the National Strategy of Solid Waste Management in Viet Nam. In decision number 2149/QD-TT (17/12/2009) on Government Strategy on Solid Waste Management to 2025 and Vision to 2050 the Prime Minister of Viet Nam writes: "Up to 2025, 100% of discharged MSW has to be collected and treated and 90% of this has to be recycled, reused or converted to energy or compost products. And up to 2050, all MSW are collected, treated and recycled using technologies, that are modern, environment friendly and suitable to local conditions in order to get a minimum volume of MSW at landfills". In the annex of this decision, ten government programs have been formulated to support the implementation of this strategy. These are:

(1) The program to encourage prevention, reduction, reuse and recycling of solid waste,
(2) The program to encourage "solid waste separation at source",
(3) The program to invest in solid waste treatment facilities at local level,
(4) The program on MSW treatment for the period 2009 - 2020,
(5) The program on environmental recovery at solid waste treatment plants or landfills/dumping areas,
(6) The program on improvement of solid waste management in rural areas and handicraft villages[1],
(7) Data base and monitoring program on solid waste,
(8) The public awareness program,
(9) The program on developing the system of regulations, policies and laws on solid waste management, and
(10) The program on medical solid waste treatment for 2009 – 2025[2] (MONREd Viet Nam 2009).

In the wake of these national programs and related measures at local level, many solid waste projects are underway. Understandably therefore, the report "Viet Nam market analysis" of the International Research and Markets Company contends that "Viet Nam is one of the fastest development markets on solid waste management in the Asia-Pacific area[3]". It shows that the environment for business and society in Viet Nam now has improved and supports foreign investment.

Although, as shown, enabling policies are in place or at least desired, the realities in the field are obstinate. The main treatment technology in Viet Nam up to the present is various forms of

[1] "Handicraft village" means the village where most of households have their own small scale enterprise that process the same products and discharge the same type of wastes.
[2] http://www.monre.gov.vn/van-ban-phap-luat.
[3] http://www.researchandmarkets.com/reports/1395924/Viet Nam_solid_waste_market_analysis.

landfill, which requires enormous areas of land (DONRE HCMCe 2006). Moreover, only 17 of the 91 big dumping sites in Viet Nam are sanitary landfills that comply with the environmental regulations. Forty-nine inadequate dumping sites have to be improved quickly based on a decision of the Prime Minister (Liem 2007). As Viet Nam, similar to other countries, copes with the NIMBY (Not In My Back Yard) syndrome, it is very difficult to site new landfills close to residential areas. Even local authorities do not want new landfills in their areas or receive waste from outside their constituencies as this may damage some branches of the economy, such as tourism and the export of products. As a consequence, an urgent need for land-saving waste management strategies and treatment methods has risen.

In line with the above policies the Vietnamese government has encouraged public and private companies to invest in solid waste management, including reuse and recycling, collection, transport and treatment. Investments have taken place in solid waste treatment plants such as the ones named Cau Dien, Nam Dinh, Ninh Thuan and Thuy Phuong (Giac Tam et al. 2006). However, the total capacity of these plants is still very small compared to the discharged waste volumes. In Viet Nam at this time apart from landfill composting is being used as well. Anaerobic digestion and incineration are hardly applied. Incineration is currently used but on a very small scale (maximum 21 tons/day) for hazardous and medical wastes (DONRE HCMCa 2010). The anaerobic digestion technology has been applied to pig manure and sludge, but not to MSW. In order to better understand the strength and weaknesses of new strategies and land-saving technologies for MSW handling Viet Nam has encouraged research. It has looked to approaches in West European countries, for example Denmark, Germany, Belgium and the Netherlands, that were first in implementing new strategies and technologies. Decision makers in Viet Nam like in other developing countries are aware, however, of possible difficulties associated with transfer of these strategies and technologies from The North to countries like Viet Nam. One should take into account the different societal and physical conditions of the two situations.

In order to overcome the lack of know-how concerning the accelerated introduction of land-saving, feasible and sustainable waste treatment technologies in complex situations in developing cities, this thesis elaborates a decision support tool named SURMAT (Sustainable URban waste MAnagement Tool) based on a mathematical optimization model. The objective of SURMAT is to enable decision makers in cities of developing countries to select technologies for MSW management that well fit the situation under study. This tool had to be developed for and tested in a concrete situation for which the case of HCMC, the largest city of Viet Nam was chosen. As will be shown in this thesis this city is urgently seeking appropriate methods for more sustainable treatment of its increasing amounts of MSW. The application of the method developed in this case study to other cities in Viet Nam and developing countries in general will be discussed in the final chapter of this thesis.

1.2 Ho Chi Minh City as a case-study

As mentioned above the decision support tool is elaborated making use of the case of HCMC. Before we describe the research questions and methods of this thesis the solid waste management challenges of our case-study area are pointed out here. HCMC is a big developing city, which will become a mega-city (more than ten million inhabitants) in the near future. The amount of MSW is high and increases quickly following the increasing population and economic development. As in many tropical and developing cities, MSW of HCMC contains a high percentage of organic matter, which results in high pollution emissions to the atmosphere and to ground and surface water via leachate. Typical for most cities in low-income countries the main MSW treatment technology in HCMC is landfill. In this city the land use of landfill requires not less than 15 ha/year (Kim Oanh 2009) and comes with considerable treatment costs (20 USD/ton MSW) (DONRE HCMCb 2009).

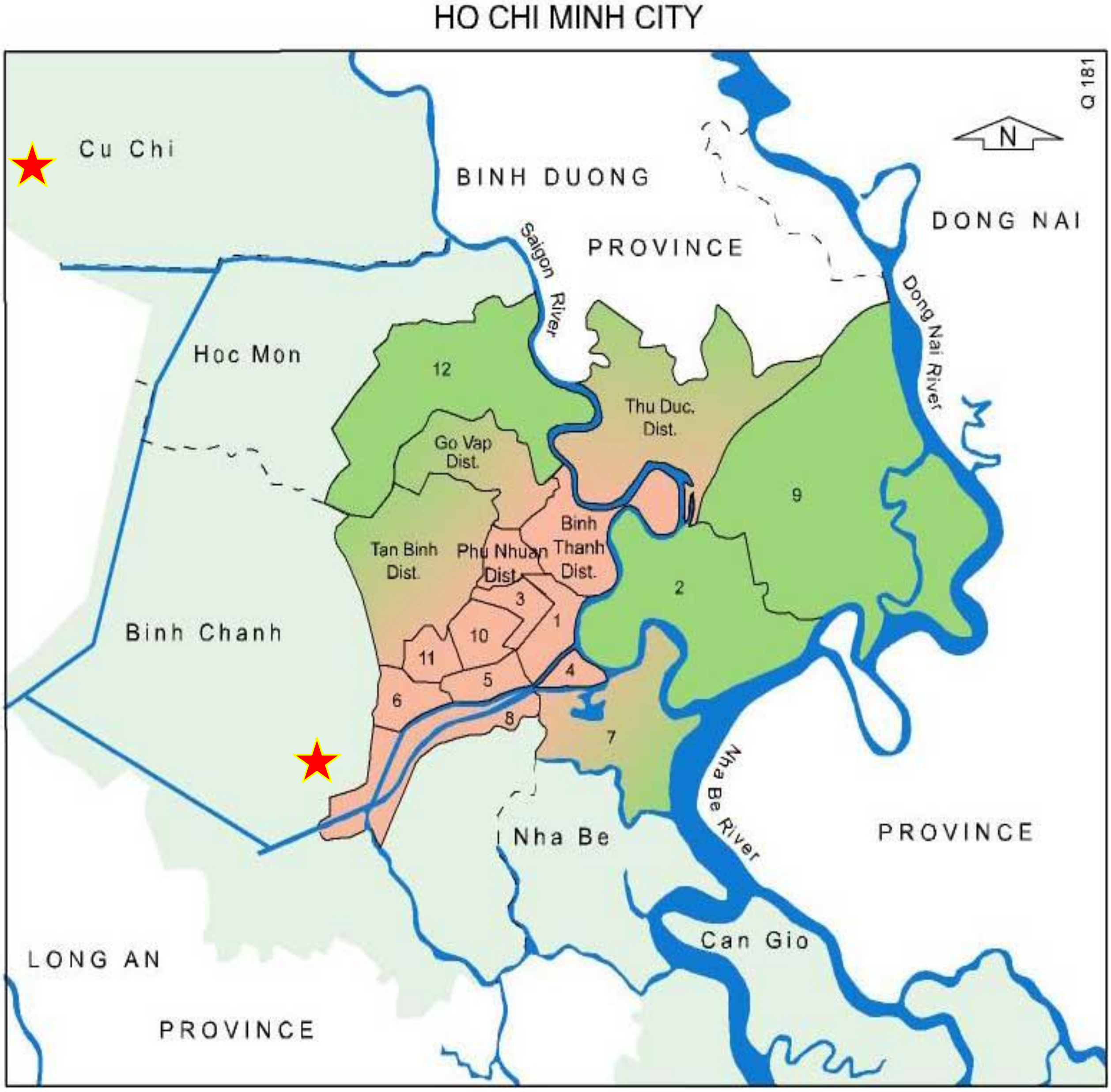


Figure 1.1 Map of Ho Chi Minh City.
Source: Adopted from Van Buuren (2010).
Note: ★ *location of MSW treatment zone 1 and 2.*

In agreement with Viet Nam's national sustainable solid waste management strategy, HCMC is looking for solutions to reduce the volume of MSW, to control the pollution emissions and to produce valuable products from wastes. The challenges to waste managers in HCMC are typical for those of Viet Nam and developing cities in general: inadequate insight into treatment technologies, lack of budget and scarce land. There are several land-saving local and foreign technologies to invest in. But, until now (2012), the government could not decide yet, due to the fact that there is no integrated approach to select the best system option for HCMC.

1.3 Main research objective and research questions

In view of the challenges in the field of MSW management in developing countries the main research objective of this thesis is: *To be able to take more sustainable and cost-effective* *decisions on solid waste management in the complex situation of cities in developing countries, in particular in Viet Nam*.

This broad objective in the domain of solid waste management planning has been translated to the following main research question of this dissertation: *Which technology or combination of technologies should be chosen to handle the fast growing amount of MSW in a specific situation in cities in developing countries, in particular in Viet Nam?*

This research question is going to be answered by means of developing the above mentioned decision support tool SURMAT and applying it for the case of HCMC. In setting up this tool various sub-questions have to be answered. These questions are detailed in the next section.

1.4 Research questions according to the chapters of the thesis

The present first chapter is followed by five research chapters (2 until 6). Together they constitute the decision support tool mentioned above. The research questions underlying these various chapters are explained here.

The key research question at the basis of chapter 2 is: *In which way should the conditions of the situation under study be described to yield the data needed for selection of a sustainable and cost-effective solid-waste management system?* As HCMC is presented as a case under study, the research question becomes: *What are the conditions relevant to the selection of a MSW treatment technology in HCMC?*

Following the Integrated Sustainable Waste Management (ISWM) concept (Van de Klundert and Anschuetz 2001) the descriptive analysis in chapter 2 of the conditions for which a selection of a system has to be made is subdivided into three main domains: the components of the chain of the present MSW waste management infrastructure, the stakeholders in the management system and the aspects. The aspects include the legal and institutional framework, financial and economic aspects, physical and technical conditions, environmental issues and social and cultural aspects, all related to solid waste management. This base-line description of the conditions forms the input to the following chapters 3 until 5 that elaborate the technologies appropriate to the situation under study and the strategy modeling in chapter 6.

As more know-how on the possibilities of anaerobic digestion of MSW in Viet Nam was needed, chapter 3 reports about experiments using the relatively low-tech Biocel technology. The Biocel technology has been designed for batch anaerobic digestion of Organic Fraction of MSW (OFMSW). This technology is applied at full-scale in The Netherlands and seemed to be one of the most suitable, but yet unknown, technologies for urban conditions in developing countries and also for HCMC. The outcomes of the research under chapter 3 could be important in the selection of specific anaerobic technologies for developing countries in chapter 4.

The research questions underlying chapter 3 are: *Is it possible to apply the Biocel technology to digest the organic fraction of MSW under the conditions of Viet Nam?*

The research question behind chapter 4 is: *What are feasible MSW treatment technologies for developing cities and for HCMC in particular?*

In order to answer this question first an overview is given of MSW treatment technologies applied worldwide adding to each of them a list of strengths and weaknesses relevant to developing countries. Then, a list of criteria is developed for technologies feasible in developing countries. Using this list of criteria and taking into account the strength and weaknesses of the mentioned technologies a selection of eight feasible technologies is made. For each of these eight technologies the requirements and characteristics are elaborated in more detail as they form the basis of the strategy analysis to be made with the decision support model in chapter 6. As only few of the proposed technologies are in use in Viet Nam at the moment, the transfer of knowledge about MSW treatment from industrialized western countries to Viet Nam is an important consideration in this chapter.

Since the costs of waste treatment is a very important factor in the decision making about management systems, the main research question of chapter 5 is: *What are the costs and revenues of the MSW treatment technologies selected as feasible for developing countries in chapter 4?*

Chapter 5 reviews costs of the MSW treatment technologies selected in chapter 4 from international and Vietnamese literature and converts these cost data to estimated present investment and operation costs in Viet Nam. The same is done for revenues (financial benefits) from the sale of generated electricity and other utilizable products from MSW. An overview is made of overall land use and net costs (gross costs minus revenues) of the eight technologies selected in chapter 4. These figures are key input data to the strategic modeling of chapter 6.

Decision-making about a future solid waste management system for a certain situation can be supported through the calculation and analysis of strategies for such a system. This is the purpose of chapter 6. For the different strategies several preconditions, here mentioned as constraints, can be adopted.

The main research questions here are: *Which existing model could be used to handle material flows and the choices on MSW collection and transport, processing technologies, and locations? and How can the model be configurated so that it produces the desired strategies for HCMC?*

The developed tool (i.e. the model including the knowledge gathered in the previous chapters) is named SURMAT and is the main outcome of the thesis, as it enables its user to develop waste management strategies for different situations.

After shaping the model it has been applied to work out waste management strategies for the case of HCMC. The underlying research question for this central part of the thesis is: *What strategies for MSW handling in HCMC does the chosen optimization model deliver using information about feasible technologies, local conditions and selected constraints?*

The model optimizes the logistics and treatment of waste flows, incorporating the supply and demand issues. Two societal objectives were used in working out strategies: least net costs and maximum electricity output.

Chapter 7 finally takes a critical look at the value and the limitations of the SURMAT tool. Also this chapter takes a step back from the case-study of HCMC and discusses the value of SURMAT for developing cities in general.

The research question of this chapter is: *What are the added value and limitations of the SURMAT and its outcomes in enabling decision making about MSW handling in developing cities?*

The combination of the above mentioned research questions are integrated into the conceptual research framework presented in figure 1.2.

The scientific challenge at academic level is to bring together technological and managerial information in the determination of sustainable solid waste management strategies in an integrated decision support tool. The tool aims at the development of an optimal approach to solve the problem of solid wastes management. Innovative are the combination of relevant knowledge about logistics, waste treatment and operations research and the very specific aspects of the solid waste management situation in developing cities, specifically in Viet Nam.

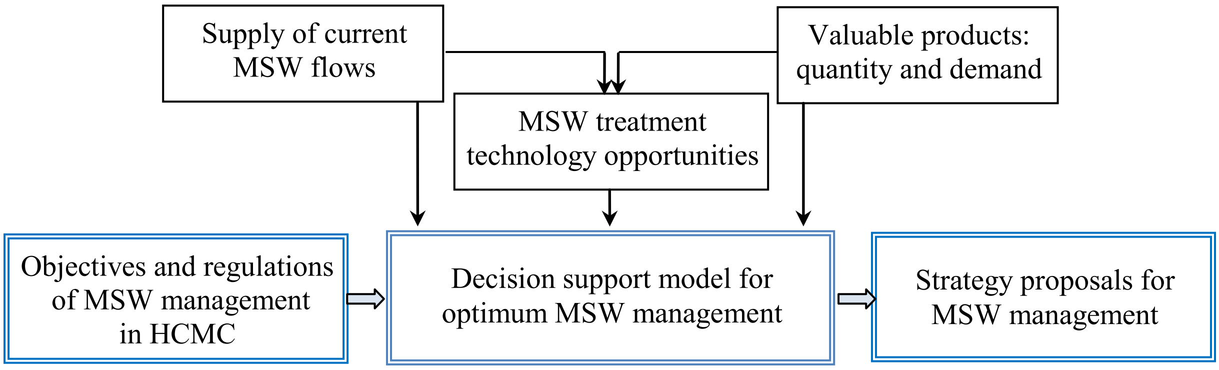


Figure 1.2 Conceptual framework of the research.

1.5 Research methods

In the analysis of characteristics of the MSW management system in Vietnamese cities and especially HCMC (chapter 2) the research methods used were extensive study of 'grey' Vietnamese literature, attending workshops and conferences on solid waste management. Most important were the ISWA conference in Hamburg in 2010, the ISSOWAMA (integrated solid waste management) board project meetings and workshops in Bangkok, Siem Reap and New Delhi in 2009, 2010 and 2011, the municipal solid waste management-stakeholders dialogue in HCMC in 2007, the workshop on knowledge exchange on incineration technology between HCMC and Kyoto in 2011 and the workshop on solid waste management in Nanyang Technological University, Singapore in 2012. Furthermore, participation in local and international projects on solid waste management provided much information. Worth mentioning are the EU-Asia Pro-Eco Project on biowaste reuse in South East Asia (2006 - 2007), the Dutch ISSUE 2 project (2007 - 2010), the EU funded ISSOWAMA project (2009 - 2011), the project on anaerobic digestion of MSW in HCMC (2007 - 2009), the solid wastes separation at source program in HCMC (2007 - 2008), the project on development of criteria and standards to select MSW treatment technologies in HCMC in 2006 and the project on decentralized composting plants in Viet Nam led by UNESCAP and Waste Concern in 2011. Interviews with key persons on solid waste management in HCMC, such as the heads of the Solid Waste Management Office, the Recycling Fund and the Science and Technology Office, were important to learn about their views on the critical issues of the current system and government policies. In addition, field visits to treatment plants provided crucial information about different treatment technologies.

In order to find out the possibilities and constraints of batch-wise anaerobic digestion of MSW with the Biocel technology (chapter 3) experimental work at demonstration and lab-scale was carried out.

The detailing of a data-base for technology selection in chapter 4 demanded extensive study of international grey and peer-reviewed literature on MSW treatment both on technological as on management aspects. The work on the inventory of assessment criteria needed for the screening of technologies feasible for Viet Nam required both literature study and interviews with stakeholders from management agencies and public and private providers in the MSW sector.

The costs and financial benefits analysis of chapter 5 included the formation of a data-base on technology costs and revenues of end products. The data came mainly from international literature and to a small extent from Vietnamese sources. The data obtained at excursions and through interviews with staff of Vietstar Company in HCMC were an important local source. Practical mathematical models had to be applied to convert the found financial figures to figures for Viet Nam in the chosen base year 2009. This included conversions using inflation rates and cross country comparisons. In some cases cost savings or additional costs for technologies about which no data were available were approximated by gross estimations. These are always explained in the text.

The strategies which will be modeled in chapter 6 were developed based on information of the grey literature, knowledge and experiences from workshops and projects and the exchange of information with key experts on solid waste management. The strategy modeling required a study of the operations research literature with respect to goods flow modeling and decision support tools (Claassen et al. 2007; Maximal Software 2002; Winston 2004). The selected model was put to work using the input data about HCMC collected in chapter 2, 3, 4 and 5.

1.6 Scope and outline of the thesis

Using a decision support tool named SURMAT this thesis develops strategies for MSW management in HCMC for the coming 20 years. It consists of 7 chapters. Chapter 1 presents the societal problem of the lack of adequate planning tools for MSW management in Vietnamese cities in general and in HCMC in particular and translates this problem to the research objective, research questions and methods applied in this thesis. Chapter 2 describes the current situation of MSW management in HCMC, Viet Nam using the framework of the ISWM concept. This description is meant as a typical case of a large city in a developing country. It is for this kind of conditions that this thesis intends to generate waste management strategies. Chapter 3 reports about the feasibility of the anaerobic Biocel technology for solid wastes treatment under Vietnamese conditions. Chapter 4 presents a literature review of various modifications of composting, anaerobic digestion, incineration and landfill. In this chapter eight technologies are selected feasible for waste treatment under the conditions of Vietnamese cities. Furthermore, this chapter gives for these eight technologies descriptions of the technological processes as well as the social and environmental characteristics. Moreover, it reviews their strengths and weaknesses. Chapter 5 presents the costs analysis of these selected treatment options for MSW in HCMC. Chapter 6 elaborates on the operation research model using input from Chapter 2, 3, 4 and 5. This chapter deals with the design of an "optimal" structure for the MSW treatment system in HCMC under the conditions expected from the present until the year 2032. Chapter 6 also searches for strategies under which a maximum energy production from MSW is achieved. Chapter 7 discusses the strengths and weaknesses of the SURMAT tool and discusses the significance for other cities in Viet Nam and in other developing countries. This chapter also summarizes the main conclusions and recommendations of the thesis.

Chapter 2
Current municipal solid waste management system in Ho Chi Minh City, Viet Nam

2.1 Introduction

The present chapter analyzes the solid waste management system in HCMC. This chapter is important in its own right as a baseline study about the MSW management developments in a fast-growing South-east Asian City and as source of input data to the decision support model applied in chapter 6. This analysis is structured according to the ISWM concept, i.e. first a description is given of the various components of the waste management chain from waste sources to disposal, then secondly an identification and analysis of the relevant stakeholders playing a role in this system and thirdly a discussion of important aspects of the solid waste management system. ISWM is designed as a diagnostic tool for decision-makers to look in a systematic way at their waste problems. The concept is based on the experiences from the Urban Waste Expertise Program (1995 - 2001) carried out by WASTE advisers from the Netherlands (Van de Klundert and Anschuetz 2001). Before proceeding to the ISWM analysis important information about HCMC is given.

The surface area of HCMC is approximately 2,094 km^2. It is Viet Nam's largest economic hub that generates 20.2% of its GDP (Statistical Publishing House of HCMC 2009). The average per capita income in HCMC is the highest in Viet Nam, being 2,800 USD/year (Wikipedia 2009). Belonging to the Southern key economic zone of Viet Nam and being the driving force in the region, HCMC has a strong potential for economic expansion, commercial services and social and cultural developments. However, HCMC is facing serious urban and environmental management problems, of which MSW management is one of the biggest. Therefore, authorities of HCMC are most interested in and prepared to invest in MSW solutions.

The population of HCMC amounted to over 7.1 million in 2008. In addition, the city counted probably more than one million unregistered inhabitants (Statistical Publishing House of HCMC 2009). The collected MSW is about 5,600 tons/day in 2008 (DONRE HCMCa 2009) with a growth rate of 6 - 8%/year during the last 10 years (DONRE HCMCb 2009). About 60% of the transported waste could serve as raw material for composting (CENTEMA 2008). HCMC is a densely populated city with complicated and narrow roads. Infrastructure and equipment for MSW collection, transportation and treatment are inadequate. The MSW collection system is complex and lacks integration of the many public and private transporters causing overlap in work, especially among the private informal collectors. Public awareness on environmental protection among the general population is low. These issues cause pollution within the MSW collection chain and illegal discharges into waterways and on unoccupied land.

The city has a tropical wet climate with an average humidity of 75%. The year has two seasons: the rainy and the dry season. The rainy season provides most of the annual rain of about 1,800 millimeters on average (about 150 rainy days per year). The average temperature is 28 °C. The temperature sometimes reaches 39°C, while the lowest temperature may be below 16 °C (Meteorology and Hydrology Station 2009). In this climate, organic fraction of MSW can easily degrade causing negative effects for the environment due to odor, leachate, spreading of pathogens and related factors. However, this climate is suitable for biological treatment of the organic fraction of MSW.

The environmental law of Viet Nam was set up in 1999 and refined in 2005. Taking this law as point of departure, the Vietnamese government supports the environmental management system with at least 1% of GDP[4]. Similarly, HCMC is putting more and more efforts in environmental protection. One of the impression example is that the expenditure of HCMC on solid waste management, which has increased from 902 billion VND in 2007 to 1,392 billion VND in 2008 (54% increase in one year)[5](DONRE HCMCi 2009). The environmental management strategy of HCMC (DONRE HCMCd 2002), the national environmental protection strategy (MONRE Viet Nam 2004) and the master plan of the MSW management system of HCMC for the period of 2008 - 2020 (DONRE HCMCe 2006) stipulated that MSW had to be treated with modern technologies by 2010 - 2015. The primary aim is to limit the volume of MSW disposed of at landfills.

Due to limitations of the MSW management budget, HCMC is very interested to attract investments from private and foreign parties. In order to stimulate those investments the city government has simplified administrative formalities, supports environmental projects with land at zero costs and bases the MSW treatment fee on the type of technology. However, one of the reasons why the investments are still limited is the absence of clear investment rules. Until now, only a few MSW treatment projects have applied for investment in HCMC. Some project investment proposals, such as the Earthcare composting plant, have been approved about 5 years ago, but until now (2011) is still not executed. The approval process of investment projects has made apparent that the government has no tool and methodology to select suitable technologies. As a consequence, some projects were not approved, especially those applying new technologies, such as incineration with energy recovery and anaerobic digestion. After this general introduction about HCMC, the description of the MSW management system is presented in the section 2.2, 2.3, 2.4 and 2.5 using the ISWM methodology.

2.2 Municipal solid waste management system components

2.2.1 Waste definition

Waste is an object the holder discards intends to discard or is required to discard. Once a substance or object has become waste, it will remain waste until it has been fully recovered and no longer poses a potential threat to the environment or to human health[6].

Urban solid waste in HCMC is classified into five categories as follows (DONRE HCMC 2009):

1. MSW is the commingled solid waste from households, offices, schools, restaurants, hotels, markets, streets and the domestic and non-hazardous waste from hospitals and industries. It is collected, transferred and transported to sanitary landfills and composting plants in the Phuoc Hiep and Da Phuoc treatment zones;
2. Construction and demolition waste is collected and transferred to the construction dumping site in Dong Thanh;
3. Sediment from sewerage and canals is collected and discharged to an open area in Can Gio District without treatment. Sludge from wastewater treatment plants is treated on site or at private treatment companies;
4. The City Environmental Company (CITENCO) collects medical solid waste (hazardous waste from hospitals). Three public incinerators belonging to CITENCO treat this waste;

[4]In the "Environmental Protection Law" there are several articles on environmental protection. For example, Legislation no. 52/2005/QH11 dated 29/12/2005 stipulates the generalities of solid waste management. Decree no. 80/2006/ND-CP date 9/8/2006 stipulates and gives guidelines to implement some of the articles in the Environmental Protection Law with 25 articles and 2 references. Decree no. 21/2008/ND-CP date 28/2/2008 modifies and adds some articles in Decree no. 80/2006/ND-CP.

[5]Exchange rate: ~ 18,500 VND/USD in December 2009.

[6]European Directive 75/442/EC.

5. Public or private treatment companies collect and treat hazardous waste from industries under the contract between the plant and the treatment company.

MSW is collected separated from other types of waste (construction, sediment, hazardous and industrial, and medical waste). It is collected and transported directly or via transfer stations to sanitary landfills or composting plants. The recyclable waste is separated during the collection activities. This is sold to itinerant buyers and then to recycling companies. The major components of this collection system appear in figure 2.1.

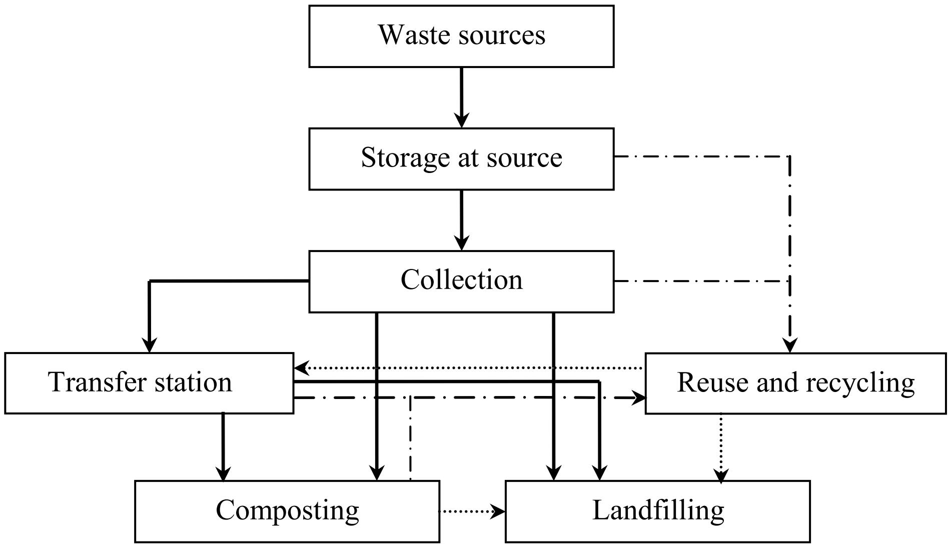


Figure 2.1 Municipal solid waste collection chain in Ho Chi Minh City.
Note: ⟶ *Commingled MSW flow,*
– · → *Recyclable flow,*
······→ *Residue (rejected waste) flow.*

2.2.2 Generation

Households and other waste generators do not have standard containers for MSW storage. Currently waste is stored in plastic bags, tins, bamboo containers, etc. Most households, especially those with confined living areas, use plastic bags to store their commingled waste. Offices, schools, etc. have their own type of containers. Markets store their MSW directly on the floor or in containers. Many restaurants have special storage containers of food waste to be utilized as animal feed. No separation of MSW takes place at the source; all sorts of MSW are discharged and stored together. However, most households separate the valuable wastes such as cans, plastic, paper, etc., from their domestic waste and sell this to itinerant buyers. Also many individual waste pickers go around to pick up valuable materials from public waste containers or wastebaskets of the households (during the time the wastebaskets are waiting for collection in front of the houses). This activity causes health problems for the waste pickers and has a negative impact on the urban environment. Therefore, in 2009, district 6 of HCMC carried out the demonstration program "solid waste collection on time" to overcome these problems.

Approximately 15% of the generated MSW in HCMC is not collected due to lack of public awareness, insufficient detailed regulations (discharge guidelines, penalty regulations, etc.) and lack of collection systems in un-urbanized areas (DONRE HCMCb 2009)[7]. The composition of commingled MSW changed since 2002 when the first sanitary landfill, Go Cat, was set up. Since then the construction waste, medical hazardous waste and hazardous industrial waste were

[7] The information were collected from the meetings in 2009 between representative of DONRE HCMC with private collector to implement the decision 88 (DONRE HCMC 2008) on re-setting up the collection system.

collected and treated separately from MSW (DONRE HCMCe 2006). However, the composition of the present commingled MSW is still complex and contains other types of waste, sometimes hazardous, from illegal discharges. Appendix 1 presents the details of quantity and composition of MSW in HCMC.

In 2007, a demonstration program of solid waste separation at the source was carried out at pilot scale in five wards (neighborhoods) of District 6 of HCMC (DONRE HCMCf 2005; DONRE HCMCc 2009). Within this project, the households were given two waste storage containers: one for organic waste (compostable waste) and the other for the rest of the household waste. The results of this program after one and half year were not meeting expectations due to many reasons. These were, among others: (1) the integration among the stakeholders were weak; (2) the public awareness was not sufficient; (3) the lack of regulation/guidelines reduced the efficiency of the activities; (4) the infrastructure for this program was lacking or inadequate, such as a lack of appropriate collection trucks, absence of transfer stations for two different types of MSW, and there was no composting or anaerobic digestion plant to treat the collected organic waste; (5) lack of managerial experience and capacity building; (6) lack of funding. The government became aware that these issues have to be adequately addressed before restarting this program.

In summary the critical points related to the waste generation at sources are: high amount of commingled MSW generated no standard containers for MSW storage, limited place at households for placing containers, high amount of leachate and malodor production; lack of public awareness, and high amount of recyclable waste sorted at source.

2.2.3 Collection

MSW is transferred from discharge sources to gathering points using handcarts with a loading volume of 660 liters. From there, a truck transports the waste to transfer stations or directly to landfills or composting plants. Depending on the length and quality of the transport routes, the capacity of the trucks can be selected. MSW from sources along main streets is transported directly by big trucks (7 - 12 tons/truck) to landfills or composting plants or by small trucks (2 - 4 tons/truck) to transfer stations. The collection equipment is not standardized. This is especially true for handcarts of informal private collectors. The handcart of informal collectors is self-designed and not adapted to the requirements of good hygiene. The volume of this handcart is usually much higher than 660 liters to maximize the amount of carried wastes. Safety facilities such as gloves, hats, and clothes are not strictly required and often not worn. The MSW collection system also collects bulky wastes such as old tables, chairs, beds, etc.

Regarding collection of MSW in HCMC, critical points are: old and damaged narrow transport pathways in the dense areas; non-standardized collection facilities and lack of safety facilities; lack of collection skills and the activity of separating recyclable wastes causes delay in collection time and pollution; lack of monitoring and control; non-integrated management.

2.2.4 Waste transfer and transport

There are three modes of MSW collection and transport (figure 2.2).

Mode 1. MSW is collected and transported to gathering-points with handcarts. Subsequently, the MSW is loaded into small trucks (2 - 4 ton capacity) and moved to the transfer station (open heap, standard transfer station or compressing station). From there, big trucks (7 - 12 ton capacity) transport the MSW to a sanitary landfill or composting plant.

Mode 2. Handcarts collect and transfer MSW to gathering-points. Subsequently, big trucks (7-12 ton capacity) or compacting trucks transport the MSW to a sanitary landfill or composting plant. In mode 2 transfer stations are not used.

Mode 3. MSW is gathered and discharged in street containers with a volume of 240 - 660 liters alongside roads, or the MSW is coming from concentrated sources (supermarkets, commercial centers). The content of the containers is loaded into small trucks and transported to transfer stations or loaded into big trucks and transported directly to a sanitary landfill or composting plant. This mode is particularly used for street-sweeping wastes but also for a considerable quantity of household waste. In mode 3 gathering points are not used.

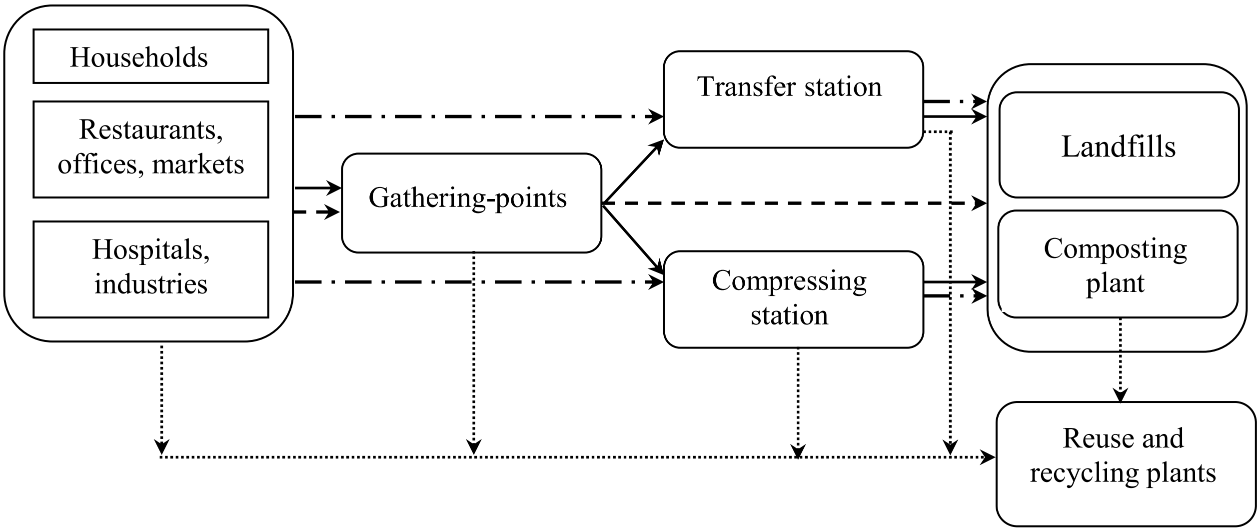


Figure 2.2 General diagram of collection and transportation of MSW in Ho Chi Minh City.
Note: → *MSW flow, mode 1,* - → *MSW flow, mode 2,* —→ *MSW flow, mode 3.*
······→ *Recyclable waste flow.*

HCMC counts about 2,300 public MSW containers with different sizes (25, 50, 240 and 640 L), 300 gathering-points, 46 open heaps and eight transfer- or compressing stations (CENTEMA 2009). The local districts manage the 46 open heaps and the eight transfer stations belonging to CITENCO. Waste is collected and transported by about 600 MSW trucks with loading capacities varying from 2 - 12 ton/truck (DONRE HCMCk 2009). There are three types of transfer stations in HCMC: (1) open heaps where MSW is discharged on the floor in an open area with or without roof and fence; (2) transfer stations where MSW is stored in a container or on the floor inside; (3) stations where MSW is compressed before transport to a landfill or a composting plant.

The transport system is complex and inadequate for the following reasons: (1) there are many companies involved in this activity, including CITENCO, 22 public service companies, some cooperatives and some private companies, which are working independently from each other. Therefore, it is difficult to organize and integrate the transport activities and transport routes; (2) inadequate infrastructure, such as narrow and badly paved transport routes, non-standardized collection cars/trucks, lack of gathering-points and transfer stations; (3) a lack of tools/ guidelines/ regulations to support the transport system; (4) poor management capacity and (5) insufficient funding.

2.2.5 Treatment

In a review of various MSW treatment practices in HCMC this section discusses composting, anaerobic digestion, incineration and recycling.

- **Composting**

Vietnamese farmers have a long tradition of composting animal manure and agricultural waste at household scale to produce compost for their crops. Large-scale composting of MSW has been developed during the past decades. As early as in 1982, HCMC imported technology from Denmark for the Hoc Mon composting plant. However, the plant was closed soon after start-up as the technology was inadequate for the local MSW. The key problem was the deficient quality of the product, which was due to insufficient separation of unwanted materials from the commingled MSW. Subsequently, Viet Nam imported more installations from Spain (Cau Dien – Ha Noi) [8], New Zealand (Tan Thanh – Ba Ria Vung Tau) and France (Thuy Phuong - Hue and Nam Dinh - Ha Nam). These foreign installations have not been adapted to the typical Vietnamese MSW and had to be closed or operate at low capacity. It has become clear that most foreign technologies must be modified to deal with the Vietnamese MSW. Lately, composting plants with 100% Vietnamese technology were started, such as Thuy Phuong (renewed from old Thuy Phuong plant) and Tan Thanh.

During the last 5 to 6 years, HCMC PC (People Committee of HCMC) has given construction licenses for four composting projects: (1) Vietstar composting plant for 600 ton MSW/day in the first phase, increasing to 1,200 ton MSW/day in the second phase; (2) Earthcare composting plant for 1,500 ton MSW/day; (3) VWS company for 1,000 ton MSW/day and (4) Tam Sinh Nghia composting plant for 1,000 ton MSW/day. Three of these projects are USA based. Only Tam Sinh Nghia is a Vietnamese company. Those composting factories were planned to be operational in 2009 - 2010. If these four composting factories would run at full capacity, not only 100% of the organic MSW in HCMC would be treated to produce compost, but also a part of industrial compostable solid waste, or MSW from the surrounding areas of HCMC, could be treated. However, now at the time of writing this thesis, only the Vietstar project, set up in 2008, has started to run in December 2009. Until the end of 2010, the Vietstar plant ran at a capacity of 600 ton MSW/day and increased its capacity to 1,200 ton MSW/day in the beginning of 2011. The technology at the Vietstar composting plant is similar to most of the composting plants in Viet Nam, namely aerated static pile composting technology. The composted MSW in all Vietnamese plants is commingled waste and therefore the separation process has to take place after transport, which is complex, costly and requires a lot of labor. An abundant component in the waste in Viet Nam is plastics, which needs to be removed before the waste is composted. At Vietstar the plastics are separated, cleaned and processed to fuel pellets or raw plastic material. As will be shown below (2.4.3) the plastics recycling contribute significantly to the income of the plant.

Many MSW composting plants in Viet Nam invested in a process that uses compost as input material to produce organic fertilizer: E.g. the Cau Dien, Nam Dinh and Thuy Phuong composting plants. By exception, the Vietstar composting plant produces only compost and subsequently sells the compost at 30 – 35 USD/ton (2010) as raw material to the organic fertilizer plants. No data is available on compost product quality of the Vietstar composting plant. Based on the survey of Giac Tam (2006), the quality of the compost products of most plants in Viet Nam satisfied the Vietnamese standard (10-TCN-526-2002) in terms of heavy metals, organic carbon, and moisture content. However, nitrogen and phosphate concentrations were low and the pH was higher than the required standard (see appendix 1, table A.1.4). Besides, several aspects, not defined in the standard, point at a less than satisfactory compost quality, such as the presence of injection needles, broken glass, rock, etc.

[8] In brackets are the names of cities where the plants are located.

Although composting is the second popular technology in Viet Nam (after sanitary landfills), it still faces critical issues, such as: high costs and low profits, operational problems due to high moisture and impurities from the input commingled MSW and unfamiliarity of farmers with the final compost product. Additionally, the development of composting in Viet Nam is hampered by the complicated, non-transparent and lengthy licensing procedure for large-scale plants, lack of details on quality standards for compost and inadequate documentation to certify and assess the quality of compost.

Despite the shortcomings of the present MSW composting practice, composting can be a good choice for Viet Nam as the MSW has a high percentage of organic material and the climate is suitable for biological processes. Moreover, Viet Nam is an agricultural country and has a high demand for organic fertilizers/soil conditioners. It has been shown that the amount of produced organic fertilizer is small compared to the effective demand and very small compared to the agricultural need (Giac Tam et al. 2006). The grossly insufficient supply of organic carbon causes a strong deterioration of the soils in Viet Nam nowadays.

- **Anaerobic digestion and incineration**

Investigations on dry anaerobic digestion of MSW have been conducted in HCMC with a batch system (chapter 3 of this thesis). The biogas production reached 59 m^3/ton of a mixture of was input. This is not high compared to the yields reported in literature. However, the research shows that anaerobic digestion is a reasonable technology in HCMC where there is a lack of electricity, especially in the dry season.

At the moment neither Viet Nam nor HCMC apply incineration technology for MSW. Incineration is applied to treat medical hazardous wastes or industrial waste at a small scale. Presently, the maximum capacity of incineration in HCMC is 21 ton/day (March 2011). HCMC needs incineration technology to reduce the area of land needed to dispose of the huge amount of hazardous and industrial waste. HCMC considers investing in a big scale incineration plant to treat MSW (Viet, 2009)[9]. However, high costs of investment and operation are the biggest constraints.

- **Recycling**

Besides organic waste, which can be recycled to produce compost or biogas, MSW contains other reusable and recyclable materials like plastics, nylon, glass, paper, cardboard, metals and rubber. These are collected at several stages of the collection chain at households, at gathering-points, at transfer stations and during transport and at composting plants.

With its about 8 million inhabitants, 15 industrial zones and 25,000 small and medium scale enterprises HCMC collects about 1,500 to 1,800 ton recyclable waste per day (DONRE HCMC 2009). Most of these recyclables are processed by its local reuse and recycling sector. A part of the recyclable waste, like nylon, is exported to China. Depending on the market price, some types of recyclable waste are collected more than others. Additionally, recyclable waste comes from other cities and provinces in the vicinity and is processed in HCMC.

Figure 2.3 presents a diagram of waste recycling in HCMC. Recyclable materials (nylon, plastics, paper, glass, metal) are collected at the sources and sold to the small waste depots. The waste depots further sort the waste prior to reselling it to larger depots or enterprises. Some waste depots with sufficient facilities (space, equipment, labor, etc.) carry out the re-processing step. Most transfer stations function as temporary waste stores and reusable materials are

[9] Personal communication on 4/12/2009. Dr. Viet was at that time the head of the Solid Waste Management Office of DONRE of HCMC.

collected there. According to a survey (CENTEMA 2008, 2009) on waste composition at the landfills, the percentage of recyclable waste in discharged MSW is still high and the fraction of recyclables in commingled MSW of HCMC has increased in recent years. Thus, it is clear that the efficiency of collecting recyclable wastes could be improved.

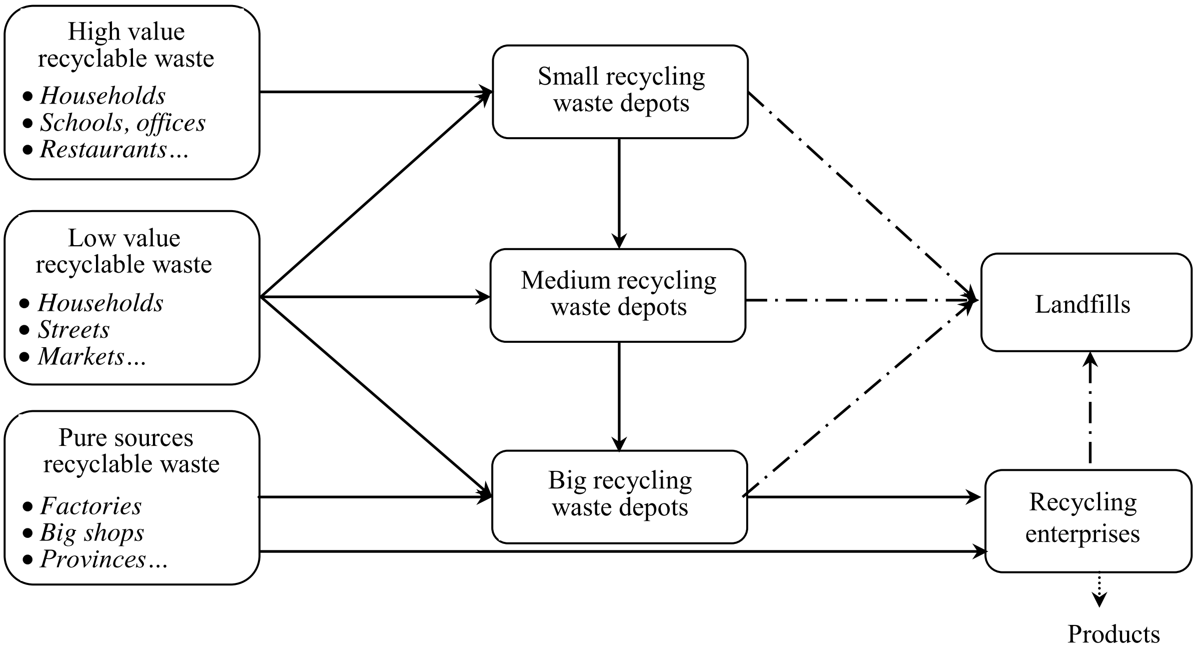


Figure 2.3 Diagram of wastes reuse and recycling in Ho Chi Minh City.
Source: DONRE, 2006.
Note : ⟶ *Recyclable waste flow,*
–·–› *Residue (rejected waste) flow.*

Most of the recycling plants in HCMC are small and medium scale. These enterprises have old-fashioned (old and low-tech) often polluting technologies and consume much energy. Moreover, their products are also of low quality. Fortunately, these low quality products still have big markets.

The typical issues in the recycling sector in HCMC are: (1) MSW is not separated at source but the recyclable waste is sorted during the collection and at the composting plants; (2) The fraction of recyclable waste is increasing which could lead to higher benefits; (3) The network for recycling activities is large including many stakeholders and not well controlled in terms of environmental protection; (4) Most of recycling plants in HCMC are small and medium scale with old and poor technology; (5) Recycling processes discharge much pollution; and (6) There is a market for recycled products, but the price is low due to low quality.

2.2.6 Disposal

There are presently six landfills in HCMC: Dong Thanh, Go Cat, Phuoc Hiep 1, Phuoc Hiep 1A, Phuoc Hiep 2 and Da Phuoc. Dong Thanh, Go Cat and Phuoc Hiep 1 and Phuoc Hiep 1A were closed in 2002, 2006, 2006 and 2007, respectively. The landfills of Phuoc Hiep 2 and Da Phuoc are currently in use. All landfills in HCMC are sanitary landfills, except Dong Thanh, which is a controlled dumping site.

In the past at Dong Thanh all types of urban solid wastes including MSW, hospital waste, hazardous waste, industrial waste and construction waste were dumped. Now it is still in use for the disposal of construction waste with a capacity of about 1,000 ton/day (DONRE HCMCc 2009). As a dumping area, Dong Thanh had no measures against environmental problems except soil covering after each dumping day and applying an enzyme that could abate odor. After closure, Dong Thanh was covered with HDPE (high desity polyethylene) and a part of the leachate was being pumped out and treated. Since its closure in 2002, Dong Thanh keeps polluting the environment, especially the groundwater. In 2002, HCMC started to operate its first sanitary landfill, named Go Cat (DONRE HCMCa 2009). A Dutch company has designed, constructed and operated this landfill. The design included dumping cells, a biogas collection system and generators and a leachate treatment system. This landfill is located on soil with geology, suitable for landfill. Therefore, no construction failures or environmental problems have occurred except for leachate. Initially, the leachate treatment plant was not working well due to failing technology. Consequently, the actual capacity of this plant was only 60 m^3/day instead of the planned 400 m^3/day. The owner has set up another leachate treatment plant with a capacity of 200 m^3/day (CITENCO 2010). By virtue of the appropriate geological soil structure and its location close to the City center (about 10 km), the construction investment costs and the transport costs of the Go Cat landfill are relatively low.

Phuoc Hiep 1, 1A and 2 are located in the same area (Phuoc Hiep – Cu Chi), which is different from Go Cat and Da Phuoc. Local experts designed and constructed Phuoc Hiep 1. Due to lack of experience with construction of landfills on weak soil, many construction and operational problems have occurred, which have caused environmental problems and an increase of the investment and operation costs. Phuoc Hiep 1A is a small sanitary landfill constructed for temporary use during the construction of the Phuoc Hiep 2 landfill. Phuoc Hiep 2 and Da Phuoc are currently in use with a capacity of 3,000 ton/day each. As HCMC lacked more suitable land for landfills, these more recently selected sites for landfills and other MSW treatment facilities are located far from the city and situated on geologically weak soil. Phuoc Hiep lies about 48 km and Da Phuoc 24 km from the city center. Therefore, the costs for transport and construction are much higher. According to DONRE HCMCg (2006), the construction costs of landfills in geologically weak sites are about twice as high as compared to those in geologically strong areas. The location of these landfills leads to traffic congestion and pollution along the transport roads as well. The areas for MSW treatment and landfills in HCMC that are still free for future use are located in Phuoc Hiep and Da Phuoc.

Both operational landfills in HCMC are designed as sanitary landfills. However, they face serious environmental problems: inefficient leachate treatment plants cause serious pollution of water reservoirs and groundwater. The latter affects the sources of water supply of HCMC and the areas surrounding the landfills. From 1998 to now, many studies on leachate treatment in Viet Nam have led to improved plant layouts. However, the current leachate treatment plants are not efficient or they are very expensive. Most of them do not reach Vietnamese discharge standards. In addition, the landfills cause air (mainly odors and pathogens) and noise pollution.

Considering specific problems of potential MSW treatment technologies the following aspects stand out: (1) landfilling is expensive on sites with weak geological structure and it needs leachate treatment; (2) composting encounters problems with commingled waste, high moisture content and risky contaminations; (3) anaerobic digestion is a new technology and its feasibility depends strongly on the characteristics of MSW and the product market; (4) incineration technology must deal with the high costs, high moisture content and low heat value of the commingled MSW.

Table 2.1 summarizes the technical data of all landfill sites in HCMC.

Table 2.1 Technical data of landfill sites in Ho Chi Minh City.

Content	**Dong Thanh**	**Go Cat**	**Phuoc Hiep 1**	**Phuoc Hiep 1A**	**Phuoc Hiep 2**	**Da Phuoc**
Current situation	Closed in 2002	Closed in 2006	Closed in 2006	Closed in 2007	Operating	Operating
Location	Hoc Mon	Binh Chanh	Cu Chi	Cu Chi	Cu Chi	Binh Chanh
Type of landfill	Dumping	Sanitation	Sanitation	Sanitation	Sanitation	Sanitation
Hydrogeology	Good geological structure	Good geological structure	Weak geological structure	Weak geological structure	Weak geological structure	Flooded area
Type of solid waste	Urban SW	MSW	MSW	MSW	MSW	MSW
Total design capacity (ton)	No	3,650,000	2,700,000	900,000	18,210,024	16,744,000
Actual total dumping capacity	8,334,699	5,600,000	3,000,000	900,000	-	-
Design capacity (ton/day)	No	2,000	3,000	3,000	2,500	2,500-3,000
Operation capacity (ton/day)	1,600	3,500	1,500	3,000	3,000	3,000
Lifespan (years)	1991-2002 (12 years)	2002-2006 (5 years)	2003-2006 (4 years)	2007 (1 year)	2007-2012 (5 years)	2008-2030 (22 years)
Total area (ha)	43.27	24.77	44.93	9.75	187.7	128
Total number of cells	3	5	4	1	6	7
Total cell area (ha)	38.94	17.50	19.0	-	93.34	104
Density of compressed solid waste (ton/m^3)	-	0.85	0.65	-	0.9	0.75
Total height of cell (m)	11.5-32.0	23.05	25	-	-	33
Capacity leachate treatment plant (m^3/day)	-	400	1,000	-	-	1,000

Sources: DONREg (2006), DONREc (2009).

2.3 Stakeholders

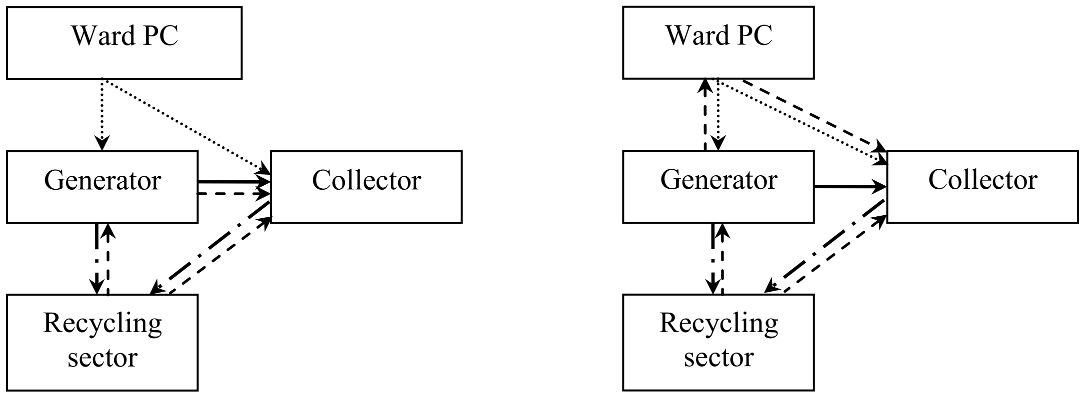
"Stakeholders" is the second main element in the ISWM concepts (Van de Klundert and Anschuetz 2001) which analyses a MSW management system. A stakeholder is a person or organization involved in the MSW system. Each stakeholder has his own role and interest in the system and can cooperate with others for a common interest (Van de Klundert and Anschuetz 2001). Stakeholders and their roles are differing from place to place. In the MSW management system in HCMC, the stakeholders include generators, collectors and transporters, the treatment sector, the recycling sector (including waste pickers, itinerant waste buyers, the recycling workshops and end-user industries), composting plant and landfill owners, operators, government managers at different administrative levels and donors[10]. These stakeholder groups are discussed here.

[10] The information was collected from the stakeholders dialog meeting in the Biowaste reuse in South East Asia project in 2006-2007 (Giac Tam et al. 2006).

2.3.1 Generators

Households, restaurants, markets, offices, tourist, etc. are considered generators. About 80% of the MSW comes from households (DONRE HCMCb 2010). The average per capita discharge was 0.8 kg/person/day in 2009. The generator has a direct contact with collectors and informal buyers of recyclables. The buyers walk around in the neighborhood and buy the recyclable wastes from generators. The MSW management at the level of the generators and the neighborhoods is formally in the hands of the ward PC.

A re-organization of the MSW collection system in the districts has been implemented since 2008. This affected the interrelationships between (private) collectors, generators and the governmental agencies. Figure 2.4 presents the relationship between the stakeholders before and after the introduction of the new management system. The changes of 2008 are discussed below.



(a) Old system (before 2008) (b) New system (after 2008)

Figure 2.4 Relationship between generators and other stakeholders at neighborhood level.
Note:
- *MSW flow,*
- *Recyclable waste flow,*
- *Money flow,*
- *Management direction.*

2.3.2 Collectors

Public and private collectors collect the MSW. HCMC-wide the public sector performs 40% of the collection activity and the private sector 60% (DONRE HCMCb 2009). The situation with regard to this ratio does not seem to have changed after the introduction of the new system in 2008.

Public collectors are workers of CITENCO or the 22 District Public Work Service Companies (DPWSCs). The public sector sweeps streets, collects public waste and a part of the household waste, mostly along the main streets. Public collectors work for and earn money from public companies and receive benefits, like other public workers, such as: health care and social insurance. The public company supplies safety equipment and clothes. Besides, their interests are protected by the Labor Union, the Women's Union and the Youth Union.

Private collectors belong to the informal sector. They only collect waste from generators in the narrow alleyways. Before 2008, the private sector regulated the work informally by themselves. They negotiated their fees directly with the households they served. Officially, the PCs of the wards had to control the private collectors, but this remained a dead letter due to a lack of tools and power. Private collectors were not protected by an organization and had no medical and social insurance. They did not have the opportunity for loans or investments in standardized equipment and safety clothes. It was easy to distinguish between public or private collectors at work based on their equipment and clothes.

Before 2008, mode and time of collection were not adapted to householders' requirements. This especially held for the private collection. The performance of the informal private collectors was deemed inadequate in many respects such as a lack of suitable sanitary collection equipment, (standard handcarts, safe working tools and protecting clothes), a lack of training, street littering and health hazards due to the picking of valuable recyclables during collection, and untimely and irregular collection. The MSW left in front of the houses along the collection routes caused pollution. In addition, there was a lack of transfer stations and the current transfer stations were not adapted to the requirements of environmental sanitation. Therefore, in March 2008 the HCMC PC decided to reorganize the whole MSW collection system. The aim of this activity was to set up a system with more control over the informal private collectors and improvement of their effectiveness and efficiency.

The changes introduced mainly affected the way the collectors receive their income (figure 2.4). While before 2008 the households paid private collectors directly based on private negotiations, the ward government came in between. In the new arrangement households pay the local government for MSW collection and this government pays the collectors working in a certain area. This arrangement gives the local government an instrument to control the work of private collectors in terms of collection efficiency, hygienic practice and the collection time. The local government keeps a part (10%) of the collection fee paid by the households for itself to carry out measures to support the private collectors (DONRE HCMC 2008). Another aspect of the new system is the height of the collection fees. In the new system, the collection fee is not negotiated but based on the location where the waste is collected, the type of generator and the volume or weight of the waste discharged. With respect to location the fee differentiates between urban or suburban areas and along the main streets or in the pathways, and with respect to the type of generators between households, offices, shops, restaurants, markets, etc. (see table 2.4). The work in public areas, like sweeping streets, public waste bin collection, cleaning, etc. remained an exclusive task of the public sector.

The new arrangements affected the private collectors thoroughly. They have lost an important part of their freedom as informal entrepreneurs. Therefore, the government has introduced the following measures in order to support the private sector: (1) formation of groups of private collectors with a representative to take care of their needs; (2) standardizing collection equipment and provision of safety equipment; (3) offering health and social insurance, and (4) giving more opportunities for loans from the government budget.

2.3.3 Transporters

The MSW transport activities are shared by CITENCO, 22 District public service companies and co-operatives (in the private sector) in a ratio of 55, 30 and 15% of the waste, respectively (DONRE HCMCb 2010). Transporters can be divided into three groups: (1) public transporters belonging to CITENCO and the District Public Work Service Companies (DPWSCs); (2) private transporters under contract of CITENCO and the DPWSCs, and (3) private transporters under contract of the district PC. The private transporters must fulfill the requirements of the PC with regard to transport trucks and transport activities.

The public company CITENCO is responsible for the transport of MSW from the gathering points and transfer stations to landfills and the composting plant. CITENCO also has the responsibility for treatment of MSW. They receive money from the PC of HCMC and remain under the technical control of DONRE of HCMC. CITENCO is not able to transport all MSW of the city due to its increasing volume. Therefore, the PC of HCMC has decentralized recently the transport for seven out of the 24 districts of HCMC. These seven districts have delegated this transport to DPWSC and private transporters. These transporters receive money from district PC and are controlled by district DONRE.

Every year, the PC of HCMC makes a budget for the transport of MSW. Based on this transport budget and based on the amount of transported MSW, the money for MSW transport is distributed among CITENCO and the district PCs. With the assigned budgets CITENCO and the seven decentralized district PCs contract private transporters. The transport contracts are granted to the cheapest private transporters.

2.3.4 Treatment and disposal sectors

In HCMC there are currently 2 sanitary landfills and 1 composting plant. The Phuoc Hiep landfill is owned by the HCMC PC and is managed by CITENCO. Two American companies: the Da Phuoc landfill (California Waste Solution Company) and the Vietstar composting plant (Lemna Corporation) are built, owned and operated by themselves.

DONRE of the City monitors the pollution at the composting and landfill sites. The quality of compost from the composting plant is monitored/regulated by the Department of Agriculture and Rural Development of HCMC, based on the Vietnamese standard for compost quality. Biogas from the landfills is converted a part to electricity, another part is burned. The produced electricity is bought by the Department of Electricity of HCMC and fed into to the state's electric network. Currently, the heat produced during electricity generation is not used.

2.3.5 Recycling sector

There is a tendency that richer households do not keep recyclable wastes separated and discharge them with the rest of the waste as they are less interested in the financial benefits. Other households collect the recyclable waste separately. The income households gain from selling recyclable waste is comparable to the collection fee they pay. For the collectors, the income from recyclable wastes is the main source of income, comparable with their income from collecting waste. Besides, there are many waste pickers collecting discarded materials from streets and transfer stations. Depending on the collected amount, the recyclable wastes are sold to small, medium or large waste depots (see figure 2.3). At the waste depots, workers separate wastes into different types.

The Ministry of Industry (MOI) certifies the technologies that the recycling sector uses. The Ministry of Science and Technology (MOSTE) monitors the environmental quality and pollution control. There are about 740 private enterprises to process about 2,000 tons recyclable solid waste/day. This activity generates a benefit of 1 billion VND/day (54,000 USD/day) and supplies work to about 21,000 people (Nhan 2008)[11]. These plants are not efficient; the labor is lowly qualified and salaries are low (Ha 2006). All recycling activities belong to the private sector. In order to promote recycling of waste, DONRE set up the Recycling Fund in 2007 (DONRE HCMCb 2009). The aim of this fund is to support the recycling sector in terms of improving processing and reducing their emissions of pollution. It had an initial budget of 100 billion VND (about 5 million USD). The budget supports small and medium scale recycling enterprises. These enterprises can loan at low interest from this budget to invest in modern and less polluting equipment for their processing activities. However, due to complex procedures and unclear protocols of lending, the budget has not been used up to 2010. The private recycling sector has formed a Recycling Association. The Recycling Association is representative for the recycling sector and gives feed back to the government and supports the activities of the Recycling Fund in

[11] DONRE website (http://www.donre.hochiminhcity.gov.vn) publication date 4/7/2008 and download date 27/7/2009.

terms of funds and technology. The last stakeholders in the recycling chain are the end-user industry that purchases the recyclable waste as raw material for its processes and customers who use recycled products. A part of the processed recyclable waste is sold outside the city and abroad.

2.3.6 Governmental agencies

The government plays a role in MSW management at three levels: City, District and Ward. At City and District level especially the PCs and DONRE are important. The PC at ward level takes care of the local environment. The PCs are responsible for the administrative and financial aspects, while DONRE controls the technical and environmental aspects. Besides, there are many organizations involved in the system. Section 2.4.1 (Institutional framework) goes into more detail about the roles of these organizations.

2.3.7 International donors

Many projects implemented to improve the MSW management in HCMC have received support from external donors. Two well-known examples are: (1) the project "Urban renewal and sanitation of the Tan Hoa - Lo Gom area"[12]. This project included many activities in MSW management. It has invested in the sanitary transfer station of Ba Lai. The project also provided sanitary equipment such as hand-carts and safety equipment. Most importantly, the project carried out public programs and training activities to improve the awareness of local people and build capacity among local managers. The donor in this project was the Belgian Technical Cooperation; (2) the Dutch government in cooperation with the PC of HCMC invested in the first sanitary landfill in HCMC (Go Cat landfill) with a capacity 3,000 ton/day and an operational lifespan of 5 years. Based on the experience of this project, two sanitary landfills were constructed and managed by local staff. Apart from these two there have been many more small international cooperation activities in the field of MSW management.

2.4 Sustainability aspects

The third level of analysis according to the ISWM concept is the "aspects". In the study of aspects, an important question is what makes this system sustainable or unsustainable. In this section, the following aspects are discussed: the institutional framework (2.4.1), the legal framework and policies (2.4.2), financial and economic aspects (2.4.3), the technical and environmental aspects (2.4.4), and social and cultural aspects (2.4.5). Finally, this section is completed with its conclusions in 2.5.

2.4.1 Institutional framework

- **National institutional framework**

The Ministry of Natural Resources and Environment (MONRE) is the major state authority responsible for environmental affairs in Viet Nam. At a higher level still the Ministry receives its directions from the Prime Minister and the Communist Party. Under the direction of MONRE the Viet Nam Environment Administration (VEA Viet Nam) proposes policies, regulations, guidelines and standards. VEA also gives directions and checks the activities of all DONREs at city/province level and deals directly with companies in some cases, e.g. to license hazardous waste treatment companies. In short, MONRE manages "policies" and VEA manages "operation" of the solid waste management system at national level. DONRE is the highest authority responsible for the environment at city or province level. DONRE works under the direction of MONRE and VEA for environmental aspects and under the direction of city or

[12] http://webapps01.un.org/nvp/indpolicy.action?id=724

provincial PC for managerial (administrative) control. Additionally, seven other ministries and the provincial PCs are also directly involved in waste management activities. The MOI and Ministry of Health (MOH) are dealing with their own specific waste (industrial and hospital waste), but are not involved in MSW management. Some other ministries have a specific role in solid waste management. Table 2.2 summarizes the governmental agencies and their tasks related to the waste management system in Viet Nam. In which, MONRE, VEA and DONRE take the main responsibility and the others: MOC, MOI, MOH, MPI, MOF, MCI, MOT, MOSTE, DOSTE have involved a part in the waste management system.

Table 2.2 Governmental agencies of waste management system in Viet Nam.

Ministry of Natural Resources and Environment (MONRE) - Developing national policies, regulations, guidelines and standards on waste management, - Controlling and managing the activities of VEA and DONRE, - Compiling annual and long-term waste management plans in coordination with other ministries.
Viet Nam Environment Administration (VEA) - Preparing proposals for the Minister of MONRE: documents on policy, strategy, planning, programs, projects and national standards for the environment, - Guiding, checking and implementing laws, regulations, strategy, planning, projects and programs, - Publishing and explaining guidelines, - Monitoring and preventing environmental pollution, - Setting up databases, surveying pollution sources and estimating the impacts.
Department of Natural Resource and Environment (DONRE). - Every city/province in Viet Nam has a DONRE. - Formulating policies and strategies, plan and allocate budgets for research and development relating to waste treatment projects, - Appraise and approve Environmental Impacts Assessment reports for waste treatment projects, - Guiding the application of the Vietnamese environmental standards. Within DONRE of HCMC there is a HCMC Environmental Protection Agency (HEPA). The main role of HEPA is environmental monitoring and control.
Ministry of Construction (MOC) - In cooperation with MONRE, MOC formulates policy and legislation, planning and construction of solid waste facilities. It has the responsibly for developing, managing and monitoring plans for the construction of waste-related infrastructures nationally and provincially.
Ministry of Industry (MOI) and Ministry of Health (MOH). - These Ministries deal with special industrial or hospital wastes. Responsible for developing and monitoring plans to force businesses/hospitals to comply with regulations on industrial or hospital waste management.
Ministry of Planning and Investment (MPI) together with Ministry of Finance (MOF). - Based on the long-term and short-term planning on waste management of all organizations, MPI and MOF will analyze, check and provide the funds for the activities, - Issues of economic incentives to facilitate waste management activities.
Ministry of Culture and Information (MCI) - Directs dissemination and popularization of legal documents on waste management in order to raise public awareness and responsibility for environmental protection.
Ministry of Transportation (MOT) - Planning and managing infrastructure for national and provincial air, land, railway and maritime transport.
Ministry of Science and Technology (MOSTE) and Department of Science and Technology (DOSTE) - Research on environmental technology and management, - Technology transfer.

Sources: MOC Viet Nam (2009), World Bank (2004), DONRE HCMC (2009), MONRE Viet Nam (2009), Viet et al. (2009) and VEA Viet Nam (2009).

- **Ho Chi Minh City institutional framework**

The organization diagram of HCMC's governmental agencies with a task in solid waste management is sketched in figure 2.5. Here a detailed overview of the tasks of the different units is presented.

The People's Committee of HCMC (HCMC PC) is the local representative of state authority. It is responsible for state administration at the city level. Their responsibilities in waste management are: (1) to implement state regulations on environmental protection in the respective localities, directing their DONRE in organizing, and coordinating with other city organizations the elaboration of annual and long-term plans for waste management, and taking measures to help the localities to perform their tasks in environmental hygiene; (2) to evaluate and approve waste treatment projects in their localities based on the demographic, socio-economic, and industrial conditions of these localities; (3) to encourage investment in the construction of waste treatment sites and stimulate private and foreign companies to participate in waste collection and treatment; (4) to direct DONRE and Department of Construction (DOC) in implementation of waste treatment projects in terms of design, construction, monitoring, environmental impact assessment (EIA), etc., according to Viet Nam's environment and construction standards; (5) to direct the CITENCO and DPWSCs in organizing waste collection, transport and treatment activities and approve waste collection and treatment fees (Viet et al. 2009).

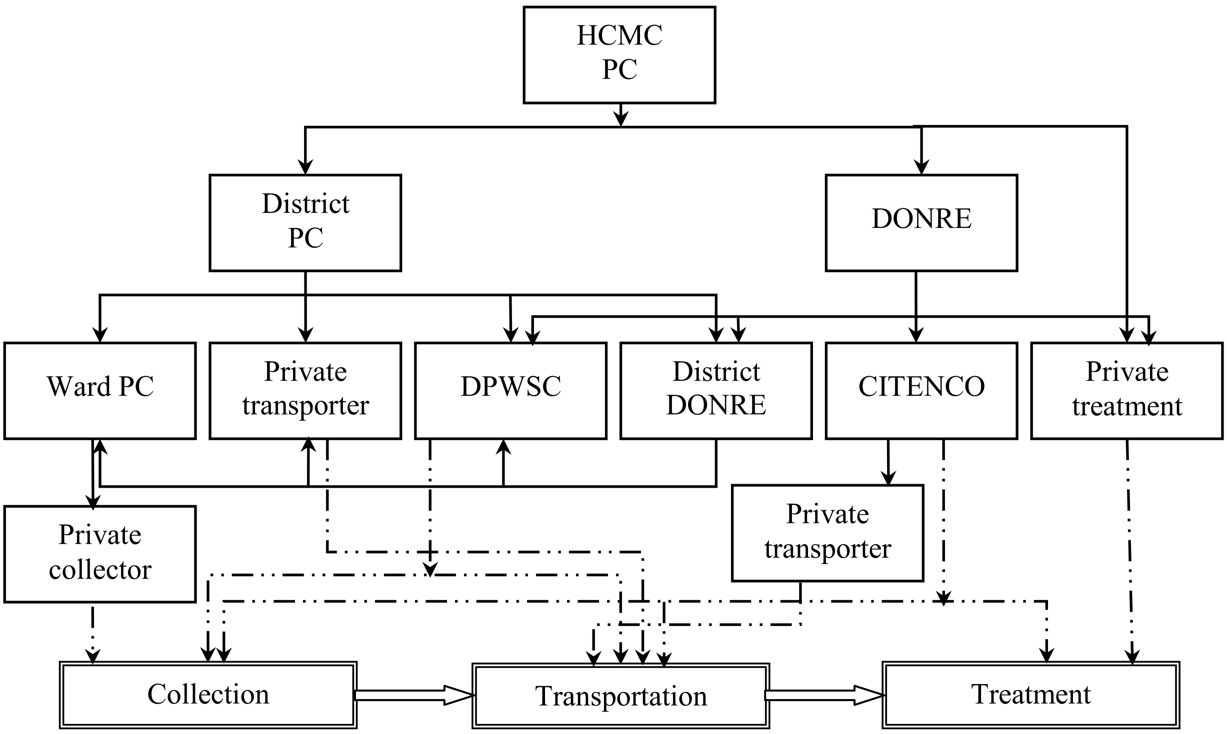


Figure 2.5. Organization diagram of the MSW management system in Ho Chi Minh City.
Note: ⟶ *Management activities,*
–·· → *Technical activities,*
⇨ *MSW flow.*

The DONRE operates under the HCMC PC regarding administrative and political decisions and under MONRE regarding collaboration, support and technical guidance. DONRE plays an important role in waste management with respect to monitoring the environmental quality, managing and implementing waste management policies and regulations issued by MONRE and the PC and appraising EIAs for waste treatment projects. DONRE also cooperates with DOC and

CITENCO in proposing potential treatment sites to the PC, which selects and approves the most appropriate site. Solid Waste Management Office is in DONRE and carries out the work on solid waste management.

Under DONRE the HEPA is responsible for monitoring the environmental quality in HCMC, measuring and checking environmental pollution, the collection of environmental protection fees, public information and environmental training, supporting cleaner production projects, and project management and environmental consultancy.

The CITENCO is the governmental company in charge of waste collection, transport and treatment, including the hazardous hospital waste of the whole city. CITENCO also cooperates with the private sector for transportation and treatment of solid waste. CITENCO is the only agency responsible for the management and operation of governmental landfills projects.

There are 22 DPWSCs, which are part of the District PC. DPWSCs service the solid waste collection and transportation at district level.

Ward PCs manage private collection groups. Those private collection groups only work in the field of collection, especially in narrow alleyways, while public service companies collect most of the MSW along the main streets.

Besides, at city or province level, there are ministerial departments involved in the MSW management system and working under the control of People's Committee. There are the Department of Construction (DOC), responsible for construction and sites of solid waste treatment facilities, the Department of Finance (DOF) that approves the price of transport and MSW treatment and management and the Department of Planning and Investment (DPI) that approves plans and investments, and finally the Department of Culture and Information (MCI) with a task in helping to raise public awareness.

Critical points with regard to organization

The organizational structure of the MSW management system in HCMC and in Viet Nam is complex and many organizations are involved. It is not always clear what role and responsibilities each organization has. Consequently, some activities overlap between the organizations. Even within one organization, many offices are involved, and activities of the offices overlap. For example, DONRE has a solid waste management office, a water quality management office and an environmental management office with overlapping activities. In addition, HEPA is a part of DONRE, but operates quite independently. HEPA also has offices on management of water quality control, solid waste management, etc. with some activities similar to DONRE's. In other cities and provinces of Viet Nam this structure is less complex. It can be understood that the DONRE of HCMC takes the responsibilities on both "policy" and "operation"; while, in other cities or provinces, these works are divided between DONRE and HEPA.

Especially at the level of the districts and the wards, public organizations struggle with their tasks. For example, the Ward PC is responsible for the management of the private collection sector. However, this management is not effective, because the Ward PC has no proper tools to control this sector. The private collectors directly contact the generators to collect waste and receive collection fees while in fact the Ward should receive these fees. When something is wrong fines do not work. Because the collectors are too poor, they will stop their work when fined, which may cause even more environmental disruption.

Within each stakeholder organization complex sub-systems exist. For example, currently there are the three groups of transporters: CITENCO, its subcontractors (private or DPWSCs) and subcontractors of District PCs (DPWSC or private sector) (2.3.3). This complex system does not deliver the desired efficiency. In particular the following issues are significant: (1) the collection routes are not well integrated; (2) the expenditures are used inefficiently since the government pays CITENCO and subsequently CITENCO pays the companies; and (3) each collection group has a different manager and monitor.

2.4.2 Legal framework and policies

- **The Ho Chi Minh City legal framework**

The national legal framework of decisions, decrees, etc. is presented in appendix 2. This framework forms the basis for the solid waste management policies in HCMC of which a few main topics are discussed here. The Vietnamese national regulations provide a general framework for sustainable solid-waste management, but leave the specific formulation of policies and measures to lower government levels. In response to new legislation, HCMC has begun to take its own steps towards sustainable solid waste management.

In 2000 they published the guideline "Socialized solid waste management" (DONRE HCMCa 2009). The aim of this guideline was to strengthen the participation of formal private and foreign actors in the solid waste management system. In 2002 the HCMC PC setup an "Environmental management strategy for the city toward 2010" (DONRE HCMCd 2002). This strategy gave concrete directions for environmental protection. The first direction regarded public awareness and the fifth direction proposed application of modern technology. This strategy also discussed the current situation of HCMC, which did not allow a fully privatized solid waste management system. Based on the two mentioned guidelines many activities have taken place, mainly focusing on transport and treatment (see 2.3.3 and 2.4.3). This policy of the PC of HCMC resulted in a demonstration program on "Solid waste separation at the source". It started in 2006 to research public participation and the technical and economic feasibility.

MONRE of Viet Nam was designated to be the Clean Development Mechanism (CDM[13]) National Authority via the official document No. 502/BTN MT-HTQT, 24/03/2003. They listed activities that cause greenhouse gas emissions to be reduced by measures under a CDM regime. Such measures could qualify for CDM payments called Certified Emission Reductions (CERs). HCMC took part in two CDM projects: the Phuoc Hiep 1 landfill and the Dong Thanh landfill. At present, HCMC PC is encouraging more CDM projects. As is shown in this thesis (chapter 7) CERs could significantly contribute to net costs reduction of solid waste management.

In 2006, HCMC PC developed the "Master plan for urban solid waste management in HCMC toward 2020" (DONRE HCMCe 2006). The aim of the plan was to enhance management efficiency and improve the service of collection, transportation and treatment of solid waste in HCMC. HCMC PC also set up a "Master plan for land use toward to 2010" in which the lands for MSW treatment zones were selected.

In order to better control the private collectors the HCMC PC issued decision no. 88 in 2008 and its guideline (DONRE HCMC 2008) to implement a new method to control the collection system and to reset the collection fees. The consequences of the resulting policy, especially to the fate of the informal collectors, were described above in section 2.3.2.

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[13] The Clean Development Mechanism (CDM), defined in Article 12 of the Protocol, allows a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol (Annex B Party) to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits, each equivalent to one tonne of CO_2, which can be counted towards meeting Kyoto targets (UNFCCC, 1997).

Critical remarks about the legal and policy aspects

According to the Ministry of Justice, there are 300 legal documents on environmental protection (Cuong 2008). However, important and specific regulations still have to be elaborated, e.g. regulation on tax for environmental protection, on environmental audits, on specific provisions for assuring legal responsibility for environmental damages and on specific stipulations for encouraging the use of ecological products. Moreover, the language of the environmental legislation documents is not clear and sufficiently detailed, which leads to confusion (Cuong 2008). For example, in the Environmental Law of 2005, article 131 says: "the decline of function and usefulness of the environment can be divided into three levels: level 1 means there is a decline of the environment, level 2 means there is a serious decline and level 3 means there is severe serious decline." However, there is no document defining what serious and severe serious is. What are the criteria and standards to assess the decline? Another problem is that some environmental legal documents appear to be not effective (Cuong 2008). For example decision no. 80/2006/ND-CP was issued in 2006 and had to be modified one year later. Besides, the conditions to ensure good environmental protection activities, capacity building and equipment are not included in the regulations. In case of environmental law violations, the sanctions and penalties are weak: in 2008 the highest fine was 70 million VND (~3,500 USD), whereas the construction of a treatment plant costs billions of VND. The companies, therefore, may be willing to pay fines and leave it at that.

As mentioned, HCMC set up the guideline "Socialized Solid Waste Management" in 2000, "the Environmental Management Strategy toward 2010" in 2003, and "the Master Plan for Solid Waste Management" in 2006 and undertook many activities to encourage solid waste management. However, until now (2011) the applied MSW treatment technologies include only two sanitary landfills and one composting plant. The aim of application of modern technology mentioned in the strategy of environmental management in 2003 has not been reached. This could be due to the following reasons: (1) the strategy did not define what "modern technology" was; (2) there were no legal or policy documents supporting the development of "modern technology"; (3) no detailed targets and therefore no planning how to reach the targets were given; (4) preparations for new technologies, such as: infrastructure and financial and technological support were hardly made, and (5) the government did not have a tool to select suitable technologies. In addition, some projects, which would enhance the application of new technologies, have been delayed. This was the case for the program of solid waste separation at the source, which has been delayed since 2008. The CDM program requested for the Phuoc Hiep and Dong Thanh landfills also has been delayed since 2007. In order to improve the application of "modern technology" in HCMC, the issues addressed above require more serious attention. This is one of the topics of this thesis.

An important element of the master plan of 2006 was the introduction of waste separation at the source, aiming at an increased rate of processing recyclables and food wastes. However, most of the concrete actions based on these plans suffer from delays (DONRE HCMCb 2009)[14]. Intensive publicity campaigns have created a positive citizen attitude towards innovations in solid-waste management. However, it appears difficult to get a high degree of participation in waste separation at the source, due to: (1) lack of regulations and policies to support the program, such as fine and penalty regulations, collection of fees, investment encouragement policies and regulations to control private collectors; (2) lack of or ill-qualified manpower to regulate the MSW management; (3) lack of investments in adequate collection and transport trucks for different types of waste, transfer stations for separated solid waste, storages and also recycling technologies for biowastes, such as composting and anaerobic digestion; (4) lack of

[14] The author was involved in this project as an expert of the consultancy organization named CENTEMA.

integrated management with source separation, collection, transportation and treatment; (5) lack of motivation among private collectors; (6) low awareness especially among the low-income population and (7) increase of the collection fees (Giac Tam et al. 2006; DONRE HCMCb 2009).

2.4.3 Financial and economic aspects

Figure 2.6 depicts the flow of MSW and the concomitant financial flows in HCMC. Solid waste management expenditure in HCMC is based on the budget of the environmental protection fund in HCMC. The expenditure for solid waste management in 2008 was about 70% of the environmental protection fund of HCMC (DONRE HCMCa 2009). This expenditure mostly covers transport and treatment plants and a small part goes to the public collectors. Public companies (CITENCO or DPWSCs) collect money from the generators and pay the salaries of their workers (collectors). Private collectors are paid by generators either directly (old system) or via the Ward PCs (new system since 2008).

The expenditure of the MSW management system is increasing due to the enlargement of the collection system and the investment of treatment plants. With the recent increase of wealth, many households stopped collecting and selling recyclables themselves and they accumulate in the MSW. The collectors can now earn additional income by sorting and selling these recyclables.

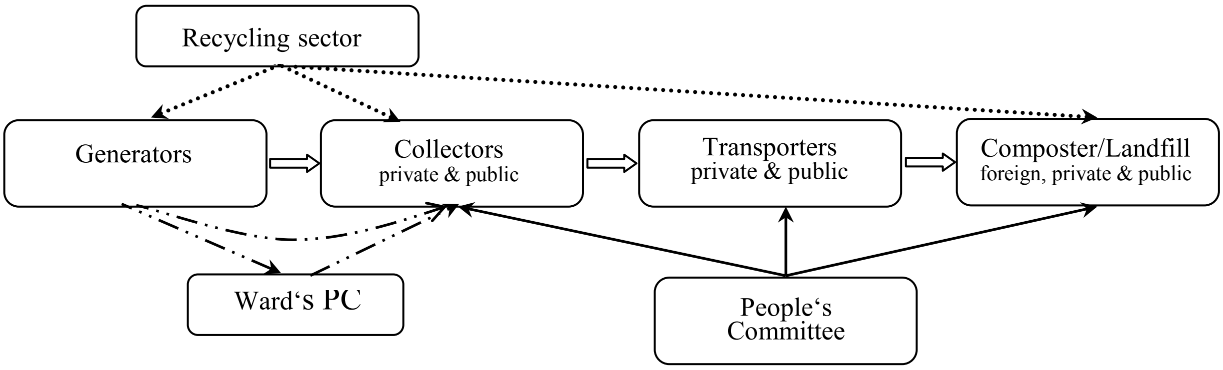

Figure 2.6 Financial flows in municipal solid waste chain in Ho Chi Minh City in 2010.
Note: ⟶ *Government fund,*
– · · ➝ *Collection fee,*
········➝ *Payments for recyclable waste,*
⟹ *Solid waste flow.*

Table 2.3 presents the actual expenditures for solid waste management in HCMC in 2007. At the beginning of the year the expected costs for solid waste management are estimated to request budget from the PC. At the end of the year, the actual costs are calculated and the budget is recalculated based on the real costs.

Table 2.3 The actual expenditures for urban solid waste management in Ho Chi Minh City in 2007.

No.	**Item**	**Annual costs** (billion VND/year)	**Fraction of total** (%)
1	Collection at source	187	20.7
1.1	*Households **	*131*	
1.2	*Other sources**	*56*	
2	Street sweeping and garbage collection	149	16.5
3	Collection of solid waste from canals	8	0.9
3.1	*CITENCO*	*5*	
3.2	*District Public Work Service Companies*	*3*	
4	Transport	314	34.8
4.1	*Transport company of districts*	*39*	
4.2	*CITENCO*	*275*	
5	Treatment	245	27.1
5.1	*MSW treatment fee (for two sanitary landfills)*	*123*	
5.2	*Leachate treatment (at Phuoc Hiep landfill)*	*13*	
5.3	*Construction waste: collection, transport and disposal*	*83*	
5.4	*Hazardous medical waste: collection, transport and incineration*	*19*	
5.5	*Others*	*7*	
	Total expenditure	903	100

Source: DONRE HCMC (2008).
Note:
** Data is estimated by DONRE,*
Exchange rate: 1 USD = 15,700 VND in December 2007.

The total solid waste management expenditures for HCMC in 2007 were 903 billion VND. The expenses for transport, cleaning and collection, and treatment at the landfills (there was no composting plant in 2007) were 314 billion VND (35%), 344 billion VND (38%) and 245 billion VND (27%) respectively (DONRE HCMC 2008).

- **Collection**

In the old system (before 2008) public collectors collected fees from households along the main streets amounting to 10,000 VND/month/household and for households along alleyways to 15,000 VND/month/households. This collection fee covered only about 20% of the total expenditures. The rest is covered by the budget from the HCMC PC. In the areas covered by private collectors, the collection fee was negotiated between the private collectors and generators. There the fees amounted to around 10,000 - 20,000 VND/household/month.

In the new system (since 2008) the collection fee system was modified for the whole city, based on the location of the houses and the class of apartment in buildings (table 2.4).

Table 2.4 The unit prices for collection fees and environmental protection fees for municipal solid waste.

Generators	Unit	Total fee	Repartition	
			Collection fee	Environmental protection fee
Household (HH)				
- Households along the street, apartment in high-class building (class 1 & 2)	VND/HH/month	20,000	20,000	0
- Households in alleyways, apartments in medium or low – class buildings (class 3 & 4)	VND/HH/month	15,000	15,000	0
- Households in suburban areas along the street	VND/HH/month	15,000	15,000	0
- Households in suburban areas in alleyways	VND/HH/month	10,000	10,000	0
Non-households				
- Group 1	VND/shop/month	60,000	50,000	10,000
- Group 2	VND/shop/month	110,000	100,000	10,000
- Group 3	VND/m^3 or VND/ton	176,800 420,950	160,000 380,950	16,800 40,000

Source: DONRE HCMC (2008).

Critical issues related to the new system are[15]:

- The income of private collectors in some areas has decreased due to lower collection fees in those areas and the 10% deduction by the Ward PC. In the new system the collection fees in alleyways are lower than in main streets. Most private collectors work in alleyways and public collectors in the main streets. As a consequence, the income of public collection companies may increase while private collectors income decreases;
- The Ward PC collects the fee monthly and it takes time before the private collectors receive their payments. This the mostly poor collectors do not like;
- With the new collection system, 10% of the collection fee is allocated to the MSW management budget and partly destined to support the informal collectors. However, the informal collector hardly see this support;
- The collection fee increased from 10,000 to 20,000 VND (table 2.4) for households along the streets, and decreased for households in alleyways from 20,000 to 15,000 VND. The generators along the main streets protested against the increase of the collection fees with the argument that they have to pay more while the work of collection is easier. On the other hand, some households had to pay less and of course they are happy;
- The minimum fee for collection from a shop went up to 60,000 VND per month (table 2.4). However, there are many types of shops, such as mobile phone shops, clothes shops, that hardly generate waste. Previously they did not pay for MSW collection because they discharged the shop waste together with the household waste, since the household and the shop are one. Owners of such shops are discontented with the higher fees under the new system;

[15] The information were collected from the meetings in 2009 between the representative of DONRE HCMC with private collector to implement the decision 88 (DONRE HCMC 2008) on re-setting up the collection system. The information were also collected from the excursion and survey during the implementation of ISSUE 2 projects (2007-2011).

- Even if the government could collect the full 100% collection fee from households and other discharge sources, the amount would still be small compared to the actual costs of MSW management of HCMC (about 21% of total expenditure, see table 2.4). To get in line with other countries in the region the collection fee is due to increase further: a foresight that users of the system do not like.

- **Transport**

The HCMC PC has set unit prices for the transport of the MSW to the treatment sites. The unit price fluctuates based on the price of diesel fuel and inflation in the calculated year. In general, the transport fee increased over time but the transport quality stayed the same. Table 2.5 shows an example of the unit prices for transport.

Table 2.5 The unit prices to transport municipal solid waste from Ho Chi Minh City to the landfills.

Landfill		Unit prices in 2009	
		VND/ton/km	USD/ton/km
Phuoc Hiep	Day	3,491	0.18
	Night	4,684	0.23
Da Phuoc	Day	5,282	0.26
	Night	5,570	0.28

Source: DONRE HCMCi (2009).
Note: Exchange rate: 1USD = 18,500 VND in December 2009.

The expenditure for transport has increased over time due to increasing amounts of MSW and longer distances to the new landfills. According to table 2.4 above transport costs took a share of abut 35% in the total waste management costs in 2008. However, based on (DONRE HCMCb 2010), this expenditure could drop by about 30 - 40% if decentralized transport (districts manage their own waste) would be applied for the whole city. The transport costs would also decrease if the government selected appropriate treatment technologies and located these in a suitable place.

- **Treatment and disposal**

It is interesting to observe that the treatment costs in HCMC differed much: in fact they were moving. According to table 2.7 they were 20 USD, 16.4 USD and 5 USD for one ton of commingled MSW at a governmental sanitary landfill, a private sanitary landfill and a private composting plant, respectively (table 2.6, years 2009 and 2010).

Table 2.6 The investment and treatment costs of the landfills and composting plant in Ho Chi Minh City.

Name treatment plant	**Capacity**	**Investment costs** (million USD) [construction year]	**Treatment costs** (USD/ton) [year of the costs]
Go Cat landfill	2000 tons/day for 5 years	26 [2001]	6.6 [2002]*
Phuoc Hiep 1 landfill	3000 tons/day for 5 years	23 [2002]	5.8 [2003]**
Phuoc Hiep 2 landfill	3000 tons/day for 6 years	10 [2006]	20 [2009]
Da Phuoc landfill	3000 tons/day for 21 years	107 [2006]	16.4 [2009]
Vietstar composting plant	1200 tons/day for 20 years	36 [2008]	5 [2010]

Source: DONRE HCMCb (2009).
Note:
The investment costs in the year of implementation of each plant.
** Treatment costs do not include the additional costs to treat leachate. The original leachate treatment plant was not working well.*

*** Treatment costs do not include the additional costs repairs and to solve environmental accidents caused by the lack of experience with using a site with weak geology.*

The two main landfills of Da Phuoc and Phuoc Hiep have different financial arrangements. Da Phuoc is a foreign owned landfill, which receives 16.4 USD/ton via the tipping or gate fee since 2007. Public companies own the other landfills. Here, investment and operation is paid from the government budget. Based on the actual costs for building and operation, the treatment costs at the Phuoc Hiep 2 landfill were about 20 USD/ton MSW in 2010. Table 2.7 shows the repartition of these costs over the different activities at the landfill. About 63% of the costs were related with operation and maintenance. The total treatment expenditure in HCMC dropped in 2010 somewhat due to the opening of the Vietstar composting plant which calculated a tipping fee of only 5 USD/ton at that time (since December 2009). It went up again in March 2011, when the tipping fee of Vietstar increased to 12 USD/ton (An 2011). In order to promote solid waste treatment projects, HCMC PC has provided all infrastructures, such as clearance, roads, drainage, electricity supply, etc. to the gate of the treatment plants free of charge.

Table 2.7 Breakdown of the tipping fee for commingled municipal solid waste at Phuoc Hiep 2 sanitary landfill in Ho Chi Minh City.

No.	**Descriptions**	**Expenditure** (USD/ton input)	**Ratio** (%)
1	Investment cost	7.44	37.2
2	Leachate treatment cost	4.19	21
3	Landfill cover	6.51	32.6
4	Operation cost	0.47	2.4
5	Maintenance cost	1.40	7
	Total tipping fee	20	100

Source: DONRE HCMCc (2009).

The MSW treatment costs were in the range of 25 - 30% of the total solid waste management expenditures (table 2.4) (DONRE HCMC 2008).

- **Recyclable waste handling**

The sources of recyclable wastes are households, the public and commercial sector, industries and hospitals. The prices of the main types of recyclable wastes in 2006 are given in table 2.8. The financial importance of recycling can be explained with the case of the Vietstar composting plant in HCMC. At this plant the revenues from plastics were comparable to the income from the compost product as the following calculations show (Vietstar Company 2010). MSW in HCMC contained on average 32 kg of recyclable PE plastic per ton. The amount of processed plastic product was about 40% of the amount of recyclable PE plastic input. The average market price of processed plastic products was 450 USD/ton. That meant that the income from recyclable PE plastic was about 5.76 USD/ton of commingled MSW (0.032 * 0.4 * 450). The compost price was 30 - 35 USD/ton and the amount of compost that can be produced from MSW was about 20 - 25% of the commingled MSW input (Tchobanoglous et al. 1993, p702; Vietstar Company 2011). Therefore, the income from compost is about 30 * 0.2 = 6 USD/ton of commingled MSW.

Table 2.8 The prices of some recyclable wastes in Ho Chi Minh City in 2006.

Type of recyclable waste	**Price range** (VND/kg)	**Price per ton** (USD/ton)
Paper	500 – 2,000	31 – 125
Plastic	2,500 – 8,000	156 – 500
Nylon	300 – 6,000	19 – 375
Copper (Cu)	20,000 – 55,000	1,250 – 3,437
Aluminum (Al)	7,000 – 18,000	438 – 1,125
Iron (Fe)	1,000 – 3,300	63 – 206
Zinc (Zn)	4,000 – 4,500	250 – 281
Glass	50 – 1,000	3 – 63
Rubber	500 - 800	31 – 50

Source: DOSTE HCMC (2006).
Note: The exchange rate: 1USD = 16,000 VND in 2006.

The revenues from recyclables are not only important to the formal but also as noted before to the informal waste processors. The prices mentioned in table 2.8 are important input to the scenario modeling in chapter 6 of this thesis.

2.4.4 Technical and environmental aspects

Technical aspects have been extensively discussed in the description of the solid waste system components in section 2.2. In this section only the most notable issues of technical nature related to MSW management are recalled. At the household level, the constraints are small houses with no place, no standard containers to store MSW, narrow and poorly paved alleyways that hamper collection and transport. At the level of collection and transportation, self-designed collection equipment and the lack of standardized transfer stations are the main problems. Regarding the treatment, the critical points are out-dated technology for the processing of recyclable wastes and inadequate control of leachate and air pollution at landfills and composting plants.

In principle, all the activities related to MSW collection, transportation, treatment and recycling must comply with pollution control standards published by MOSTE. However, the present system still copes with several serious environmental shortcomings. Only about 85% of the total amount of MSW in HCMC is currently collected. The remaining 15% is discharged illegally in public areas and canals due to low public awareness and the lack of collection systems in some of the suburban areas. (DONRE HCMCk 2009)

The major environmental problems in the MSW collection chain in HCMC occur at the transfer stations. There are only seven sanitary transfer stations. The other 47 open heaps lack any form of pollution control. These open heaps are located at places too confined for an appropriate MSW transfer station with leachate or air pollution treatment. This situation negatively affects public health and the environment. In general, HCMC lacks place for upgraded transfer stations. Therefore, the MSW collection system is currently shifting to a system with more gathering points where the MSW is not stored but immediately removed by appointment between the collectors and the transport trucks.

2.4.5 Social and cultural aspects

The handling of solid wastes including sorting and recycling of valuable materials from wastes gives jobs to many low-educated and poor people. This is an important social aspect. Viet Nam has a tradition to produce compost from agricultural waste. Therefore, using compost from MSW is not a fundamental problem or a big change. Cultural or religious issues do not seem to affect the collection and treatment of MSW in HCMC. The widespread lack of public awareness influences MSW management in several ways and raising this awareness through public information campaigns is an ongoing activity of governmental agencies. The high level of formal education in secondary schools and universities in HCMC is a strength from which future upgrading of the solid waste management system can benefit. Advanced curricula in environmental technology and management may render the application of more advanced treatment technologies like anaerobic digestion and incineration feasible.

2.5 Conclusions

The analysis of solid waste management in HCMC presented in this chapter showed a city of nearly 8 million inhabitants with a high economic and population growth rate and an amount of MSW that has increased by 6 – 8% annually over the past decade. By 2008 5,600 tons of MSW were generated daily. Since 2001 the People's Committee of HCMC developed a host of activities to stimulate solid waste management. The important steps herein were the establishment of the Solid Waste Management Office residing under DONRE and the setting up the environmental management strategy toward 2010 in 2002 and the master plan for urban solid waste management in 2006. In particular, three major activities have contributed to improvement of the system, included: the socialized solid waste management guideline in 2000, the program on solid waste separation at source in 2006 and the program on reorganizing the collection system in 2008. The most remarkable successes of these programs were: (1) improve public awareness on solid waste sanitation and management, (2) increase of the collected waste as fraction of the generated waste, (3) the involve of foreign and private sector on the solid waste management chain, which improved the collection system and treatment technology.

As this chapter has shown as well the present system is still plagued by many shortcomings. We would like to start the discussion about these shortcomings from the perspective of the internationally widely adopted principle of the waste hierarchy. This principle prescribes solid waste management activities in an order of decreasing preference as follows: waste prevention (highest preference) > recycling and reuse > composting > incineration > landfilling (least preferred). This order is based on the sustainability principle of maximum protection and recovery of the resources in waste. For the practical policy of HCMC application of this principle would mean a strong emphasis on activities that avoid the generation of (hazardous) wastes, on stimulation of reuse and recycling and on recovery of valuable materials (like energy, compost and metals) from collected wastes.

From this perspective first a note should be made about separation of MSW at the source. Waste separation at source could reduce the flow of waste materials going to landfills and deliver recyclable materials in a pure form thus reducing the costs of processing and leading to products of a higher quality. However this study noted that waste separation at source did not take off for two reasons. First pilot projects on separation at source showed issues like the lack of suitable means of storage in the households and adequate infrastructure for collection and transport, but perhaps most important was the absence of a composting facility for source-separated biowastes at the time. The second reason was the rise of private foreign players on the waste scene in HCMC as a consequence of the governmental policy to involve private investment capital. The Vietstar Company started to process commingled waste with compost and plastic as end products. Although this composting plant could be well used for source-separated biowastes, it rather seems to have taken the pressure off the government's attempts to promote waste separation at source.

As shown in this chapter recycling of materials like plastic and paper is carried out widely by the private sector mostly in small-scale enterprises. The recycling system in HCMC has developed over an extended period left to market forces and without an overarching plan. The used technologies are out of date, causing environmental problems and a low quality of products. The city government has created possibilities for support to this sector, but this support has hardly been used up to now.

While the waste hierarchy prescribes a preference for treatment technologies like composting and anaerobic digestion with utilization of biogas, the main technology in HCMC is sanitary landfilling applied to 90% of collected MSW. A relatively small amount of MSW is composted (10% of the waste in 2009). Though sanitary landfilling is a big step forward in comparison to dumping, landfilling will reach its limits, sooner or later: there will be a lack of land, inhabitants will difficultly accept the environmental pollution associated with landfilling and the need to recover materials will grow, which demands other technologies.

Politicians in HCMC are therefore in direct need to find suitable new MSW treatment technologies, but miss the tools to select the appropriate ones. Understandingly they are hesitant to embark on new technologies that have not been tested under Vietnamese conditions. It is the main aim of this thesis to provide such a tool. It should be noted that large scale stimulation of composting and anaerobic digestion would have to be accompanied by a coherent policy on the application of compost in agriculture.

The stakeholder relations with respect to waste collection have changed importantly in recent years. Collection of waste is in the hands of public and private collectors. The government considered the informal private collection insufficiently controlled in terms of finances, quality of the services and integration with the public collection. Since 2008 the local government squeezed itself between generators (households, shops, etc.) and informal collectors to control the collection of fees and service quality. This may have led to some improvement of the performance but the informal collectors regret their loss of autonomy and probably also income.

With regard to the waste transport system can be concluded that the enlargement of the city has overcharged the capacity of the public transport company CITENCO. Recently, in seven out of 24 districts of HCMC the MSW transport system has been decentralized. Although the transport system develops, the newly created autonomy of the districts hinders further integration of the system as a whole and has not led to the expected efficiency gains.

Finally, public awareness and human resources related to solid waste management have improved through many activities in capacity building and international cooperation. If well and timely managed such improvements can be of great value.

Chapter 3

Combined anaerobic and aerobic treatment of municipal solid waste[16]

3.1 Introduction

Concerning climate change Viet Nam is one of the five most strongly affected countries[17] in the world (Thanh 2008). In order to respond to national and international programs on climate change (HCMC People's Committee 2010), the HCMC strategy for solid waste management places the production of biogas through anaerobic digestion of organic solid waste as replacement of fossil fuels on the top priority list.

HCMC generates about 5,600 tons of commingled municipal solid waste (MSW) each day in 2008, of which about 60% consists of biodegradable components (called OFMSW) (CENTEMA 2009). Currently, 90% of the total amount of MSW in HCMC is treated, mainly by disposal in sanitary landfills. The remaining 10% of MSW is composted in the Vietstar composting plant with a planned capacity of 1,200 tons/day. If this capacity is effectively reached, still about 2,600 tons/day of OFMSW end up on the city's landfills. This is a problematic practice as landfill is expensive (20 USD/ton) and the occupied land cannot be used for other purposes for a long time (30-50 years). Another type of biowaste that needs effective treatment is pig manure of which farms generate about 700 tons/day (DONRE HCMCb 2009). A small part of this pig manure is treated by anaerobic digestion in households and small farms to produce biogas for cooking, but electricity production is not considered. Many pig farms do not have a system to treat pig manure and they discharge their wastes illegally in surrounding areas.

Worldwide, the most accepted methods for the treatment of the organic wastes are composting and anaerobic digestion. Composting is commonly used in Viet Nam on a small scale for many decades and recently also in large scale facilities. The aerobic composting technology fits the Vietnamese situation due to its simplicity, low investment and operational costs, and use of the produced compost as a raw material in the production of organic fertilizer. However, as mentioned in chapters 2 and 4, the composting process also has several weaknesses. Anaerobic digestion of solid waste is promising as the produced biogas may replace fossil fuel and thus contributes to avoiding greenhouse gas emissions. Anaerobic digestion of solid wastes is increasingly applied in developed countries, but in developing countries it is quite new. In Viet Nam, anaerobic digestion technology of OFMSW has not yet been applied in practice. Therefore, the HCMC council encourages research and development of this technology.

There have been some research projects dealing with anaerobic digestion of OFMSW in HCMC. Cuong and Hai (2006) carried out lab scale experiments based on the Valorga technology under mesophilic and thermophilic conditions. Chi (2008) performed pilot-scale experiments with the Dranco and Compogas technologies. The research results from these investigations showed that the volumes of biogas obtained are low compared to the amount of biogas found in developed countries. Cuong and Hai (2006) and Chi (2008) produced only 50-150 l biogas/kg VS while in other research projects productions of about 160 l /kgVS (Forster, Perez, et al. 2008), 200 lit/kg VS (Bolzonella et al. 2006) and up to 400 l/kgVS (Guendouz et al. 2008) were found.

[16] This chapter was accepted for publishing on 8/8/2012 at International Journal of Environmental Protection (IJEP) with the title: Renew energy from municipal solid waste in developing country.
[17] The others countries are Bangladesh, Myanma, Honduras, Nicaragua (http://germanwatch.org/klima/cri.pdf)

Anaerobic digestion systems treating OFMSW for biogas production applied in developed countries, like the BTA, Dranco and Compogas technologies have to be considered as high tech regarding construction, equipments and operation. These are, in general, difficult to operate in developing countries like Viet Nam with their lack of financial means and skilled operators. In order to be able to apply anaerobic digestion in Viet Nam, a technique is chosen that fits the Vietnamese conditions: the batch reactor technology with leachate recycling. Some advantages of the batch technique are (Orgaworld Company 2006; Ten Brummeler 2000; Bidlingmaier et al. 2004; Van Buuren and Potting 2011, deliverable 3.1; De Baere 2000, 2006) (1) low investment, operation and maintenance cost; (2) the technique for filling and emptying the reactor is more simple than for a continuous reactor; (3) no operational problems with mixing in the system; (4) less energy consumption due to absence of stirring; (5) no water addition; (6) leachate is recycled into the reactor, so that water and microorganism are distributed uniformly into the solid waste bed in the reactor, and pH and temperature also can be easily controlled. In addition, from many research projects can be concluded that the biogas productivity increases when the MSW is mixed with other types of wastes such as pig manure, cattle manure, septic tank sludge, bread waste, kitchen waste, etc (Corral et al. 2008; Comino et al. 2009; Valencia et al. 2009; Dareioti et al. 2009; Alvarez et al. 2010). Especially, Corral et al. (2008) showed in their research on the two-phase wet anaerobic digestion system that methane production of OFMSW only is 37 m^3/ton while it is 172 m^3/ton dry waste of a mixture of OFMSW and cow manure, nearly five times higher. Moreover, several researchers showed that the digestion rates increased after adding inoculate: Forster et al. (2008) used about 30% inoculates and Guendouz et al. (2008) added about 60-80% inoculate.

The specific objectives of the present study are to determine the applicability under the conditions of HCMC of (1) batch mesophilic anaerobic digestion to produce biogas from OFMSW and mixtures of OFMSW and pig manure (PM), and (2) composting as method of post-treatment of digestate (DOFMSW) for the production of utilizable compost. This chapter monitors the effects of process parameters such as temperature, pH, moisture content, volatile solids (VS), total solids (TS) on biogas and methane production.

3.2 Materials and methods

3.2.1 Anaerobic digestion and composting reactors

Experiments are carried out with two anaerobic digester sizes. The preliminary research is carried out with lab-scale reactors. Based on the results of the lab-scale study, the research proceeds with pilot-scale reactors which are located outdoors at ambient weather conditions of HCMC. The digestate of the anaerobic reactors is fed to a composting reactor to produce compost.

Lab-scale anaerobic reactors

For the lab-scale study 45 liter cylindrical reactors located inside were used. The reactors were insulated with polyurethane foam to minimize variations of the reactor temperature which might affect the anaerobic digestion process. The average room temperature was 27^o C. Each reactor was tightly closed with rubber tape and a screw cap to assure anaerobic conditions. During the process liquid was recycled over the reactor. The recycled liquid was obtained by filtration of the digester effluent through a screen (mesh size 1 mm) to avoid clogging of pipes and then distributed over the top of the solid waste in the reactor by a pump and spray-taps system. From the cap of the reactor biogas was collected in a biogas bag. The pictures and the detailed design of the lab-scale reactors are shown in Figure 3.1. Each reactor was loaded with 20kg OFMSW or a mixture of various types of organic solid waste.

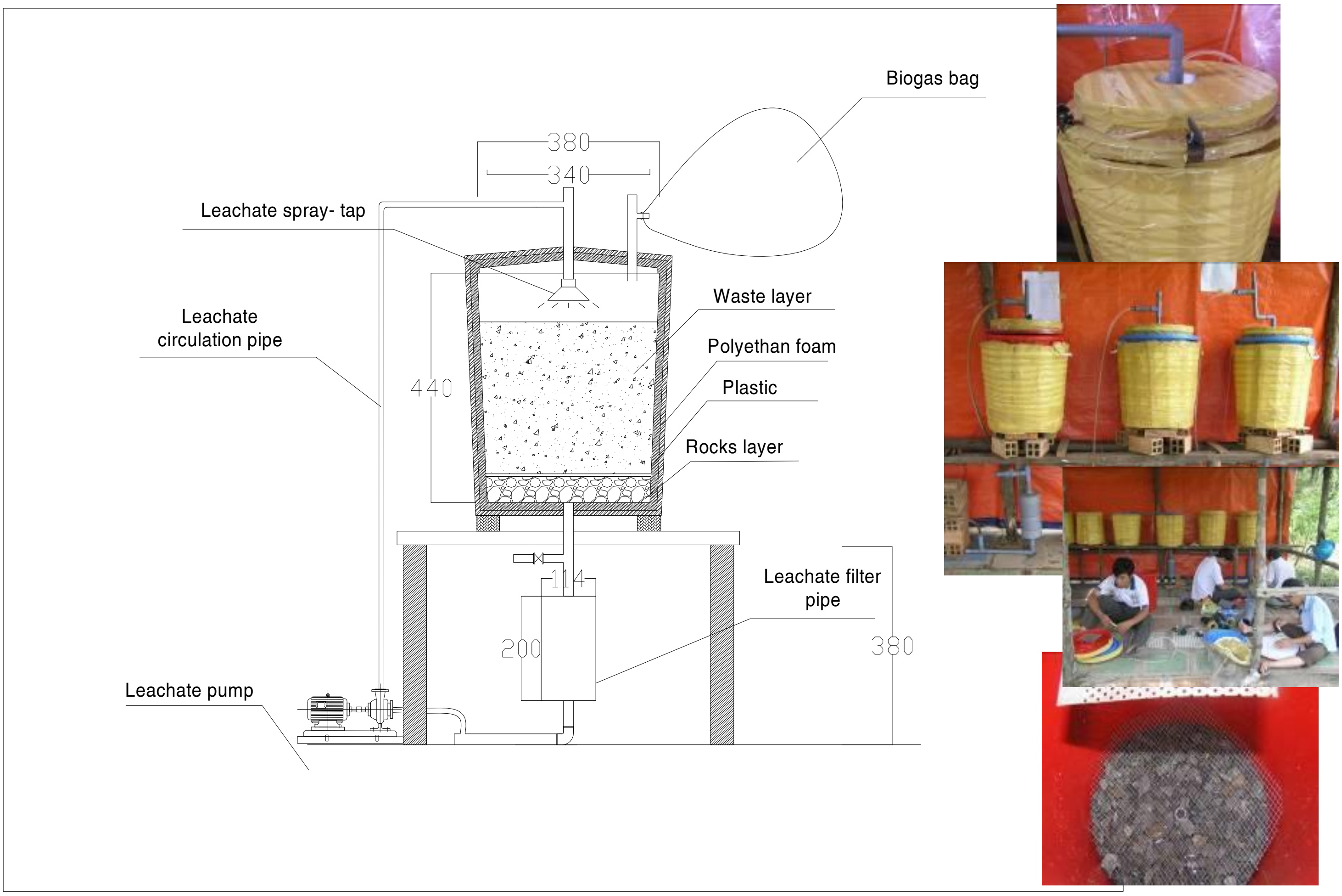

Figure 3.1 Technical design and pictures of lab-scale reactors.

Pilot-scale anaerobic digestion reactors

In the pilot-scale research two similar pilot-scale reactors, each with a volume of 5 cubic meters, were used. A schematic presentation of these reactors is given in Figure 3.2. The pilot-scale reactors were cylindrical and constructed from stainless steel. The diameter of the reactors was 2.5 m. The outside of the reactors was covered with rockwool to protect against temperature variations. The inside wall of the reactors was covered with a composite layer to protect the steel against corrosion. The design of the pilot reactor system was similar to that of the lab-scale reactor regarding the leachate recycling and the biogas collection system. An electric system was installed to automatically control the leachate recycling pump.

The mixture with the best results regarding biogas production and methane content in the lab-scale test was selected for the experiments with pilot-scale reactors. The pilot-scale reactors were installed outdoor, where the temperature was on average 27^{o}C, the maximum temperature was 38^{o}C under sunny conditions and the minimum temperature was 20^{o}C. Because of the insulation of the reactor, it could be assumed that the temperature in the reactors varied only slightly. Two reactors were used to have results in duplicate. Each reactor was loaded with 2400 kg of a mixture of organic solid wastes.

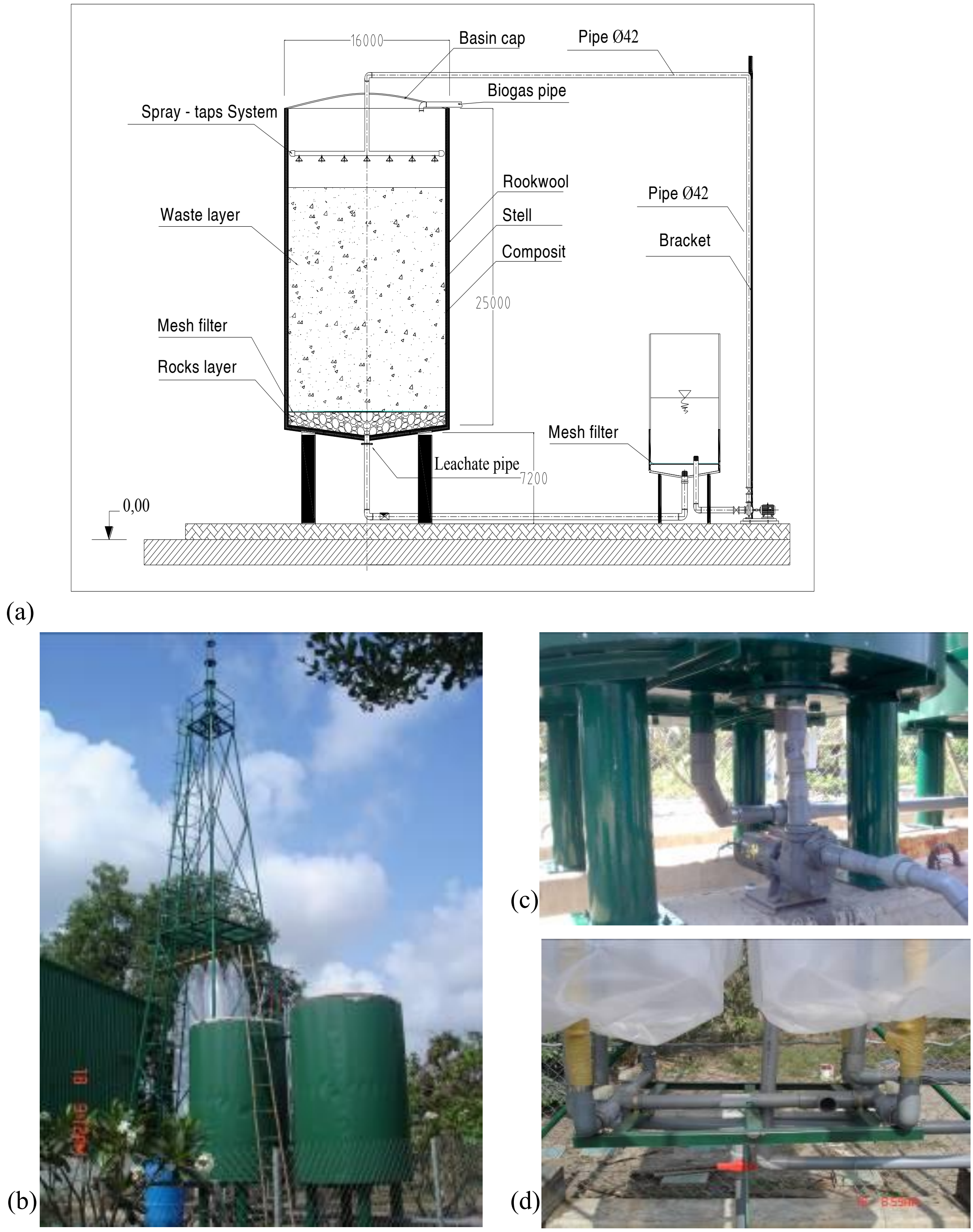

Figure 3.2 (a) technical design of pilot-scale reactors and pictures of (b) pilot-scale reactors, (c) leachate recycling system and (d) biogas collection system.

Lab-scale reactors for aerobic composting

The lab-scale reactors for aerobic composting were made of composite material with a rectangular shape having (L * W * H) dimensions of 0.3 m * 0.2 m * 0.2 m. The bottom of the reactor was provided with an air supply system. Leachate from the reactors was collected at the bottom of the reactors and discharged through a discharge pipe. This leachate was stored and redistributed to the composting process when the moisture content of the waste decreased. Figure 3.3 shows the technical design and a picture of the composting reactors.

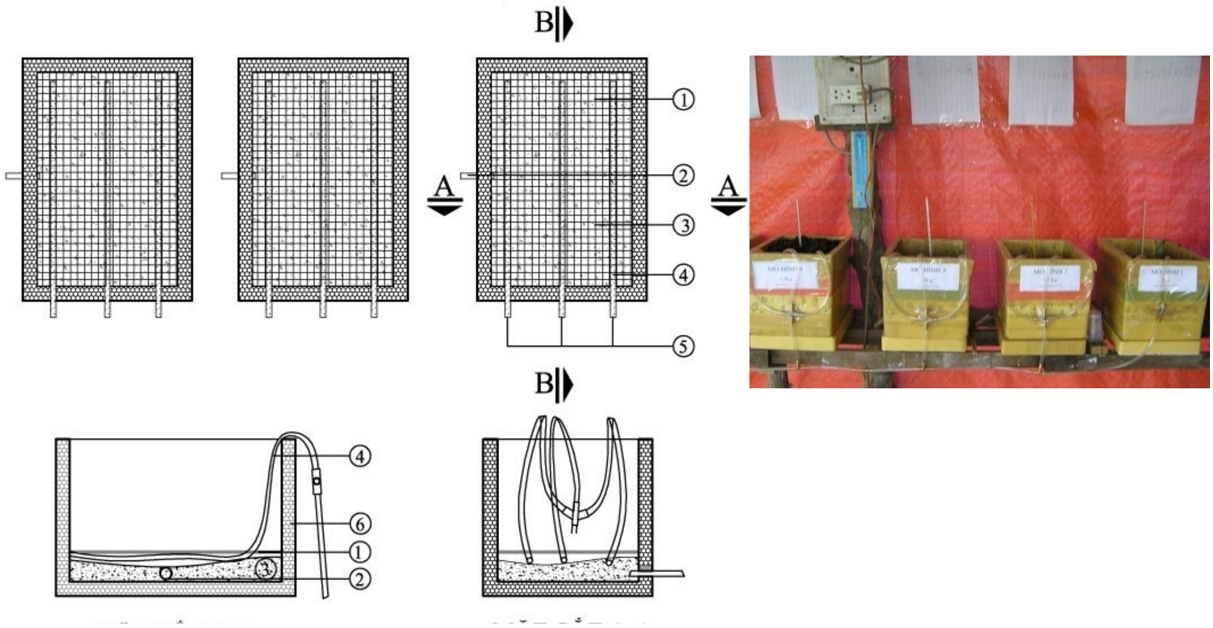

Figure 3.3 Technical design of the composting reactors and a picture of the reactors.
Note: 1. Screen, 2. Leachate collection, 3. Rock, 4. Air supply system, 5. Pump.

3.2.2 Input material- waste types

Commingled MSW was collected from a MSW transfer station in the Binh Chanh District of HCMC. At the research site, the commingled MSW was separated to collect OFMSW. The OFMSW, which was used in the experiments, represented about 58-67% of total MSW. The fresh OFMSW obtained was used in the experiments the same day.

Pig manure was collected from small pig farms in the Binh Chanh District of HCMC. In all small and medium sized pig farms in Viet Nam, pig manure and wastewater are collected separately. Therefore, the pig manure has a low moisture and lower nitrogen content compared to that of industrial pig farms, because the small pig farm manure does hardly contain urine. The pig manure was collected, stored and used in the experiments the same day.

Digestate, produced in previous research projects, was used for this research. This digestate was stored and used within one month.

3.2.3 Processing, sampling and analyzing

Processing

The procedure for processing and sampling the waste is presented in figure 3.4. Commingled MSW was transported to the research site and sorted by hand to separate the OFMSW for the experiments. Before taking a sample for analysis, the OFMSW was cut into pieces (~3 cm for lab-scale and 20 cm for pilot-scale experiments) and mixed to get a homogenous mixture.

Several experiments were performed with only OFMSW or with a mixture of OFMSW and/or pig manure and/or digestate in different ratios. The blends of OFMSW with pig manure or/and digestate were mixed thoroughly before sampling and analyzing. Each sample was analyzed for pH, TS, VS and C/N. The ratio of each mixture of OFMSW and pig manure/digestate was calculated by wet weight. If necessary, the pH was adjusted with NaOH to the optimum pH range for the biological process. The batch reactors were filled with the prepared material and then sealed to avoid the leakage of gas.

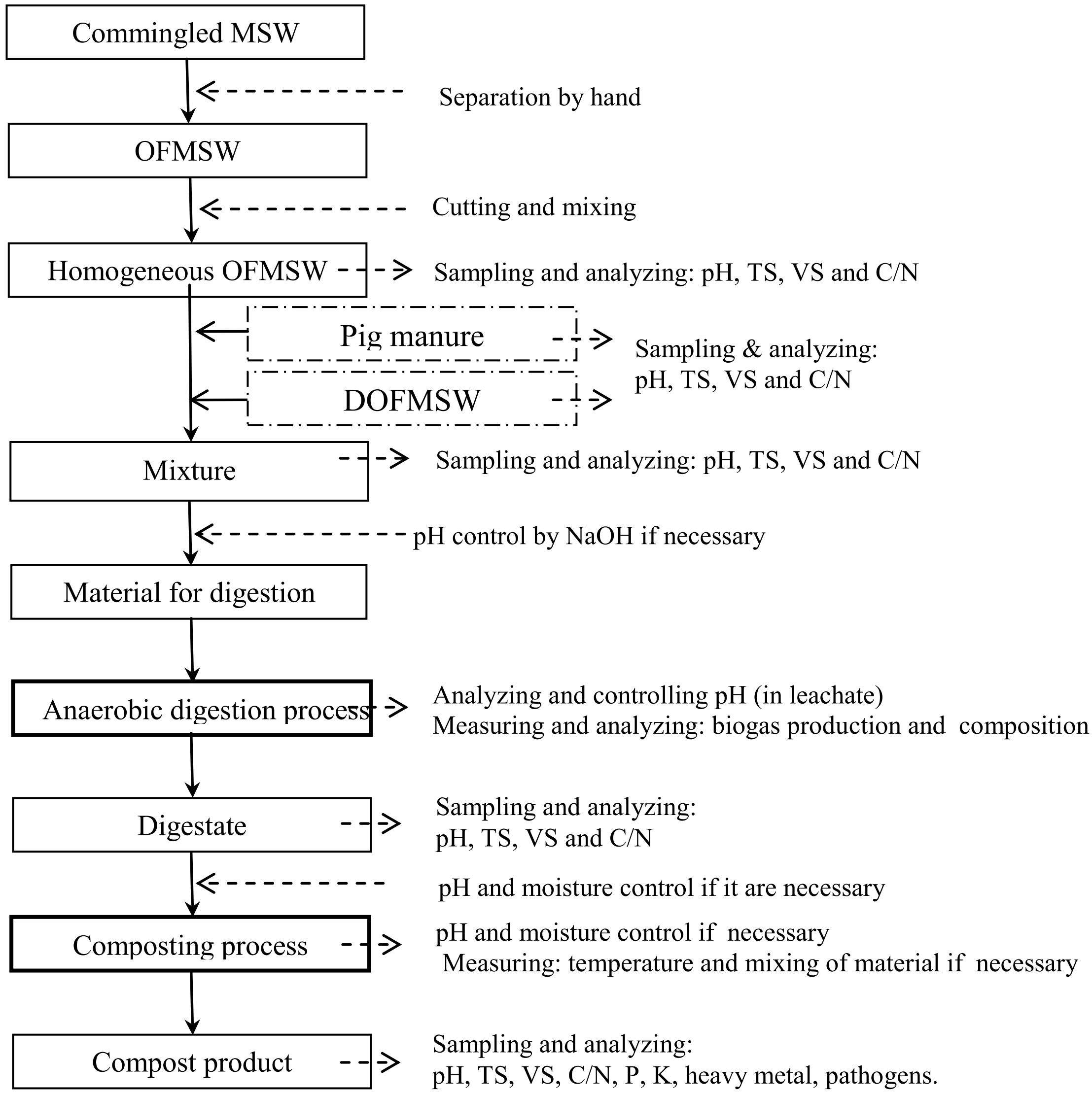

Figure 3.4 Procedure for processing and sampling.

After loading and sealing the anaerobic reactor, the pH was measured in the leachate and controlled every day, in the morning and in the evening. The first 5 days of the operation period, the pH control occurred more frequently than after this initial period. Biogas production was measured once per day. The biogas composition was analyzed three times. The first time to analyze the biogas composition was 1-3 days after the start of the process, while the second and third time was after 6-8 and 15-18 days, respectively.

The digestate from anaerobic digestion was loaded into the composting reactors, after controlling pH and moisture content for optimal process performance. For running the composting reactors, four factors had to be considered. These factors were the moisture content, pH, temperature and air supply. The moisture content of the digestate was higher than the optimum range for aerobic composting. Therefore, it was necessary to adjust the moisture content by mixing the digestate with dry material or dry it under the sun. In this study, the digestate was spread on the floor under the sun for 1 or 2 days. The pH was also checked and adjusted if necessary. The temperature was measured at least three times per day during about 3 days after the start of the process and two times per day afterwards. If the temperature increased quickly above 70^{o}C, the composting mass was mixed. Air supply was also an important factor. In this study, an air supply of 0.003 m^3/kg.hour was used (Duong and Nuong 2005). The compost product was analyzed in detail to compare its quality with the Vietnamese standards for compost quality (MARD Viet Nam 2002).

Sampling

- For every experiment, the input materials to be used (OFMSW, pig manure and digestate) were collected and sampled. The sampling was carried out for each type of material and for each mixture of material (in wet weight ratio);
- After the anaerobic process and also after the composting process, the digestate and compost product are sampled and analyzed;
- During the anaerobic process the pH of the leachate was measured and adjusted if it nessesary and also the biogas production was measured and its composition analyzed;
- During the composting process the pH and moisture content were measured and adjusted if necessary. The temperature inside the reactor was also measured and adjusted by mixing the composting mass. The air supply was continuously checked and controlled.

Analysis

The pH, TS, VS, C/N, heavy metals, E. coli and total Coliforms were analyzed according to Standard Methods (2005). For on-site measurement of temperature and pH, a portable glass thermometer and a hand-held pH meter were used. Biogas production was measured at ambient conditions (± 27°C) with a gas meter (Kokokchina Gas Meter number 217029). In the case of lab-scale, biogas is measured via the method of water displacement by biogas. Biogas was sampled for biogas composition measurement from the biogas storage bag and analyzed with a Gas Surveyor 431 Portable Gas Detector (GMI Gas Measurement Instruments Ltd., Scotland and UK).

Characterization of the OFMSW, pig manure and digestate used as input materials is given in table 3.1. Before using digestate as an input material for the composting process, it was analyzed and if necessary, pH and moisture content were adjusted to the appropriate conditions. Characteristics of mixtures of OFMSW with digestate and/or pig manure used in the experiments 1, 2, 3 are presented in Table 3.2. In the experiments 1 OFMSW and digestate were used. Experiment 1.1 (lab scale) was executed to measure the anaerobic digestion of OFMSW only, while experiments 1.2 and 1.3 (lab scale) worked with mixtures of OFMSW and digestate in ratios of 10:1 and 5: 1 (wet weight) respectively. Experiment 1.4 and 1.5 were carried out at pilot plant scale to measure the biogas productivity of the mixture which had produced the highest amount of biogas at lab scale and to measure whether there are differences between lab-scale and pilot-scale experiments with the same feedstock. In this study, the highest biogas production in experiment 1 was obtained with the mixture of OFMSW and digestate at a ratio of 10:1. Therefore, experiment 1.4 and 1.5 were done with this ratio in duplicate. In experiments 2 and 3, the procedures were the same as in experiment 1: first the experiments were done at lab-scale with mixtures with different weight ratios and then the most appropriate weight ratio was selected for experiments at pilot plant scale in duplicate.

The stability and maturity of compost product was tested by means of the Dewar self-heating test (Woods End Research Laboratory 2009). The Dewar kit included: (1) a 2-liter, steel-encased Dewar vessel of 100 mm inner diameter, (2) a thermometer to measure the ambient temperature and (3) a thermometer to insert into the vessel. Before filling the vessel the compost product was mixed intensively to provide a homogeneous sample and re-moisturized to about 55-60% with water. The temperature inside the vessel was measured three times per day during the 7 days of operation.

Table 3.1 Characteristics of OFMSW, digestate and pig manure used in the experiments.

Waste	pH	Moisture (%)	VS/TS (%)	C/N
EXPERIMENTS 1: mixtures of OFMSW and digestate				
OFMSW in lab-scale	5.05	77.3	83.4	27.6
Digestate in lab-scale	6.92	71.0	54.4	20.8
OFMSW in pilot-scale	5.80	84.3	81.9	28.7
Digestate in pilot-scale	7.50	62.7	57.9	21.3
EXPERIMENTS 2: mixtures of OFMSW and pig manure				
OFMSW in lab-scale	5.16	86.1	83.9	30.4
Pig manure in lab-scale	6.95	78.6	72.8	11.6
OFMSW in pilot-scale	6.20	80.1	87.6	28.6
Pig manure in pilot-scale	7.80	81.2	80.8	12.3
EXPERIMENTS 3: mixtures of OFMSW and pig manure and digestate				
OFMSW in lab-scale	6.20	81.6	75.6	29.1
Pig manure in lab-scale	7.10	83.8	75.6	10.9
Digestate in lab-scale	7.00	72.2	61.8	23.1
OFMSW in pilot-scale	5.60	78.4	89.2	27.9
Pig manure in pilot-scale	7.20	85.4	77.1	10.2
Digestate in pilot-scale	7.10	68.2	55.2	22.7

Table 3.2 Characteristics of OFMSW, digestate and pig manure mixtures used in the experiments.

Name, type of experiments, ratio of mixture	pH	Moisture (%)	VS/TS (%)	C/N
EXPERIMENTS 1: only OFMSW, and mixtures of OFMSW and digestate				
Experiment 1.1 Lab-scale, ratio 1 : 0	5.05	77.3	83.4	27.6
Experiment 1.2 Lab-scale, ratio 10 : 1	5.75	76.7	80.8	27.0
Experiment 1.3 Lab-scale, ratio 5 : 1	5.83	76.3	78.6	26.5
Experiment 1.4 Pilot-scale, ratio 10 : 1	5.39	82.3	79.7	28.0
Experiment 1.5 Pilot-scale, ratio 10 : 1	5.39	82.3	79.7	28.0
EXPERIMENTS 2: mixtures of OFMSW and pig manure				
Experiment 2.1 Lab-scale, ratio 20 : 1	5.12	85.7	83.4	29.5
Experiment 2.2 Lab-scale, ratio 10 : 1	5.08	85.4	82.9	28.7
Experiment 2.3 Lab-scale, ratio 5 : 1	5.17	84.9	82.1	27.3
Experiment 2.4 Pilot-scale, ratio 10 : 1	5.41	80.2	87.0	27.1
Experiment 2.5 Pilot-scale, ratio 10 : 1	5.41	80.2	87.0	27.1
EXPERIMENTS 3: mixtures of OFMSW and digestate and pig manure				
Experiment 3.1 Lab-scale, ratio 20 : 1 : 1	5.92	81.3	75.0	28.0
Experiment 3.2 Lab-scale, ratio 10 : 1 : 1	6.04	81.0	74.5	27.1
Experiment 3.3 Pilot-scale, ratio 10 : 1 : 1	6.18	78.1	85.4	26.0
Experiment 3.4 Pilot-scale, ratio 10 : 1 : 1	6.18	78.1	85.4	26.0

3.3 Results and discussions

3.3.1 Characteristics of the organic materials used in this research

The pH, moisture content (%), VS/TS and C/N of individual samples (before blending the mixtures) and of each mixture of all the experiments are shown in tables 3.1 and 3.2.The initial pH of OFMSW varied from 5.05 to 6.20 and decreased fast directly after starting the anaerobic digestion experiments (about 1.0-1.2 unit/24 hours). Therefore, in the anaerobic digestion process, the pH of OFMSW had to be strongly controlled to keep it in a range of 6-8 (Tchobanoglous et al. 1993, p.687). The pH of OFMSW depended on the way MSW was collected. If MSW was discharged and collected within one day, the pH of OFMSW was in the optimal range for anaerobic digestion. If not, it was too low and adjustment of the pH was necessary. In the case of HCMC, the MSW ought to be discharged and collected within one day. However, due to delays at discharge sources or with transportation, it could take three days for the MSW to reach the treatment site with the consequence of a strong pH decrease. The pH of digestate varied from 6.92 to 7.50 while the pH of pig manure varied from 6.95 to 7.80. Those wastes with a high pH can be appropriate buffers for OFMSW. The pH of pig manure and digestate were high due to the high concentration of ammonia in the samples. The C/N ratio of OFMSW was about 27.6-30.4 while it was 20.8-23.1 and 10.2-12.3 for digestate and pig manure respectively. Therefore, the mixtures of OFMSW and pig manure and/or digestate had a suitable balanced composition regarding the pH and the C/N content. The mixing of OFMSW and pig manure and/or digestate would keep the pH and C/N of the mixture in the ranges that are optimal for the biological process (Tchobanoglous et al. 1993, p.687).

The moisture content of digestate, OFMSW and pig manure were 62.7-72.2, 77.3-86.1 and 78.6-85.4 % respectively. Apparently, digestate contained less water than OFMSW and pig manure. Therefore, adding digestate to OFMSW slightly reduced the moisture content of the mixture to 76-82% (TS = 18 - 24%). The total solids content was high enough for batch dry digestion in which the total solid content is usually about 20-35% (Tchobanoglous et al. 1993, p.702) and about 30-40% for the Biocel technology (Ten Brummeler 1993; De Mes et al. 2003; Joshua et al. 2008).

Digestate contained a relatively high fraction of volatile solids (54.4-61.8% of TS). Probably, most of these volatile solids were hard to biodegrade. However, the primary aim of mixing digestate was to supply microorganisms to produce biogas and not to supply organic matter (Guendouz et al. 2008; Forster, Perez, et al. 2008; Hartmann and Ahring 2005).The volatile solids concentration in OFMSW was relatively high (75.6-82.9%), while in pig manure the volatile solids content was somewhat lower (72.9-80.8% of the TS). Most of the OFMSW and pig manure samples had VS higher than 82 and 76%, respectively. In general, the TS in OFMSW of HCMC are low and the VS are high compared to other data. For example, the research of Forster et al. (2008) and Guendouz et al. (2008) showed that TS values were 32- 37% and VS values 34-58%. In other literature references, the TS and VS values were higher. Laclos et al.(1997) for example measured TS values of 37-55% and VS values of 32-65% and Bolzonella et al. (2006) found TS values of 27-47% and VS values of 55-90%.

As discussed before, the mixture of waste had in general a higher pH compared to the pH of the original OFMSW (Table 3.2). However, the pH of the mixtures is lower than the optimum range for anaerobic digestion and it was necessary to adjust the pH of these mixtures before feeding them into anaerobic reactors. The moisture content of all mixtures was in the range of 74.5-87% which meant that the TS content of all mixtures was about 13-25.5%. In general, for a dry digestion process the input material should have a total solid content in range of 20-30% (Tchobanoglous et al. 1993, p.687).

Most of the mixture samples showed a VS/TS ratio higher than 80%. It should be noted that the VS concentration in the digestate was high but its effect on the biogas production was limited. The C/N ratio of OFMSW was in the range of 27-30 which was considered as appropriate for anaerobic digestion. Mixing of OFMSW with pig manure or digestate could reduced this ratio somewhat to 26-28.

3.3.2 Biogas yield

The results of the daily and cumulative biogas yields of all experiments are shown in figures 3.5-3.10. Figure 3.5 shows the daily and cumulative biogas yields obtained in the lab-scale anaerobic reactors filled with OFMSW or with a mixture of OFMSW and digestate in different ratios (experiments 1.1 – 1.3). The peak values are 28, 42 and 31 $mL.gVS^{-1}.d^{-1}$ for the experiments with ratio 1:0, 10:1 and 5:1 and the cumulative biogas yields are 146, 214 and 169 $mL.gVS^{-1}$ respectively. This result is 10% higher than the results obtained by Forster et al. (2008) who performed their research with anaerobic dry digestion in batch reactors filled with OFMSW (20% TS) and 30% inoculums.

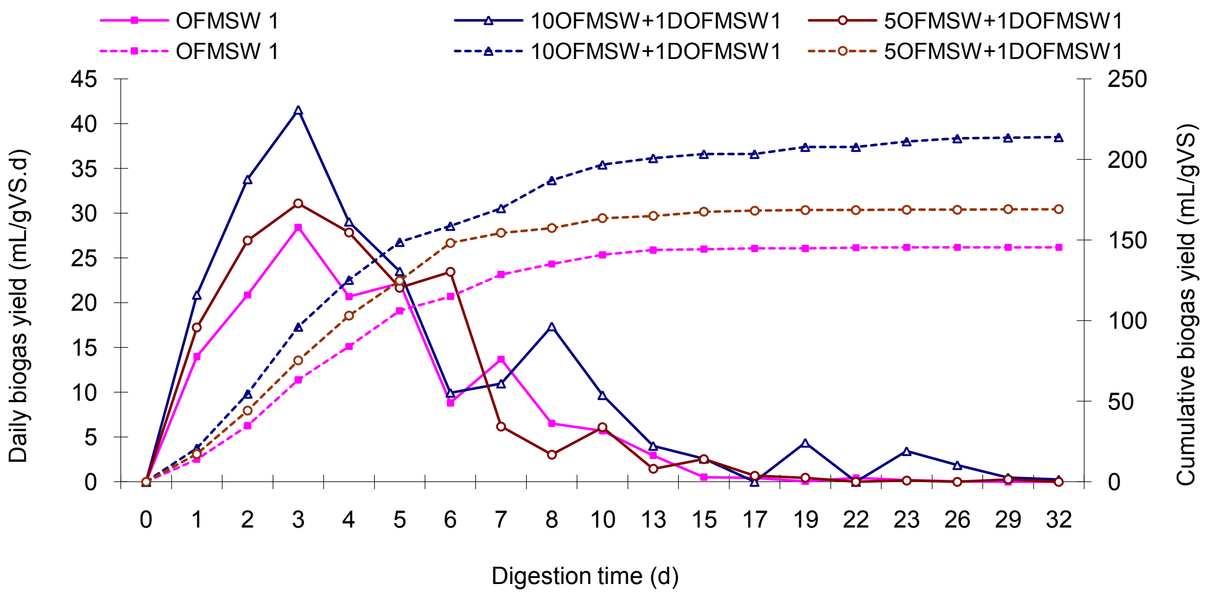

Figure 3.5 Daily and cumulative biogas yield from anaerobic digestion on lab-scale of OFMSW and a mixture of OFMSW and digestate (experiments 1.1-1.3).

Comparison of the biogas production of only OFMSW and of mixtures of OFMSW and digestate shows that the presence of digestate did significantly improve the cumulative biogas production with 47%. This was probably due to microorganisms in digestate that are responsible for the conversion of a fraction that is indigestible without the inoculums. This result matches with conclusions of Hartmann and Ahring (2005) and Nwabanne et al. (2009) that digesters for MSW will require inoculation of the feed with microorganisms to stimulate the digestion process. The better balance of the pH and/or C/N ratio when digestate is added may also be a reason for the acceleration and increase of the biogas production. However, in the research on two-phase anaerobic wet digestion Corral et al.(2008) showed a significant difference between digestion of only OFMSW and a mixture of OFMSW and cattle manure. They produced 37 respectively 172m^3 methane/ton dry wastes for only OFMSW and the mixture of OFMSW and cattle manure. The presence of cattle manure resulted in an increase in biogas production with a factor of 4.6. Between the two tested mixtures (ratio of 10:1 and 5:1) the ratio of 10:1 gave better results. This implied that in a mixture of 5 OFMSW:1 digestate, the volume of digestate added is more than required for obtaining an optimal inoculation, C/N ratio or pH buffer. In addition, the residual VS of the digestate was difficult to digest, therefore the total digestible VS in the mixture with a ratio of 5:1 was lower than in the mixtures with a ratio of 1:0 or 10:1. In comparison with other investigations on anaerobic digestion of OFMSW, the requirement of inoculation found in this research was lower than found by Forster et al. (2008) and Guendouz et al. (2008). Forster et al. (2008) used 30% inoculate of the total amount in mesophilic digestion and Guendouz et al. (2008) added 60-80% industrial digestate as inoculate.

Figure 3.5 shows that most biogas is produced within 15 days for all mixture ratios of OFMSW and digestate. With the mixture of 10:1, the cumulative biogas production could be enlarged when the digestion process was continued to about 30 days. However, this extra biogas production in the period of 15-30 days was very small. Therefore, for economic reasons, it was useful to stop the digestion process at day 15. In general, in the lab-scale experiments of the experiment 1, the experiment 1.2 with the mixture OFMSW and digestate in a ratio 10:1, gave the best results for the cumulative biogas amount and biogas production rate. Therefore, this ratio was applied in duplicate in two pilot plant reactors with the same volume to measure the biogas production and to compare this production with that obtained in the lab-scale experiments (experiments 1.4 and 1.5).

Figure 3.6 presents the averages and the standard deviation of the daily and cumulative biogas yields of the experiments 1.4 and 1.5. The results showed that the average peak in the daily biogas production is 56 $mL.g\ VS^{-1}.d^{-1}$ and the average cumulative biogas production is 244 $mL.gVS^{-1}$.These results were higher than the results obtained in the lab-scale experiments. This was probably due to the higher stability of the pilot-scale process regarding the leachate recycling and temperature fluctuations. The moisture content of the mixture used in the pilot-scale was about 8% higher than in the lab-scale experiments. Similar to the results in the lab-scale experiments, most of biogas was produced within 7-8 days after the start of the experiment and the biogas production was completed at day 15-20.

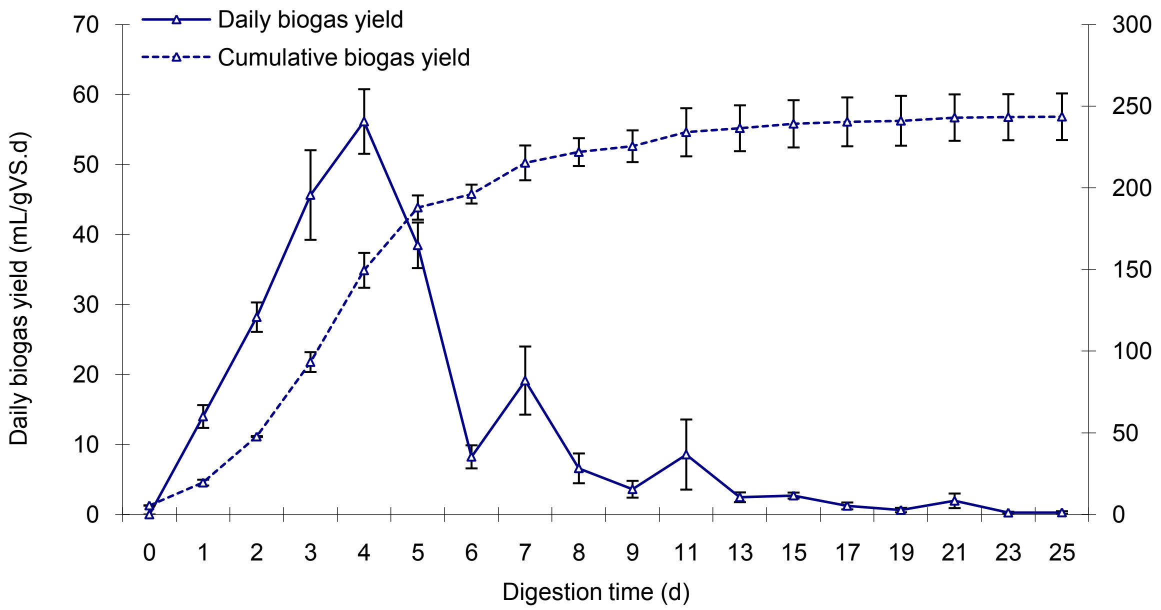

Figure 3.6 Average daily and cumulative biogas yield from anaerobic digestion at pilot-scale of a mixture of OFMSW and digestate in a ratio 10:1 (experiments 1.4 and 1.5).

Figure 3.7 shows the daily and cumulative biogas yield of lab-scale anaerobic digestion of mixtures of OFMSW and pig manure (experiments 2). The daily and cumulative biogas yields of the mixture with ratios 10:1 and 5:1 of OFMSW and pig manure showed minor differences and were clearly higher than the biogas yield with a ratio of 20:1. The peak daily yield and cumulative biogas yield of the mixtures 20:1, 10:1 and 5:1 were 59, 72 and 76 $mL.gVS^{-1}.d^{-1}$ and 273, 317 and 301 $mL.gVS^{-1}$, respectively. The cumulative biogas yields for all the mixtures of OFMSW and pig manure were clearly higher than that of the mixtures OFMSW and digestate in the lab-scale experiments (figure 3.5 versus figure 3.7). This was possibly due to the comparatively higher nitrogen content and digestible VS of pig manure. The moisture content of the waste used in these experiments was also higher (about 10%) than the moisture content of the waste used in experiment 1. Similar to the results of experiments 1 the biogas production in experiments 2 increased very quickly and reached the maximum biogas production within three days. However, the differences between experiments 1 and experiments 2 were that most biogas production in the experiments 1 is produced within the first 7-8 days and the biogas production completed after 15-20 days of operation; in experiments 2 the biogas production continued until day 20 and ended at the day 27-30.

Comparison of the three curves of experiments 2.1, 2.2 and 2.3, presented in figure 3.7 shows that there is not much difference in biogas production among these experiments that can be attributed to the ratio of added pig manure. During the period day 4-15, the biogas yield curves of the three experiments were fluctuating strongly.

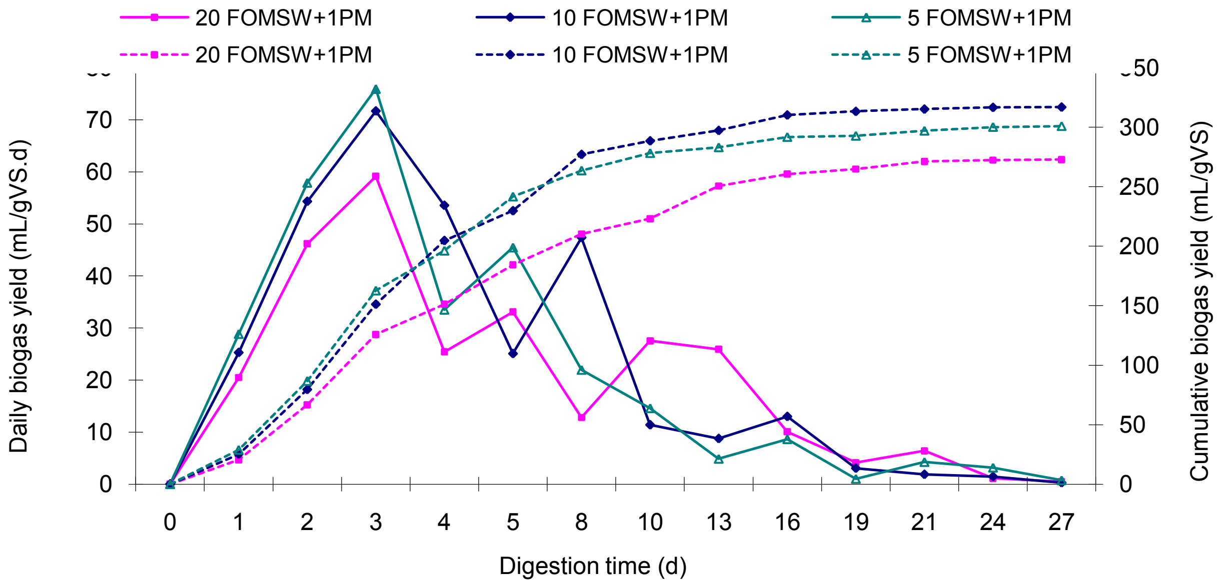

Figure 3.7 Daily and cumulative biogas yield of anaerobic digestion on lab-scale of mixtures OFMSW and pig manure (experiments 2.1-2.3).

The pilot-scale digestion of OFMSW and pig manure in a ratio of 10:1 was performed in duplicate (experiments 2.4 and 2.5). Figure 3.8 shows the average daily and cumulative biogas yields of these experiments.

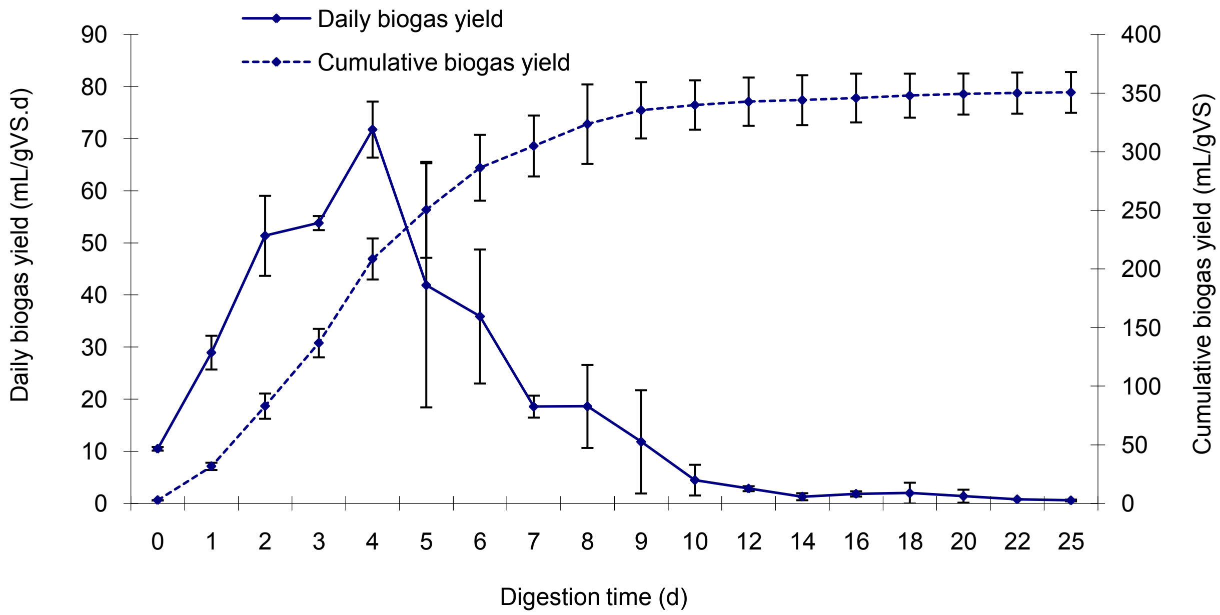

Figure 3.8 Average daily and cumulative biogas yield from anaerobic digestion at pilot-scale of a mixture OFMSW and pig manure with ratio 10:1 (experiment 2.4 and 2.5).

The average results of the pilot-scale experiment were better than the results from the lab-scale experiments with the same ratio of OFMSW and pig manure (10:1) (figure 3.7). Average peak and cumulative biogas yields were 72 $mL.gVS^{-1}.d^{-1}$ and 351 $mL.gVS^{-1}$, respectively. However, the maximum biogas production at pilot-scale occurred slightly later (at day 4) than at lab-scale (at day 3).

Figure 3.9 shows the daily and cumulative biogas yields of the digestion on lab-scale of mixtures of OFMSW, digestate and pig manure (experiments 3.1-3.2). Total biogas production from the mixture of OFMSW, digestate and pig manure was the highest among all the evaluated mixtures. The peak values of the daily biogas yield were 59 and 64 $mL.g\ VS^{-1}.d^{-1}$, while the cumulative biogas yields are 322 and 362 $mL.g\ VS^{-1}$, respectively. This could be attributed to the fact that the pig manure heightened the nitrogen content in the mixture, which was limited in OFMSW, and the digestate supplied the microorganisms responsible for the conversion of organic compounds into biogas. Similar to previous experiments (1 and 2), the maximum biogas production was reached at day 4-5 after start of the anaerobic digestion process. However, the total digestion time of mixtures of OFMSW with digestate and pig manure was longer: about 27-30 days, while for other mixtures the biogas production ended after about 20 days. The extra amount of biogas produced in this period between day 20 and day 30 was relatively small. Comparing the two mixtures of OFMSW with digestate and pig manure, it was observed that until day 5, the biogas production was more or less the same. After reaching the maximum daily biogas yield, the daily biogas production became different. The mixture with ratio OFMSW: digestate: pig manure equal to 10:1:1 gave a 12% higher cumulative biogas yield compared to the mixture with ratio 20:1:1.

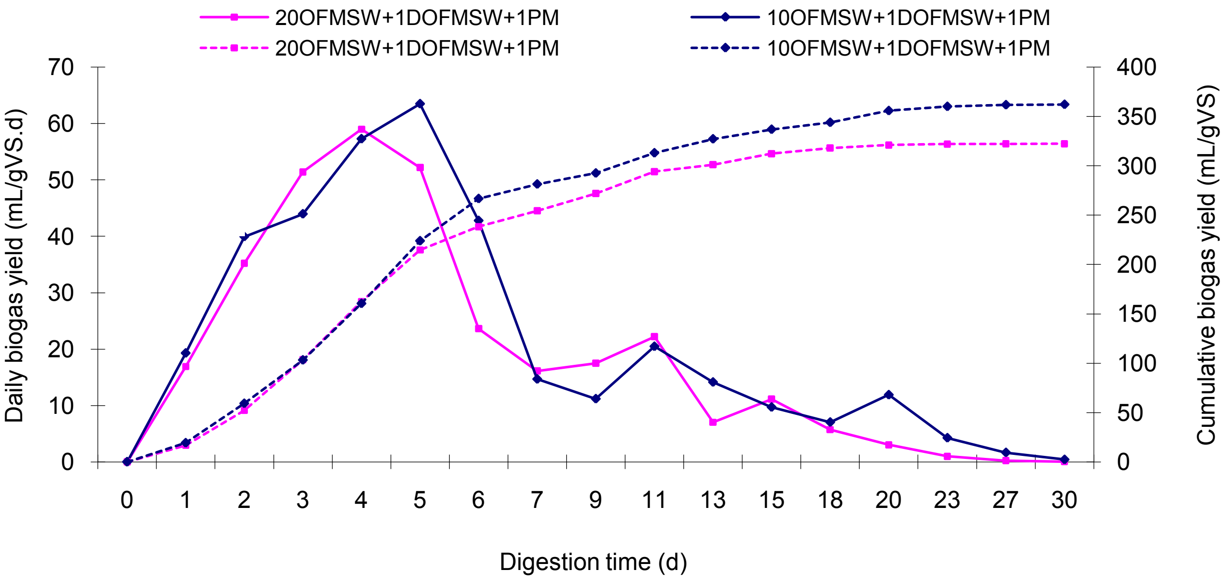

Figure 3.9 Daily and cumulative biogas yield of anaerobic digestion on lab-scale of mixtures OFMSW, digestate and pig manure (experiments 3.1 and 3.2).

Figure 3.10 shows the average daily and cumulative biogas yield from anaerobic digestion on pilot-scale of a mixture OFMSW, digestate and pig manure with ratio 10:1:1 (experiments 3.3 and 3.4).

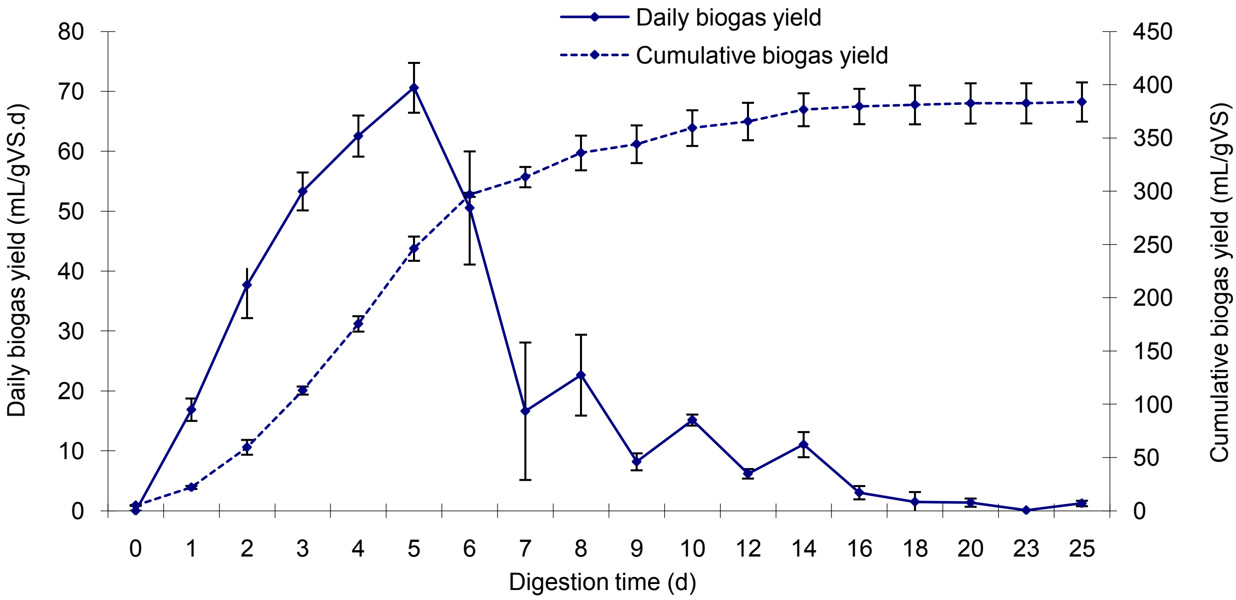

Figure 3.10 Average daily and cumulative biogas yield from anaerobic digestion on pilot-scale of a mixture OFMSW, digestate and pig manure with ratio 10:1:1 (experiments 3.3 and 3.4).

The maximum total biogas production of our experiments was 384 mL biogas.g VS^{-1}, corresponding to 234 mL methane.g VS^{-1} or 59 m^3 biogas per ton wet waste mixture. This was higher than the yield obtained by Forster et al.(2008), who found 80 mL methane.g VS^{-1} with anaerobic digestion of OFMSW in a dry-batch reactor, provided with a stirring system and operated at thermophilic conditions. Our yields were also higher than those of Hartmann and Ahring (2005) with Biocel (dry anaerobic digestion in a batch reactor) technology applied on MSW with 35% TS. They found 260 mL biogas.g VS^{-1}. Our yields were in the same range as the results of Laclos et al. (1997) and Guendouz et al. (2008) who also investigated dry digestion at mesophilic conditions in a continuous or semi-continuous one stage system with stirring. However, our yields were very low compared to those found with wet digestion of MSW by Hartmann and Ahring (2005), Angelidaki et al. (2006), Davidsson et al. (2007), Capela et al. (2008) and Zhu et al. (2009) which were in range of 450-800 mLbiogas.gVS^{-1}.If we compare the biogas production based on reactor volume, then dry digestion showed a higher efficiency than wet digestion. In addition, wet digestion needs the addition of a high amount of water and at the end a liquid residue is obtained unfit for composting due to its elevated moisture content. Accordingly, from an economic point of view dry digestion could be the preferable technology.

Table 3.3 summarizes the peak values of biogas yield from different types and different compositions of waste in lab-scale and pilot-scale experiments and adds the measured methane content of the biogas. The results show that the mixture of OFMSW and pig manure gave higher biogas yield than only OFMSW. The mixture of OFMSW and digestate resulted in biogas with higher methane content than only OFMSW. The mixture of OFMSW, pig manure and digestate showed the best biogas yields with an average of 384 mL.gVS^{-1} and 61% methane content. The methane content of the biogas was in general higher than 50%. The mixture of OFMSW and pig manure resulted in a biogas with a lower methane content, while it was highest for a mixture of OFMSW, pig manure and digestate. Furthermore, table 3.3 shows that pilot-scale experiments always gave better results than lab-scale experiments.

Table 3.3 Peak values, cumulative biogas yields and methane content for different ratios (in wet weight) of waste mixtures in lab- and pilot-scale experiments.

Waste mixture	Ratio	Scales	Biogas peak ($mL.gVS^{-1}.d^{-1}$)	Cumulative biogas ($mL.gVS^{-1}$)	Methane content* (CH_4/biogas) (%)
OFMSW+digestate	1:0	Lab	28	146	48
	10:1	Lab	42	214	53
	5:1	Lab	31	169	52
OFMSW+digestate	10:1	Pilot 1	53	233	60
	10:1	Pilot 2	59	254	59
OFMSW+pig manure	20:1	Lab	59	273	43
	10:1	Lab	72	317	52
	5:1	Lab	76	301	46
OFMSW+pig manure	10:1	Pilot 1	68	338	53
	10:1	Pilot 2	76	363	49
OFMSW+digestate+pig manure	20:1:1	Lab	59	322	53
	10:1:1	Lab	64	362	59
OFMSW+digestate+pig manure	10:1:1	Pilot 1	74	371	63
	10:1:1	Pilot 2	68	397	60

*Note: *methane content (%) in the total volume of biogas production in the storage bag.*

3.3.3 Methane content of biogas and methane yield

It was expected that the methane concentration of the biogas would increase from day 0 up to day 4 or 5 of the digestion time, while it would stay constant afterwards. In this research, we have analyzed the concentration of biogas three times during the digestion period: at day 1, 4 and 7. Similar to the results of Zhu (2009), the results of this research showed that methane concentration of the biogas increased quickly from day 1 to day 4 of the digestion period and slowly from day 4 to 7 (table 3.4). Zhu et al. (2009) and Macias et al. (2008) found that biogas methane concentrations were more or less similar for different types of waste mixtures. It varied from 52 to 61% for mixtures of MSW and paper waste, mixtures of MSW and bio-solids, mixtures of bio-solids and paper waste. In our research, table 3.4 shows the methane content which is differed with each type of waste mixture. The maximum difference of methane concentration was as high as 19% (55 to 68%).

Table 3.4 Methane content of biogas produced in the pilot plant reactors for different mixtures of solid wastes and at day 1, 4 and 7.

Mixture of waste type	Ratio	Reactor	Methane/biogas (%)		
			Day 1	Day 4	Day 7
OFMSW+digestate	10:0	1	56	65	66
		2	53	63	65
OFMSW+pig manure	10:1	1	48	55	57
		2	44	54	53
OFMSW+digestate+pig manure	10:1:1	1	55	67	68
		2	57	62	64

The methane content in the total biogas of the complete digestion period was lowest for a mixture of OFMSW and pig manure and highest for a mixture of OFSMW and digestate and pig manure. The best results achieved were 63% CH_4 (sampling at the stored biogas bag at the end of digestion time), corresponding to a methane production of 234mL methane.g VS^{-1}

(=371*0.63) (table 3.3). As already mentioned, the presence of digestate promotes the conversion of organic compounds to methane.

3.3.4 Total and volatile solids

TS and VS output after digestion and the VS reduction efficiency are shown in table 3.5.

Table 3.5 TS and VS (%) in digestate of the digestion experiments and VS reduction efficiencies (%) of the tested waste mixtures.

Type of experiments Ratio of mixtures in wet weight	TS output (%)	VS output (%)	VS reduction (%)
EXPERIMENTS 1: only OFMSW and mixtures of OFMSW+digestate			
Experiment 1.1 Lab-scale, only OFMSW	33.7	73.5	35
Experiment 1.2 Lab-scale, ratio 10: 1	30	64	49
Experiment 1.3 Lab-scale, ratio 5: 1	33	65.2	42
Experiment 1.4 Pilot-scale, ratio 10: 1	25.4	56	50
Experiment 1.5 Pilot-scale, ratio 10: 1	26.7	52	51
EXPERIMENTS 2: mixtures of OFMSW+ pig manure			
Experiment 2.1 Lab-scale, ratio 20: 1	27	74.6	41
Experiment 2.2 Lab-scale, ratio 10: 1	25	74	47
Experiment 2.3 Lab-scale, ratio 5: 1	29	72.4	41
Experiment 2.4 Pilot-scale, ratio 10: 1	30	78.3	52
Experiment 2.5 Pilot-scale, ratio 10: 1	28.7	77.6	55
EXPERIMENTS 3: mixtures of OFMSW+digestate+pig manure			
Experiment 3.1 Lab-scale, ratio 20: 1: 1	27.2	52.6	59
Experiment 3.2 Lab-scale, ratio 10: 1: 1	28.8	48.4	61
Experiment 3.3 Pilot-scale, ratio 10: 1: 1	32.8	51	64
Experiment 3.4 Pilot-scale, ratio 10: 1: 1	31	53.3	65

No water was added to the reactors at the start. Water addition was not necessary as the moisture content in Vietnamese solid waste was high resulting in a high water content of the waste mixture. The total solid concentration in the output of the reactors ranged from 25 to 34%, which meant that it was necessary to dry this residue before subjecting it to aerobic composting. The organic matter content was still high: 48-78%. The volatile solid reduction efficiencies (kg VS reduction/kg VS input) were in the range of 35-65%. The maximum VS reduction efficiency of 65%was obtained in the digestion of a mixture of OFMSW with pig manure and digestate in a ratio of 10:1:1 (experiment 3.4).

3.3.5 pH

Figure 3.11 shows the pH values of the waste as a function of the digestion time of experiment 1: digestion of only OFMSW and mixtures of OFMSW and digestate in different ratios. Three experiments were performed at lab-scale and one at pilot-scale. For the days 0 to 5 there are two data per day: the pH is measured in the morning after the night without pH control. The second pH value of the day was measured after adding chemicals to obtain the optimum pH range. From day 6 on the pH was stable. Therefore, from that day on pH adjustment was not necessary. The input materials of all experiments with only OFMSW and of mixtures of OFMSW and digestate had low pH values and for all mixtures pH adjustment was needed.

The pH dropped rapidly at the beginning of each experiment as the easily digestible fraction of organic matter was hydrolyzed and converted to fatty acids. In the experiments with mixture of waste (experiment 1.2, 1.3, 1.4) the pH slightly drop at the first day and stable after that without any adjustment. Therefore, it was not necessary to control pH. This meant that produced fatty acids were immediately converted to methane. Only in the experiment with OFMSW (experiment 1.1), the pH fluctuated and needed control during the first five days of the digestion to obtain appropriate pH conditions.

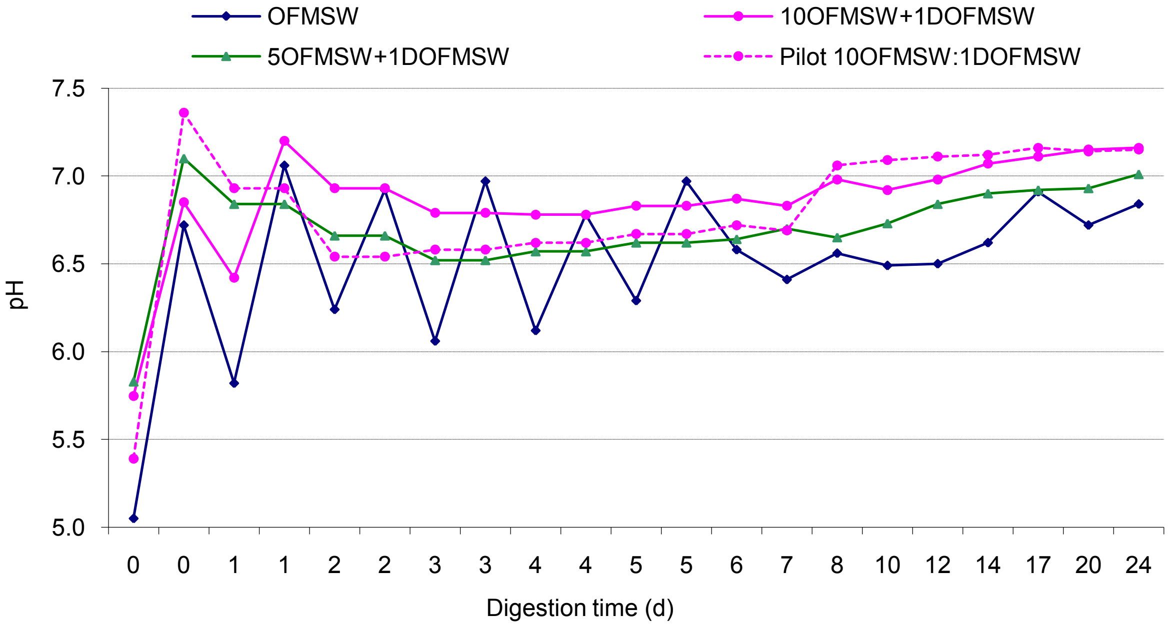

Figure 3.11 The pH development during digestion of only OFMSW (experiment 1.1) and of mixtures of OFMSW and digestate in lab-scale (experiment 1.2, 1.3) and pilot-scale experiments (experiments 1.4).
Note: For the days 0 to 5 a first figure is given of the pH value after a night without adjustment and the second value after adjustment to the optimum condition for anaerobic digestion.

Figure 3.12 shows the pH of the waste mixture OFMSW and pig manure as a function of digestion time of the experiments 2, with three experiments at lab-scale and one at pilot-scale.

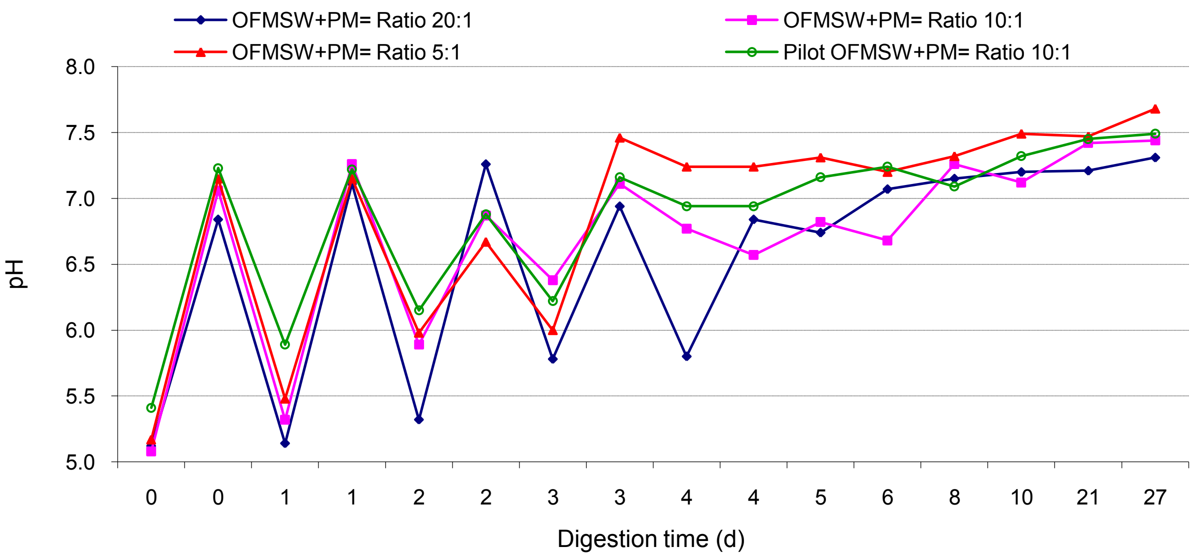

Figure 3.12 The pH development during anaerobic digestion of OFMSW and pig manure mixtures in lab-scale and pilot-scale experiments (experiments 2).
Note: For the days 0 until 4 a first figure is given of the pH value after a night without adjustment and the second value after adjustment to the optimum condition for anaerobic digestion.

In experiments 2, the pH fluctuated during the first four days for all experiments. That meant that the mixture of OFMSW and pig manure was not adequately buffered. The methanogenes is was not in balance with the hydrolysis and fatty acids production, which caused an accumulation of volatile fatty acids in the reactors. Therefore, for these waste mixtures the process needed supplementary buffering during the first four days. From day 5 on, the pH was more or less stable for all four experiments and showed a continuous increase to reach pH 7.5 at the end of the process after 27 days. There were no large pH differences between the four experiments, although the mixture with ratio of OFMSW:pig manure equal to 20:1 needed a little bit more buffering and resulted in a lower final pH.

Compared to experiment 1, the pH in experiment 2 was fluctuating more and needed more buffer. Also were the pH values of experiment 2 higher at the end of the digestion period. That may have been due to a higher nitrogen concentration originating from the pig manure, resulting in a higher ammonia concentration in the residue at the end of the process.

Figure 3.13 shows the pH development during digestion of the mixtures of OFMSW, pig manure and digestate in two lab-scale and one pilot-scale trial (experiment 3). Similar to experiments 1 and 2, the pH decreased at the beginning of the digestion process. However, the pH decrease did not go below pH 6.3 at days 3 and 4 and was less than in experiments 1 and 2. Therefore, with exception of the initial neutralization of the waste, it was not necessary to add NaOH solution.

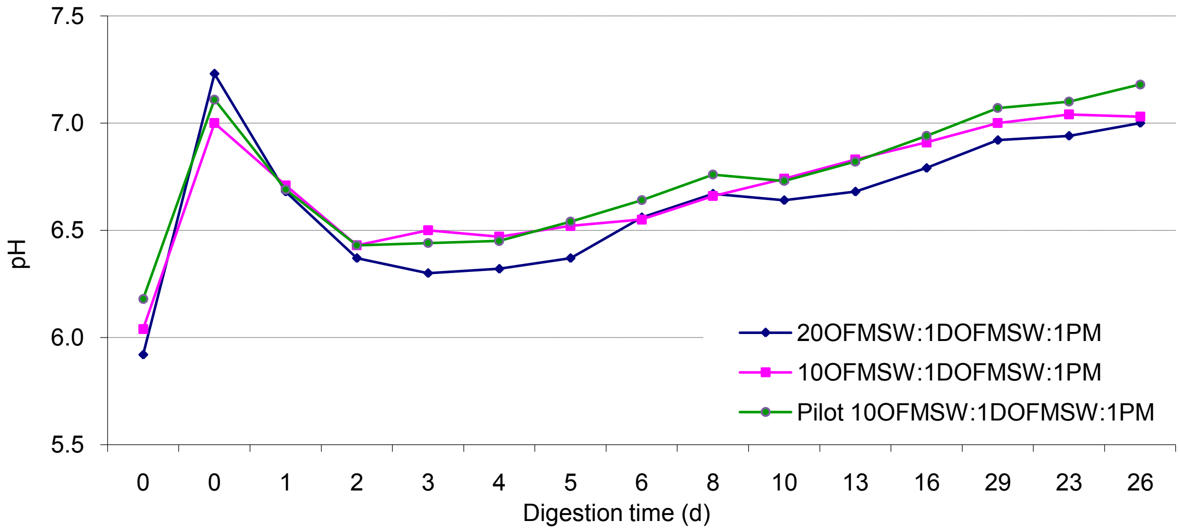

Figure 3.13 The pH development during anaerobic digestion of mixtures of OFMSW, pig manure and digestate in lab-scale and pilot-scale experiments (experiments 3).
Note: For the first day a first figure is given of the pH value after a night without adjustment and the second value after adjustment to the optimum condition for anaerobic digestion.

The drops of the pH during the initial phase of the experiments were in line with findings of Macias et al. (2008). In this research, the pH dropped during the first 5 days of the digestion while pH was only adjusted one time per day (at 8 a.m.). This infrequent adjustment may have affected the biological anaerobic digestion process and resulted in a lower biogas production and a lower methane content of the biogas.

The pH of the OFMSW and digestate mixture was more stable than the pH of the other mixtures and did not need control during the digestion process. In contrast, the pH of only OFMSW was not stable, especially during the first 7-8 days of the digestion.

The digestion of OFMSW and pig manure mixtures showed a high VS reduction and a high biogas production compared to digestion of only OFMSW and mixtures of OFMSW and digestate. These results may have been a consequence of the high N to C ratio in pig manure that compensated for the lack of N in OFMSW. However, the pH during digestion of OFMSW and pig manure mixtures was not stable within the first five days. The digestion of OFMSW, pig manure and digestate mixtures showed a slightly higher biogas production than the mixtures of OFMSW and pig manure. In all cases the methane fraction in the biogas was significantly increased with increasing pH stabilization during the digestion time.

3.3.6 Composting and compost product

The digestate from the anaerobic digestion of the mixture OFMSW, pig manure and digestate 10:1:1 at pilot-scale and lab-scale experiments were used as input for the composting experiments. The composition of the digestate is presented in Table 3.6.

Table 3.6 Composition of the digestate of the OFMSW/digestate/pig manure mixture, ratio 10:1:1, obtained in the lab-scale (experiment 3.2) and pilot-scale (experiment 3.3) experiments.

Parameter	Units	Pilot-scale	Lab-scale
pH	-	7.2	7.3
Moisture content (%)	%	67	71
Volatile solid (%VS/TS)	%	51	48
C/N	-	18.7	20.2

The digestate had high moisture content, higher than the optimum range for aerobic composting. Therefore, before putting it into the composting reactors, the residue was dried under sunshine in 1-2days to reduce the moisture content to 55-60%.

Temperature

Temperature is an important factor in the composting process: it affects the activity of microorganisms in the biological process. Temperature should be controlled during the aerobic biological process to assure optimal environmental conditions for the microorganisms and to obtain a safe product with respect to pathogenic organisms (Nelson et al. 2006).

Figure 3.14 shows the temperature development during composting of the digested mixture of OFMSW, pig manure and digestate (ratio 10:1:1) induplicate.

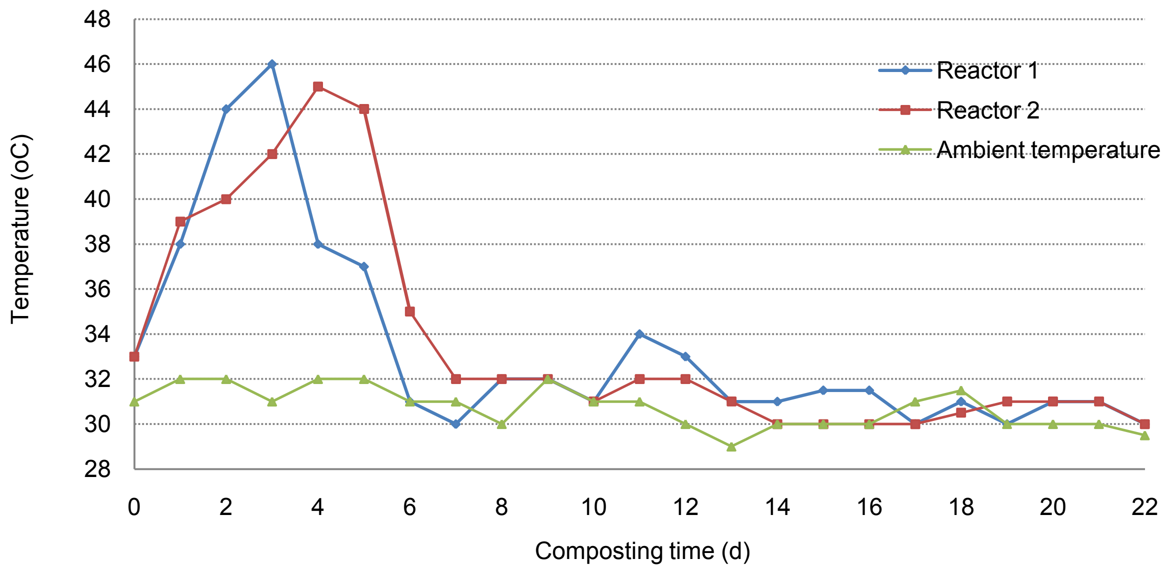

Figure 3.14 Temperature development during composting of digested OFMSW, pig manure and digestate mixture, ratio 10:1:1, in duplicate.

The development of temperature in the duplicates was more or less the same. The temperature in reactor 1 went up a little bit faster compared to the temperature in reactor 2 and the maximum temperature was also slightly higher. These maximum temperatures of 45-46 °C were appropriate for the biological process and lasted for three to four days. Most of pathogenic organisms are expected to be destroyed during composting at a temperature of about 55°C (Tchobanoglous et al. 1993, p.687) but such a high temperature was not reached here. Therefore, the compost produced during this experiment could still contain pathogens. In general, figure 3.14 shows a brief and moderate temperature increase during the first days and a fast drop to ambient temperatures after three to four days. The relatively small and short temperature leap could be due to low remaining fraction of degradable organic matter in the input material (digestate). The figure also shows that the composting process was finished after 7 to 8 days.

pH

For adequate activity aerobic microorganisms require a pH between of 6.0-7.5, while fungi and actinomycetes can operate in a range of pH 5.5-8. The final pH is an indicator for the quality of the compost product and a parameter to check the applicability of the compost product (Thompson 2001). If the pH of the composting process is higher than 8.5 the quality of the compost product is expected to be low due to the lack of nitrogen (Tchobanoglous et al. 1993, p.687).

Figure 3.15 shows the pH development in the two aerated composting reactors with a digested mixture OFMSW, pig manure and digestate in ratio of 10:1:1. The pH increased during the first 6-7 days together with the temperature. When the biological process slows down and stopped the temperature and pH stabilized. The pH was more or less stable from day 7-8 up to the end of the experiment and it reached about pH 8.3.

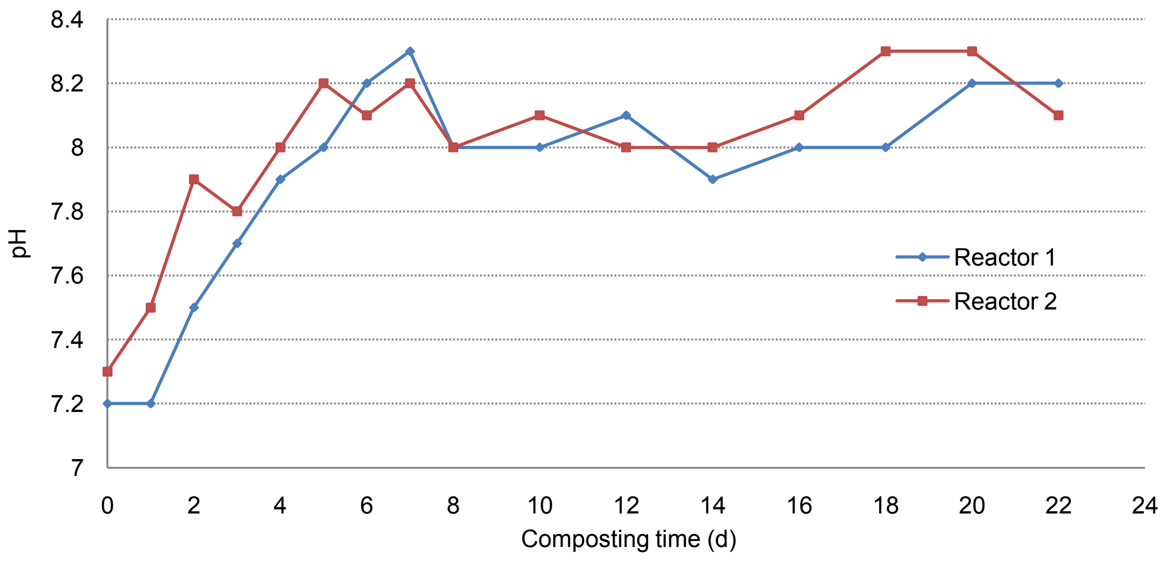

Figure 3. 15 pH development during composting with input of a digested mixture of OFMSW, pig manure and digestate, ratio 10:1:1, in duplicate.

Volatile solids (VS)

Figure 3.16 shows the VS reduction during the aerobic composting of the digestate of OFMSW, pig manure and digestate, ratio of 10:1:1, in duplicate. The volatile solids (VS) in the digestate were still high (48-51% of the total solids). During the aerobic composting the VS fraction was reduced but not much, reaching about 41-42% of the TS at the end of the experiment. The total VS reduction during the composting process was about 9-10%.

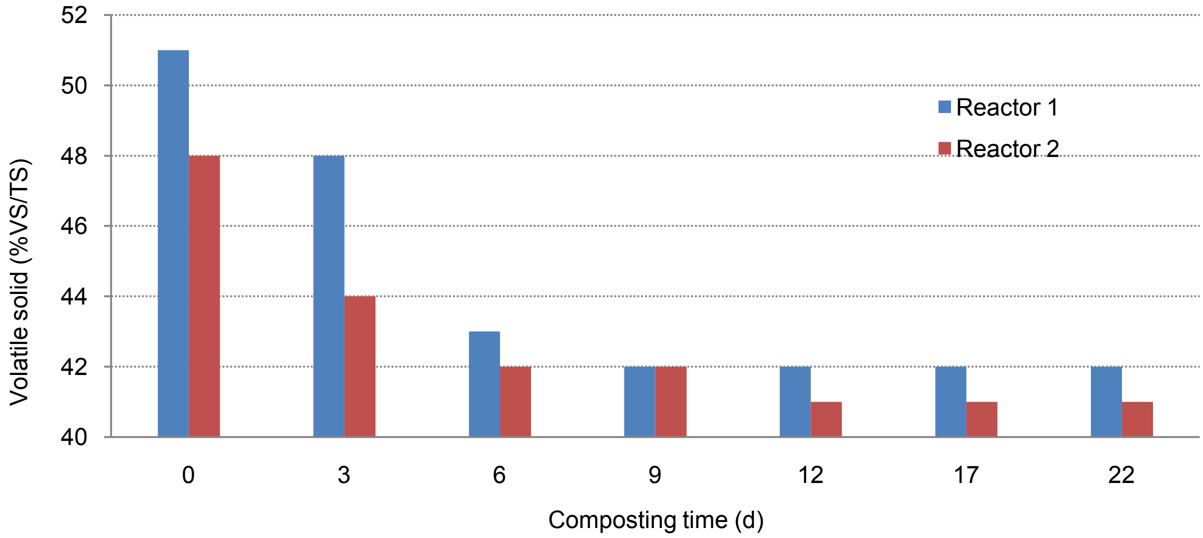

Figure 3.16 VS reduction during composting with input of a digested mixture of OFMSW, pig manure and digestate, ratio 10:1:1, in duplicate.

Compost product

Figure 3.17 presents the temperature development found by means of the Dewar self-heating test of compost products. The temperature in this test increased to a maximum of 28 – 29°C, which was about 6°C higher than the ambient temperature. In the protocol of the Dewar self-heating test it was stated that if the temperature in the self-heating test increases less than 10°C the compost qualifies as the official class of stability V, meaning that the compost product is "very stable and considered as a well-aged compost" (Koenig and Bari 1998). The compost product of our experiment satisfied the protocol for obtaining the qualification class V.

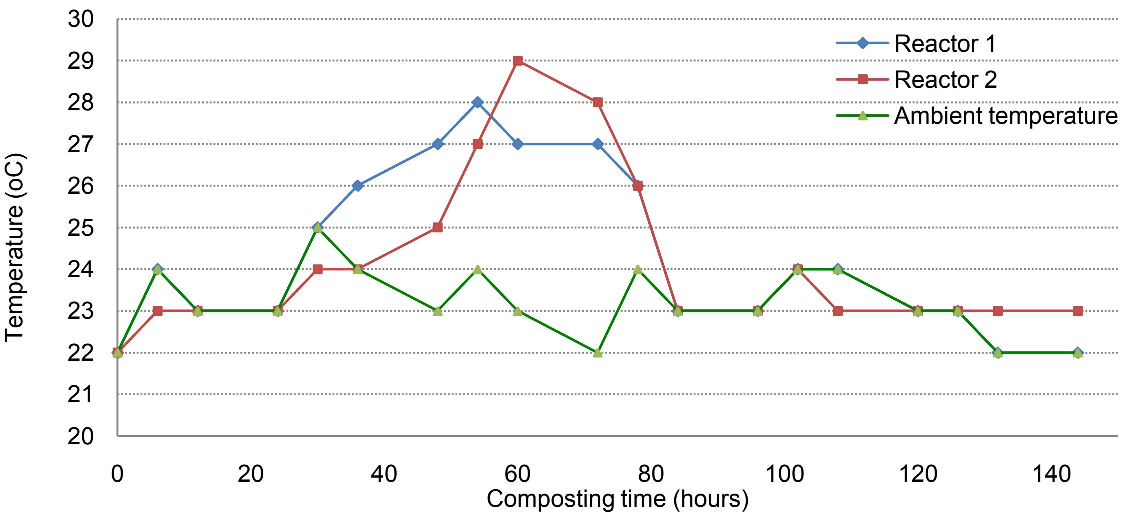

Figure 3.17 Temperature developments during the self-heating test of compost products.

The compost product quality was compared to the compost quality standards of Viet Nam (MARD Viet Nam 2002). The results are shown in table 3.7. In the last column the standard of compost product from MSW of the Ministry of Agriculture and Rural Development of Viet Nam is given. Table 3.7 shows that the compost product satisfied the Vietnamese standard in terms of toxic components. However, the nutrient content (N, P, K) was low. Therefore, this compost could be used as a raw material for organic fertilizer production for which there is a considerable demand in Viet Nam.

Table 3.7 Compost quality.

Descriptions	Units	Quality of compost	Standard (*)
Effective for agriculture		-	good
Maturity		Good	good
The particle size of compost	mm	Based on waste size	4-5
Maximum moisture	%	41	35
pH			6.0 – 8.0
Minimum effective microorganisms	CFU/ g sample	-	106
Minimum total carbon	%	22	13
Minimum total nitrogen	%	1.1	2.5
Minimum total phosphate	%	1.6	2.5
Minimum total potassium	%	0.8	1.5
Density of Salmonella in 25 g sample	CFU	-	0
Maximum Pb content	mg/kg	Trace	250
Maximum Cd content	mg/kg	N.d.	2.5
Maximum Cr content	mg/kg	Trace	200
Maximum Cu content	mg/kg	Trace	200
Maximum Ni content	mg/kg	N.d	100
Maximum Zn content	mg/kg	Trace	750
Maximum Hg content	mg/kg	N.d.	2
Minimum storing time	Month	-	6
E.coli	Ecoli/g	0	-
Total Coliforms	Coliform/g	$1*10^2$	-

Note:

n.d.: not detected.

(*) Branch standard for compost produced from MSW (MARD Viet Nam 2002).

3.4 Conclusions

Addition of pig manure and digestate to OFMSW led to a significant increase of the biogas production, while the pH was more stable when OFMSW was mixed with digestate. The maximum accumulated biogas production found was 384 $mL.gVS^{-1}$, which was equal to $59m^3$ biogas (with 61% methane content) per ton of OFMSW, digestate and pig manure with ratio 10: 1:1. The volume of biogas production was not high as compared to the yields obtained in studies on wet anaerobic digestion. This could be caused by the relatively simple anaerobic digestion technology used in this research and also perhaps by the nature of the MSW in HCMC, which contained a high concentration of the difficultly biodegradable lingo cellulose (Laclos et al. 1997). However, this research showed the possibilities of this technology in HCMC in terms of reduction of environmental problems, applicability and production of biogas.

In all experiments the gas production reached a very low level after 15 days of operation. In practice therefore, for economic reasons, the batch digestion process with this type of wastes would have to be finished after about 15 to 20 days. Volatile solids reductions in the digestion processes were in the range of 35-65% and the volatile solids in the residues were still about 43-52% after 15 days of operation. However, in the aerobic composting process which was applied as post-treatment method the reduction in volatile solids was relatively low: about 7-9%. The pH in the anaerobic digestion process fluctuated during the first 3-5 days and remained stable after that period. The pH of the mixture of OFMSW and digestate was more stable than that of OFMSW alone or of a mixture of OFMSW with pig manure. The pilot-scale anaerobic digestion of all types of wastes was more stable than the lab-scale process.

The digestate of a mixture of OFMSW, pig manure and digestate could be used to produce a high quality compost product for agricultural application that satisfied the Vietnamese standards.

With aerated composting it took only one week to turn the digestate of anaerobic treatment of OFMSW into compost. However, the digestate has be dried before composting to reduce its moisture content. The digestate had a bad odor. Therefore, it was necessary to execute the composting process in a completely closed system. At full scale in-vessel composting might be a good technology choice. The compost product yield was in range of 0.2-0.25ton/ton MSW or mixture of wastes.

Chapter 4
Treatment options for commingled municipal solid waste in Ho Chi Minh City

4.1 Introduction

In developing countries, the amount of MSW is increasing due to growth of the population and the economic output, changing lifestyles and new patterns of production and consumption. The required budget for managing MSW in cities is rising quickly, especially where the availability of land is limited or the environmental standards become stricter. Many technical and management measures may help to reduce the amount of MSW and protect the environment and public health. New technologies convert waste to valuable products resulting in a reduction of costs.

Worldwide treatment technologies have been developed and are emerging that fit with this concept of resource management. Among these composting, anaerobic digestion, incineration and landfill technologies are most common, especially in developed countries. Besides, there are advanced technologies, such as gasification or pyrolysis. These technologies have advantages in the processing of specific waste streams. However, they are costly, less suitable for wet domestic waste, still in a developing phase and not clearly proven in practice (Crowe et al. 2002). Therefore gasification and pyrolysis are not adopted in this thesis as potentially appropriate technologies for developing countries. The present chapter reviews common technologies under the headings of composting (4.3), anaerobic digestion (4.4), incineration (4.5) and landfill (4.6) and selects among the various forms of these technologies those that are appropriate to cities in Asian developing countries, and specifically to HCMC. For this selection a set of criteria is applied. These are briefly explained in section 4.2. The conclusions of the chapter are finally summarized in section 4.7. The technological options selected in this chapter are used in the chapters 5 (cost analysis), 6 (modeling) and 7 (discussions and conclusions) for finding optimum combinations of technologies for the solid waste management of HCMC under various assumptions.

4.2 Criteria for appropriate MSW treatment options

Applying the methodology to select the criteria for appropriate drainage and sanitation system by Van Buuren (2010, Chapter 4, p.47-69) and Zurbruegg and Tilley (2007, Workpackage 3), the criteria used for the selection of appropriate technologies for MSW treatment are subdivided into four groups: (1) technical efficiency, 2) environmental and health performance, (3) social manageability and (4) economic affordability. These 4 groups of criteria are detailed in the next paragraphs.

4.2.1 Technologies should be technically efficient

Appropriate technologies should be capable of processing the MSW with the quality and quantity and the climatic conditions of the city under study. The MSW in Vietnamese cities with its high content of organic matter and moisture is especially suitable for biological processes and the temperature makes composting and anaerobic digestion at mesophilic conditions attractive possibilities (Kim Oanh et al. 2007; Kim Oanh 2009).

Appropriate technologies are robust, flexible and easily operable. Robustness could mean sturdy, durable and resilient. Robust technologies need little repair and if necessary the maintenance is simple. Flexibility refers to the capacity to process a varying flow of wastes (Van Buuren 2010, p.50-52; Zurbruegg and Tilley 2007).

4.2.2 Technologies should have a high environmental and health performance

Appropriate technologies should comply with environmental and public health requirements (based on the Environmental protection law of Viet Nam issued in 2005 and Legislation number 52/2005/QH11 dated 29/12/2005. This law stipulates the generalities of solid waste management). They have to satisfy the Vietnamese standards for discharge of pollutants into air and for noise (MONREb Viet Nam 2009; MOH Viet Nam 2002), for discharge of treated wastewater into surface water (MONREc Viet Nam 2009) or into the sewerage system.

Appropriate technologies should make optimal use of resources. The performance can be expressed in indicators that reflect a low consumption of water, energy, land and chemicals and a high production of useful products such as soil conditioners, nutrients, biogas, electricity and utilizable heat (Zurbruegg and Tilley 2007; Van Buuren 2010, p.52-55). Land use of MSW treatment in particular is a critical issue in Asian cities. Therefore, there exists a strong preference for technologies that use little land, like in-vessel composting, anaerobic digestion and incineration.

4.2.3 Technologies should be manageable under the institutional conditions of Asian cities

Different MSW treatment technologies will require different regulations and control mechanisms. These requirements should fit in the existing institutional infrastructure of HCMC. The technologies should be in agreement with the solid waste management planning of Viet Nam and HCMC. There are many programs related to solid waste management, such as the program on solid waste separation at the source (DONRE HCMCf 2005), the master plan on solid waste management systems (DONRE HCMCe 2006), the strategy of solid waste management of HCMC (DONRE HCMCd 2002).

There is a lack of experts for solid waste treatment technologies in HCMC while low technology labor is available and cheap. Therefore, application of high-tech options requires time and money for training and education and entails an increased risk of failure; consequently, there is a preference for technologies that are relatively simple with regard to construction, operation and maintenance, like aerated static pile composting and sanitary landfill .

Appropriate technologies should preferably apply equipment that can be replaced and repaired locally (based on the Announcement no. 50/TB-VPCP dated 17/3/2007 by Prime Minister Nguyen Tan Dung on encourages investors to apply local technologies for solid waste treatment). In HCMC, brand-new or second-hand spare parts are available for popular equipment such as engines and pumps. The equipment is imported from the regional market at low prices but is not of high quality. Some technical equipment can be produced locally. Currently, some composting factories[18] and small incineration plants[19] are built in Viet Nam using locally made equipment or spare parts.

4.2.4 Technologies should be affordable to the cities

The costs of the solid waste management are equal to the overall gross costs minus the overall financial benefits. The gross costs of MSW treatment depend on the type of technology applied. The financial benefits are to a high degree determined by the effective demand for end products of the solid waste management systems on the local markets.

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[18] The information was collected during the site visit at Nam Thanh and Thuy Phuong composting plants and Humix fertilizer company in 2007.

[19] The information from personal communication with Dr. Lu, he is current (2011) a leader in the field of small scale incineration processing in HCMC.

The market for recyclable waste is big and active in Vietnamese cities but the quality of the products is often low (Ha 2006). New technologies should lead to a higher quality of the end products. Such quality increase is expected to improve marketability but also leads to higher product prices. Here, two products of MSW treatment are specifically discussed in some detail: electricity and compost.

At the moment (in 2010) the costs of electricity in HCMC are low at approximately 281 - 3,193 VND/kWh (1.4 - 16 cent USD/kWh) depending on the type of consumer (domestic, production & service) and time slot (normal hours, off or peak-hours)[20]. It would be helpful for the saving of energy, the stimulation of private investment in energy projects and the generation of green electricity to increase the price with special support to renewable energy sources. In 2010, HCMC encouraged investment in electricity production and was considering an increase of the price from 4 to 8 cent USD/kWh[21].

In the domain of agriculture an increase in the demand of compost is expected. Therefore technologies that produce high quality compost products could be attractive. The current price of compost in the market around HCMC is about 30 - 35 USD/ton (Vietstar Company 2011). The market in Viet Nam does not accept some of the available compost products due to a low quality and a high content of debris (needle, glass, rock) and sometimes also pesticides and insecticides (Giac Tam et al. 2006). The Ministry of Agriculture and Rural Development has formulated quality standard number 10 TCN 526-2002 for compost produced from MSW (MARD Viet Nam 2002). However, this standard is difficult to apply. For example, the standard has a lack of specifications regarding the acceptable presence of impurities like glass, plastic, rock, while the standards for heavy metals are very strict. Notably, there are no standards for the main product (liquid digestate) from anaerobic digestion processes. Therefore, this liquid digestate is not allowed as a fertilizer. When this residue is discharged it has to comply with the Vietnamese wastewater discharge standards, which makes the entire wet anaerobic digestion process very expensive. Presently, in a tentative way, it may be inferred from a publication of DONRE HCMCc (2009), that the net treatment costs (including benefits) in 2010 should be lower than 17 USD/ton MSW.

4.3 Composting technology

4.3.1 Introduction

Composting of MSW is an aerobic process where microorganisms, in an oxygen environment, decompose organic wastes as follows (Kiely 1996, p.657):

$$\text{Organic matter} + O_2 \rightarrow \text{new cells} + CO_2 + H_2O + NH_3 + SO_4.$$

Some references speak of aerobic and anaerobic composting. However, in this chapter, we classify these two biological technologies as (aerobic) composting and anaerobic digestion.

A composting process converts only the biodegradable organic matter of MSW. The organic fraction of MSW (OFMSW) is also named biowaste. The compost is a good soil conditioner as it improves the soil moisture retention, but it is a poor fertilizer (Salvato et al. 2003). The compost can be used as raw material for production of organic fertilizer (Vietstar Company 2010)[22]. It can be used for soil remediation, leveling, landscaping, etc. From the point of view of MSW management, composting of MSW does not only aim to produce compost but also to reduce the volume of MSW by about 50% (Diaz et al. 2002, p.12.1) and to convert pollutant organic matter

[20] Website of HCMC Power Cooporation (http://www.hcmpc.com.vn).
[21] Website of HCMC Power Cooporation.
[22] Survey at Vietstar composting plant in HCMC, VN in 2009.

into non-harmful matter. The presence of toxic substances such as pesticides, heavy metals, and pathogens in compost must be controlled to ensure its applicability.

Although composting has some disadvantages, such as emissions to the environment (especially odors), it becomes more and more popular due to the fact that it is a cost-effective and environment-friendly way of organic solid waste management. Increased solid waste generation and a decrease in available space for landfills have resulted in an increased demand for technologies that use less land, among which composting technologies. In recent years, composting technology seems to have emerged as the only solution for OFMSW in most of the cities and provinces in developing countries, like Viet Nam. Nevertheless, composting plants often have failed or their products could not be marketed. The strengths and weaknesses of composting technologies are summarized in table 4.1.

Table 4.1 Strengths and weaknesses of composting technology.

Strengths	Weaknesses
- Organic fraction of MSW can be stabilized via composting technology; - It can reduce the volume of OFMSW by 20 - 50%; - Composting can be performed with simple technology and standard equipment; - Composting technology has lower investment and operation costs compared to other technologies like anaerobic digestion and incineration; - Compost is a valuable product. It can be used for many applications, such as raw material for organic fertilizer processing, soil remediation, leveling, etc; - Composting has potential in co-composting of other waste streams, e.g.: paper, sewage sludge; - Composting reduces the quantity of organic wastes discharged at landfills. Therefore, it reduces the pollution caused by organic wastes in landfills, such as gaseous emissions and leachate; - Composting needs less land as compared to sanitary landfills.	- Composting has a high potential for odor and leachate production; - Composting only converts the organic fraction of the waste stream and it is sensitive to toxic compounds; - The market for composting end product is sensitive. It depends on the quality of the compost, the demand for organic fertilizer and other usages (construction material, leveling, combustion material, etc); - The composting end product is sensitive to contamination by glass and plastics. Therefore it requires careful source segregation or further post–treatment; - Products of co-composting MSW and manure are not always accepted in agriculture; - The land requirement for composting is high compared to anaerobic digestion or incineration. - Disposal of non-compostable residue needs a landfill; - Composting technology is more difficult and expensive for MSW with high moisture content.

References: Vietstar company (2010), Kim Oanh et al. (2007), Diaz et al. (2002, p.12.1), Salvato et al. (2003), Cheremisinoff (2003, p.66-80), Tchobanoglous et al. (1993, p.684-697), Hartmann and Ahring (2006), Waste-C-Control (2011), Baldasano and Soriano (2000) and Economopoulos (2010).

4.3.2 Technology

Composting is a process where OFMSW is converted by active organisms in a warm, moist environment and in the presence of oxygen. The active organisms include: bacteria, actinomycetes, fungi, protozoa, worms, and larvae (Diaz et al. 2002, p.12.3). Composting of MSW includes three steps: (1) Separation, (2) Biological conversion and (3) Post-processing.

- During the separation step the OFMSW is separated from (commingled) MSW and additions may take place to control some composting process parameters such as moisture, pH, C/N, inoculate (if necessary).

- The biological conversion is the main process. Microorganisms convert organic matter under aerobic conditions. The critical parameters in the control of the composting process include moisture content, pH, and C/N ratio which have optimum ranges of 50 - 60%, 6 - 8, 25 - 50, respectively. Composting may occur under mesophilic or thermophilic temperature conditions. However, in order to kill pathogens in MSW, the temperature during the biological process is controlled at 50 – 60°C for at least 3 days. If, however, the temperature rises beyond 66 °C, the biological activity is reduced significantly (Tchobanoglous et al. 1993, p.687). The supply of air satisfies the oxygen demand, removes water and regulates the temperature in the heap of OFMSW. The air requirement depends on the type of organic matter. The oxygen concentration in the heap should remain at least at 50% of the initial oxygen concentration, so that oxygen may reach all parts of the composting material (Tchobanoglous et al. 1993, p.687).
- Post- processing is used to mature and polish compost end products for marketing. Composting plants may include activities such as processing compost to organic fertilizer products and packaging.

Instead of using pre-separated OFMSW as initial raw material, compost may also be produced by directly applying commingled MSW to the biological conversion process. Residues are then removed from the end product after the biological process. Separation of rejects before or after the biological process has its own advantages and disadvantages. Figure 4.1 shows mass balance of MSW composting.

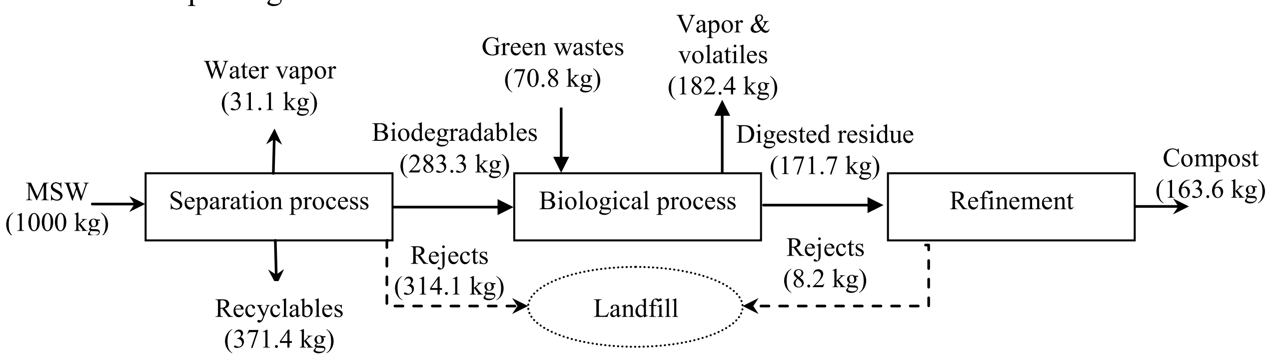

Figure 4.1 Mass balance of MSW composting.
Source: Economopoulos (2010).

A composting plant includes in addition: (1) an air emission control system consisting of an air pollution (mainly odor) collection and treatment system; (2) a leachate treatment system. The leachate is partially re-circulated to (re)balance the moisture content in the biological process since the moisture content in the organic matter decreases during the biological process. The rest is treated in a leachate treatment plant to reach the discharge standards of the local government.

There are three main composting technologies: (1) windrow composting, (2) aerated static pile composting and (3) in-vessel composting. The mass balance of composting is more or less the same for these three technologies but depends on the characteristics and composition of the waste input. Scheme of the composting process is presented in figure 4.2.

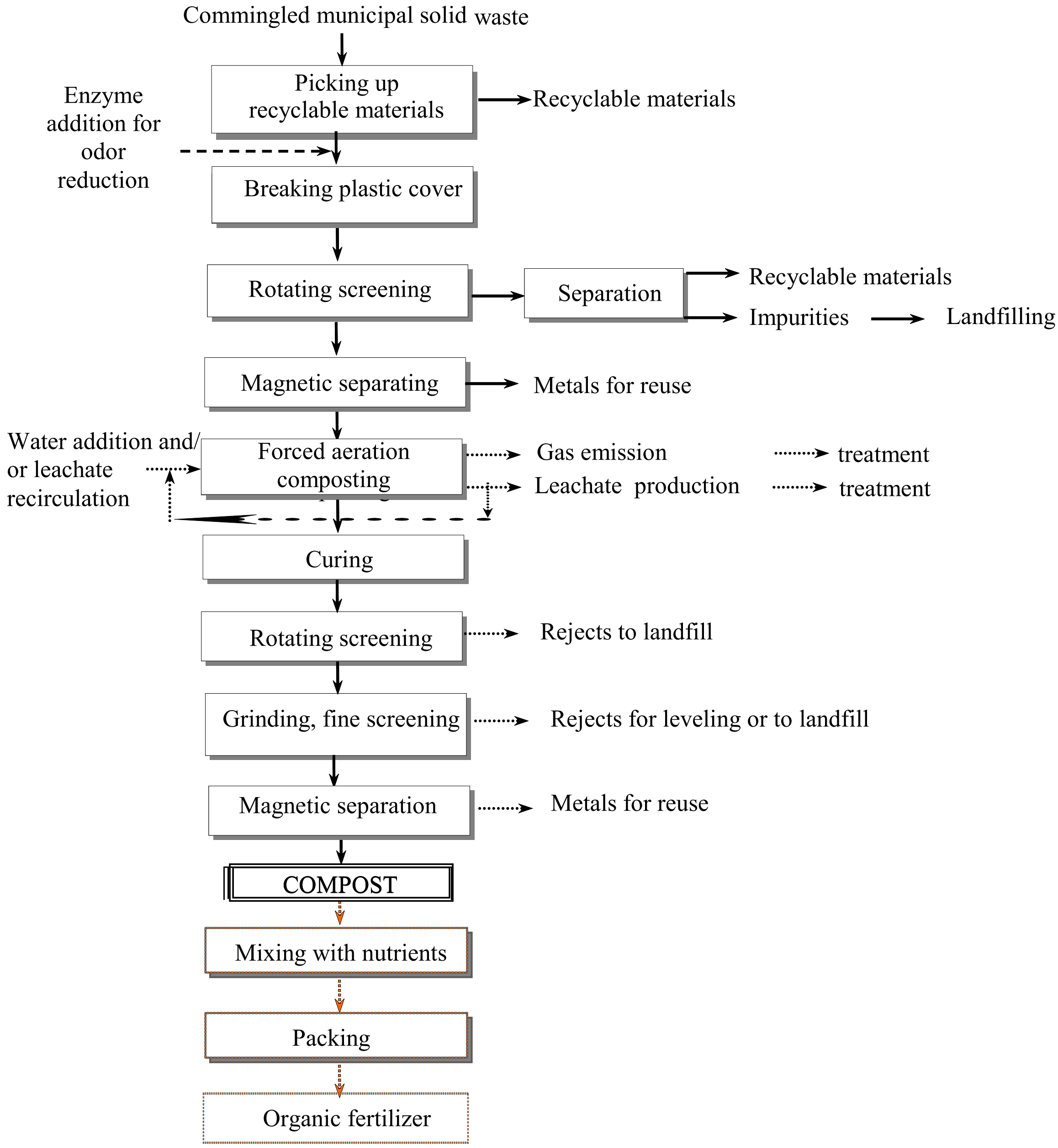

Figure 4.2 Scheme of the composting process.
Source: Giac Tam et al. (2006).

Windrow composting. In the windrow process, the OFMSW is placed in elongated piles. The windrow process is designed normally to operate in uncovered pads and relies on natural ventilation with frequent mechanical turning of the piles to maintain aerobic conditions. Turning consists of tearing down and reconstructing the windrow. Those activities do not only supply oxygen for aerobic conversion, but also make the waste more homogeneous and spongy creating a good environment for the biological process. Turning helps to transport the solid waste particles from the outer to inner layers of the windrow piles where there is a temperature sufficient for pathogen die-off. Turning also reduces the temperature when it increases beyond the required temperature (54-60^{o}C) (Diaz et al. 2002). The frequency of turning strongly depends on the design and equipment of the windrow composting technology applied and is primarily based on the rate of oxygen uptake. In general, this windrow composting is simple but the turning activities cause high emissions and loss of nitrogen in the compost end product. The nitrogen is lost via emission of N_2O and NH_3. Since air supply is sub-optimal, the complete process of windrow composting may require not less than 8 - 24 weeks for biological conversion and about a month for the maturing process (Salvato et al. 2003). The advantages and disadvantages of windrow composting are presented in table 4.2.

Table 4.2 The advantages and disadvantages of windrow composting.

Advantages	Disadvantages
- Capital and operation costs are relatively low. Capital costs increase if the system is housed in a building and uses more advanced windrow turning systems. Even so, turned aerobic windrowing is the lowest costs option. - The technology is fairly simple and standard equipment can be used. This helps to keep costs low and ensures that operators are rapidly familiar with the equipment. - During the mixing activities, moisture and temperature inside the piles can be controlled.	- The processing time of windrow composting is longest and consequently land use is highest among the three composting technologies. - If applied outdoors, the system lacks control over the environmental conditions (e.g.: rain, temperature, wind direction). These conditions may have a negative impact on the composting operation. The time required for composting may increase if the weather is cold or wet or turning cannot be conducted due to the wind direction. - European countries characterized by a low rainfall and low moisture content in the OFMSW can compost outdoors and directly on a floor of soil. But in countries with a high rainfall and high moisture content of the OFMSW, composting outdoors is almost impossible. Therefore, windrow composting in such areas should be done indoors, which increases the investment costs. - The main problem of windrow composting is air supply. Therefore, in many cases MSW is mixed with other materials called structure materials to improve the air supply. This enlarges the volume of windrow piles and therefore the land need. - As process conditions cannot be controlled, there is a relatively great potential for the formation of malodors.

References: Diaz et al. (2002, p.12.1), Salvato et al. (2003), Cheremisinoff (2003. p.66-80), Tchobanoglous et al. (1993, p.684-697),Golder Associates (2009) (Haaren et al. 2010) and Waste-C-Control (2011).

The land requirements for windrow composting plants are approximately 2.5 acres (1.05 ha) for a plant with a capacity of 50 tons/day (14,300 ton/ha/year) and for every additional 50 ton/day (15,000 tons/year) the land requirement is about 1 acre (0.42 ha) for the composting process and about 0.25 acre (0.10 ha) for buildings (Tchobanoglous et al. 1993, p.695-696). These figures include space for curing and stockpiling. Golder Associates (2009)[23] report a land use range of 0.5 – 1.0 m^2/ton/year, which is 10,000 – 20,000 ton/ha/year. The energy requirement of windrow composting amounts to 29 kWh/ton yard waste consisting of 20.59 kWh/ton of fuel and 8.41 kWh/ton electricity (Haaren et al. 2010).

Aerated static pile composting

In the aerated static pile process, the OFMSW is placed in a pile or a bin and air is provided by a mechanical aeration system. Air is either blown into or sucked through the composting material. Typically, air is provided by pulling air through the pile with an exhaust fan. Similar to windrows, static piles are often located outside and exposed to weather but can be covered with a roof to

[23] Adopted from http://www.epem.gr/waste-c-control/database/html/Composting-02.htm.

minimize the impacts of weather and provide an opportunity for odor capture and treatment. The advantages and disadvantages of aerated static pile composting are presented in table 4.3.

Table 4.3 The advantages and disadvantages of aerated static pile composting.

Advantages	Disadvantages
- The conversion time in aerated static pile composting is shorter as compared to windrow composting with about 3 to 4 weeks and the maturing process about a month (Salvato et al. 2003). - Smaller footprints compared to windrow composting. - By controlling air injection, the temperature in the pile is also kept at an optimum level for the biological process and for killing pathogens. - As there is no mechanical turning, labor costs are lower than in windrow composting. - Odor emissions are lower as there are no mixing activities. - Similar to windrow composting, this technology can be carried out indoors or outdoors depending on the climate at the site.	- Investment costs are usually higher than for windrow composting. - The air supply system needs much maintenance. - Moisture content inside the piles is difficult to control as there is no turning. - The compost end product is less homogeneous. To overcome the disadvantages of windrow and aerated static pile composting many composting plants combine both technologies.

References: Diaz et al. (2002, p.12.1), Salvato et al. (2003), Cheremisinoff (2003, p.66-80), Tchobanoglous et al. (1993, p.684-697), and Waste-C-Control (2011).

The land requirement of aerated static pile composting is about one hectare for a capacity of 14,000 ton /year (Vietstar Company 2010). Renkow (1993) found that aerated static pile composting can treat about 20,000 ton/ha/year. Hartmann and Ahring (2006), Baldasano and Soriano (2000) and Economopoulos (2010) calculated that the electricity consumption for composting is 30-35 kWh/ton MSW. Fricke et al. (2005) determined the electricity needs of aerated stated in the range of 30-60 kWh/ton OFMSW.

In-vessel composting

In the in-vessel process, the OFMSW is placed in an enclosed vessel. Many types of vessel have been used as a reactor in these systems, including vertical towers, horizontal rectangular and circular tanks, and circular rotating tanks. The mechanical system is designed to yield the best environmental conditions, particularly aeration, temperature, and moisture content. Most in-vessel systems use forced aeration in combination with mixing or tumbling. All parameters of the aerobic conversion process are kept at an optimum level and are not affected by external conditions. Besides, emissions to the atmosphere or leachate are also under control. Off-gases are scrubbed and treated before their release to the atmosphere. Because the process conditions are much more controlled the composting units can be sited near residential or commercial zones reducing transport costs. Due to the more advanced biological treatment step, the whole conversion needs only 1 to 2 weeks (Salvato et al. 2003; Le 2009). The advantages and disadvantages of in-vessel composting are presented in table 4.4.

Comparison of in-vessel composting with aerated static pile and windrow composting shows that in-vessel composting produces better compost products in a shorter time with lower emissions to the environment. However, it is a complex technology that is more expensive in investment and operation. Nowadays, there are many composting plants that combine the three technologies: in-vessel composting is applied for the first intensive stage of the composting process and the aerated or windrow composting for maturation.

Table 4.4 The advantages and disadvantages of in-vessel composting.

Advantages	Disadvantages
- Improved process control is achieved. - Malodor problems will not cause an environmental risk. - The process is faster; therefore, small footprints are achieved. In-vessel plants can be sited in locations such as factory yards to treat commercial waste at the site of production. - The quality of compost is higher due to a more homogeneous structure, more complete maturation and better possibility to control of pathogens.	- High capital investment. - The system requires a higher level of maintenance leading to higher operation costs than aerated static pile composting. - Each unit is limited in its throughput. If the quantity of incoming feedstock increases, there is little operational flexibility. This makes the system less flexible.

References: Salvato et al. (2003), Le (2009), Cheremisinoff (2003, p.66-80), Tchobanoglous et al. (1993, p.684-697), Waste-C-Control (2011) and Renkow (1993).

The treatment capacities of in-vessel composting plants in the past 15 years were mostly below 100 tons/day (Renkow et al. 1993; Davis and Kincaid 1996). However, presently there are many in-vessel composting plants with higher capacities. Due to the longer treatment time, the land use for aerated static pile composting is about 1.5 - 1.6 times higher than for in-vessel composting. Therefore, based on this ratio and also the data of Renkow (1993), the land use of in-vessel composting is estimated at about 30,000 ton/ha/year. Another source mentions somewhat lower (12,500 – 20,000 ton/ha/year) or higher specific capacities of 50,000 - 100,000 ton/ha/year[24]. The energy requirement for in-vessel composting is about 55 kWh/ton[25].

4.3.3 Financial, social and environmental aspects

The economics of composting is determined by: (1) The costs related to the facility such as capital, operation and maintenance costs, (2) The costs of disposal of residues and marketing of products, (3) The benefits from sale of products, collected tipping fees, avoided costs of environmental damage. The capital costs of windrow or aerated piles are lower than those of in-vessel composting. However, the costs increase markedly when covering is required to control odors and to protect against heavy rainfall. In general, the capital costs of in-vessel systems are the highest compared to the other two techniques. In addition, in-vessel composting is more mechanized and needs more maintenance. The enlargement of the capacity of windrow or aerated static pile composting plants is rather easy compared to in-vessel composting.

As already mentioned, the composting process reduces the volume of MSW significantly. It stabilizes organic matter and recovers resources from MSW. Therefore, it reduces the land required for landfills and also reduces the pollution from landfills. Compost end products can be used as fertilizer for agricultural soils. This practice can be extremely important in order to decrease the amounts of chemical fertilizers used.

Composting practices emit different gases: greenhouse gases, volatile organic compounds and odors. The major concern regarding soil and water systems is the leaching of salts and heavy metals from polluted compost.

[24 &24] http://www.epem.gr/waste-c-control/database/html/Composting-04.htm, down load date 03/06/2012

4.3.4 Possibility to apply composting in Ho Chi Minh City, Viet Nam

All three composting technologies discussed above are applied in Viet Nam. Qui Nhon and Tan Thanh composting plants and many other medium and small-scale plants use windrow composting. Vietstar, Cau Dien, Nam Dinh and Dong Vinh composting plants apply aerated static pile composting, while in-vessel composting can be found at the Vu Nhat Hong composting plant since 2007.

There is currently one composting plant in HCMC, named Vietstar, with a capacity of 1,200 ton (commingled) MSW/day. Another composting plant, named Tam Sinh Nghia, is under construction. Therefore, the total capacity of composting in HCMC will soon be 2,200 ton/day. Besides, according to the planning of the Viet Nam Waste Solution company, one more composting plant will be set up in the near future with a capacity of 500 ton MSW/day. At the end of 2012, the Phuoc Hiep 2 landfill will be closed. Another landfill or other technologies are needed to treat the remaining amount of MSW (3,000 ton/day). Besides, the amount of MSW in HCMC is increasing by about 6 - 8%/year (DONRE HCMCa 2009). Therefore, composting may be a good option for this situation. However, the potential of composting depends not only on production costs but also on the market demand for the product. Based on Tam, Xo et al. (2006), there is not much data about the compost market because this type of compost is a new product in Viet Nam. However, the requirement of organic fertilizer is high and going up quickly which is a good prospect for selling compost.

Most of large scales composting plants in Viet Nam apply aerated static pile technology. The composting process in Viet Nam is more or less similar to that used in Europe or the US. The main differences between Viet Nam and Europe or the US are[26] (Giac Tam et al. 2006): (1) The input material for composting in Viet Nam is commingled MSW. Therefore, the composting process in Viet Nam must include a complex separation process. In developed countries a simple separation process is applied if necessary, because the MSW is separated at the source. (2) All aerated composting piles in Viet Nam should be located indoors to protect the piles from heavy rain. In developed countries the composting piles are often outdoors. (3) The MSW in HCMC has high moisture content and the temperature in HCMC is tropical. These circumstances cause negative environmental impacts from a large volume of leachate and odor emissions. These differences make the composting process in Viet Nam relatively expensive. However, low labor costs, an increasing number of local construction firms with low priced equipment, a high demand and a relatively high price for compost end product could compensate for the disadvantages.

Windrow composting is the simplest technology with a long processing time, and a high land use. As we deal with a large volume of MSW in HCMC and a lack of land, windrow composting is, however, considered unfeasible and therefore omitted from the technology options for HCMC.

4.3.5 Conclusions

Among the composting technologies aerated static pile and in-vessel composting were selected as feasible technologies, while windrow composting is regarded inappropriate due to the high need of land. The selected composting technologies may be feasible solutions for MSW treatment in HCMC, since:

- MSW in HCMC has a high fraction of organic material, suitable for biological conversion.

[26] The information of composting process in Viet Nam was collected via the Biowaste reuse in South East Asia project in 2006-2007. The information of composting process in Europe was collected via the ADDA project between Van Lang University and Weima University in 2004-2006.

- The stable mesophilic ambient temperature is favorable for composting;
- The potential agricultural demand for organic fertilizers and soil conditioners in the surroundings of HCMC is huge and exceeds the actual supply by far;
- Compost has a high potential as raw material for organic fertilizer processing;
- Composting is a flexible, relatively simple and inexpensive technology.

In order to further assess whether the aerated static pile and/or in-vessel composting are suitable for HCMC more information is needed, such as:
- Costs analysis based on the situation of HCMC, such as: fixed and operation costs, product quality, product quantity, product prices, market requirements for compost, energy and fuel requirement;
- Costs comparison with other MSW treatment technologies;
- Environmental aspects, such as: electricity use, land use, discharge management and control, product quality and monitoring;
- Future environmental regulations: if the (avoided) costs of prevention of environmental damage are included, the preference for in-vessel composting will increase.
- Social aspects such as compatibility with local regulations and the availability of skilled personnel.

4.4 Anaerobic digestion technology

4.4.1 Introduction

Anaerobic digestion is the process in which anaerobic microorganisms digest biodegradable organic matter in the absence of oxygen. The products are biogas and digestate. Biogas is a mixture of methane (55 – 75 vol%) and carbon dioxide (25 – 45 vol%) that can be used for heating, upgrading to natural gas quality or co-generation of electricity and heat. Anaerobic digestion can be used directly to digest the OFMSW. However, the process might be more effective if the input were a mixture of OFMSW with other feedstocks (sludge, liquid waste, pig or cow manure, etc). Such digestion of mixtures may improve the environmental and economic aspects of the process significantly and has been applied in many anaerobic digestion plants. A requirement is that these feedstocks do not contain toxic organic and too much inorganic material. In many developed countries, certain organic waste streams can be introduced for co-digestion taking into account the legislation concerning the use of digested substrate in agriculture. In particular, the risk caused by heavy metals in the digested substrate has to be controlled.

Anaerobic digestion is now regarded as a fully demonstrated technology for the treatment of OFMSW and mixtures of OFMSW and other organic wastes. It can be expected that the growth of anaerobic digestion applications will continue (De Baere 2006). The installed anaerobic digestion capacity in Europe has increased sharply. By the end of 2010, the expected installed anaerobic digestion capacity to treat mixed MSW and source separated biowastes will be about 6 million tons/year divided over 200 plants in 17 European countries (Baere and Mattheeuws 2010). The energy potential of all types of waste to be treated with anaerobic digestion in Europe was estimated at 5,300 - 6,300 MW and was worldwide up to 20,000 MW by 2010 (De Mes et al. 2003). New legislation to improve waste management and production of sustainable energy as well as improvements of technical efficiency may contribute to a broader application. Among others these are the climate change levy[27], the Integrated Pollution Prevention and Control (IPPC)[28], the Landfill Directive[29]. Strengths and weaknesses of anaerobic digestion technology are presented in Table 4.5.

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[27] http://en.wikipedia.org/wiki/Climate_Change_Levy, downloaded date 22/8/2011
[28] http://ec.europa.eu/environment/air/pollutants/stationary/ippc/index.htm, downloaded date 22/8/2011

Table 4.5 Strengths and weaknesses of anaerobic digestion technology.

Strengths	Weaknesses
- Anaerobic digestion technologies offer 50 - 75% reduction in the total volume of materials and its residue has potential in agriculture as compost; - The biogas production from OFMSW or its mixture with other feedstocks (septic sludge, pig manure, etc) amounts to 80 – 200 m^3 per ton input in wet weight. - Digested substrate can be dewatered and aerobically composted to be become a compost product with about 50% in the initial OFMSW wet weight or about 25 - 30% of commingled MSW wet weight in HCMC; - The recovery of nutrients makes anaerobic digestion highly superior to incineration and landfill technology in the context of a sustainable waste treatment concept; - Anaerobic digestion has the potential to treat the wet fraction of MSW that is less amenable to incineration and composting; - Other benefits of anaerobic digestion are more difficult to measure in terms of costs, like the lower land requirement than landfills and windrow composting and the higher opportunity of recycling with a usually better end product. - Anaerobic digestion projects often qualify for financial support in the framework of the CDM program.	- The anaerobic digestion process is unable to degrade lignin which is a major component of wood; - Anaerobic digestion requires a high investment and comes with high operation and maintenance costs; - Anaerobic digestion is a more complex technique compared to composting; - The residue from the anaerobic digestion process is not completely stabilized yet. Therefore, it needs to be composted or otherwise treated to reach the standard of pollution control or deliver a salable product; - The aerobic digestion of the digestate of anaerobic digestion can be less effective for pathogen removal than aerobic digestion of MSW directly.

References: De Baere (2006), De Mes et al. (2003) , Hartmann and Ahring (2006), Kim Oanh (2009), Joshua et al. (2008), R-W-BECK (2004), European Commission (2006), Tchobanoglous et al. (1993, p.701-713) and Waste-C-Control (2011).

4.4.2 Technology

Similar to composting, the anaerobic digestion technology for MSW includes three steps: (1) Preparation or separation process, (2) Anaerobic biological conversion process, and (3) Post-processing. The main difference with composting technology is that the biological process takes place in the absence of oxygen.

- The separation step in anaerobic digestion technology is similar to the one used in the composting technology (see 4.2.2). In the separation step undigestable components are removed from MSW (in case of commingled MSW), material may be added and some parameters be controlled such as moisture, pH, C/N, inoculate (if necessary). Separation can be carried out under wet or dry conditions; but with MSW it occurs mostly in dry condition. Subsequently, MSW or the mixture of MSW with other feedstocks are reduced with regard to size and mixed to obtain a homogeneous feed for anaerobic digestion processing. In most

[29] http://en.wikipedia.org/wiki/Landfill_Directive, downloaded date 22/8/2011

anaerobic digestion applications MSW needs the separation step to purify the OFMSW. Only batch anaerobic digestion technology can digest commingled MSW without pre-treatment.

- Anaerobic biological conversion is a process in which micro-organisms derive energy and grow by metabolizing organic material in an oxygen-free environment resulting in the production of methane (CH_4) and carbon dioxide (CO_2). The anaerobic digestion occurs in a four-step process, including hydrolysis, acidogenesis, acetogenesis and methanogenesis. In general, the optimal conditions for anaerobic digestion of organic matter are near-neutral pH, constant temperature (thermophilic or mesophilic), and a relatively stable feeding rate (Joshua et al. 2008).
- Post-processing of anaerobic digestion technology includes two activities: (1) Biogas treatment to get a good quality of biogas for electricity generation, (2) An aerobic composting process which converts digested residue to compost.

Figure 4.3 shows the scheme of anaerobic digestion process. In the anaerobic digestion scheme MSW is separated to select the OFMSW before it goes to the anaerobic biological process (similar to the composting process). Collected biogas will be treated to improve the quality for electricity generation. Residue is processed under aerobic conditions to produce compost.

According to a study of the European Commission (2006) dry digestion needs about 78 liters of water and about 50 - 55 kWh to process 1 ton of OFMSW (wet weight) in European countries. The electricity could be generated at the installation itself. For the case of developing countries those requirements will be much lower due to the high moisture content of OFMSW and also the tropical conditions in which no heat has to be supplied unless thermophilic conditions are applied.

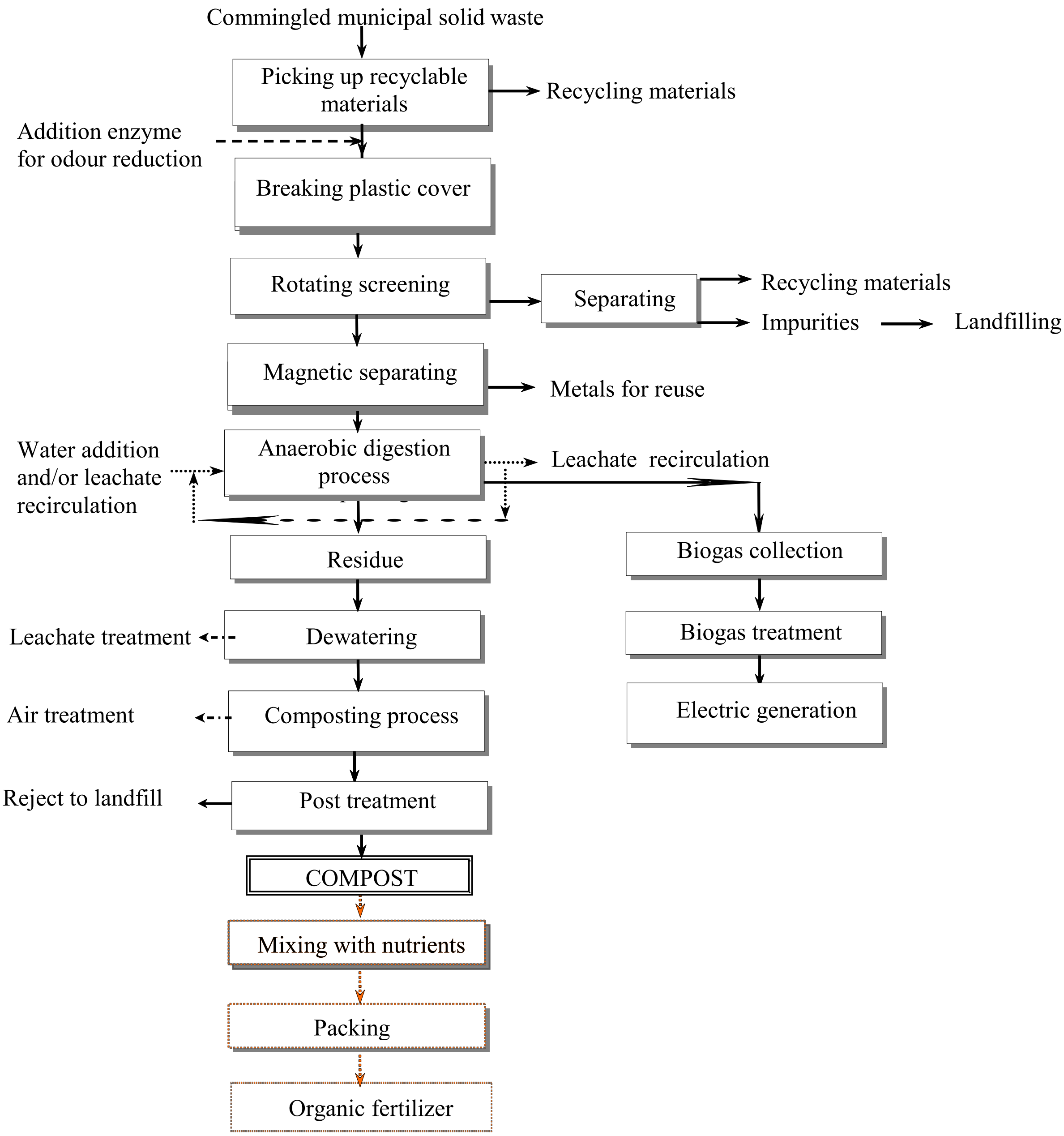

Figure 4.3 Scheme of the anaerobic digestion process.

Figure 4.4 shows the schematic overview of the various digestion systems available for MSW. Several authors categorized the most common MSW anaerobic digestion technologies: (1) Wet versus dry anaerobic digestion systems, (2) Continuous systems versus batch systems, (3) One-stage versus two-stage anaerobic digestion systems, and (4) Mesophilic versus thermophilic anaerobic digestion systems. Different anaerobic digestion technology suppliers use various combinations of these four processes (Vandevivere et al. 2002; De Mes et al. 2003; Hartmann and Ahring 2006).

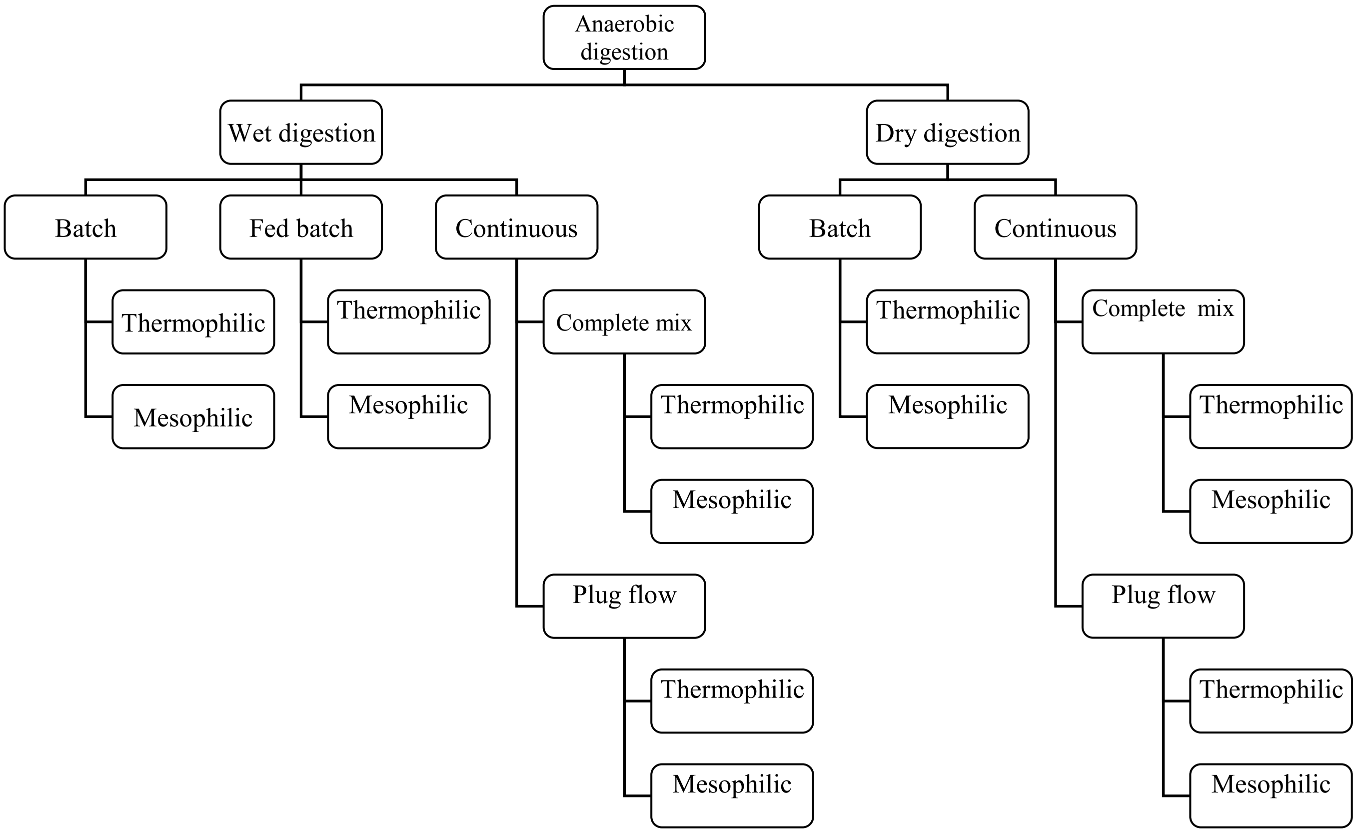

Figure 4.4 Schematic overview of digestion systems for MSW.
Source: De Mes et al., (2003).

(1) Wet versus dry anaerobic digestion systems

Total solid (TS) concentration in the anaerobic reactor is an important parameter, expressed as a fraction of the wet mass of the prepared feedstock. Based on TS concentration, the anaerobic digestion technologies can be divided into two groups: wet or dry anaerobic digestion technologies. Technologies working with a feedstock having a TS content higher than 15 – 20% are considered dry and if TS is less than 15% they are considered wet (Tchobanoglous et al. 1993, p.687). Anaerobic digestion is suitable for waste with a low TS content. The process of anaerobic digestion can occur in the range of 1% (wastewater) to 40% TS. With higher TS values both the ammonium inhibition of the anaerobic digestion process and the salt toxicity increase (European Commission 2006). Since the OFMSW is a substrate with a high-solids content of about 30% TS, the simplest treatment process for the OFMSW alone is the high-solids treatment process (Hartmann and Ahring 2006). Dry digestion had a share of 54% of the total capacity of European countries by the year of 2000 (Joshua et al. 2008). According to another survey out of more than 130 large anaerobic digestion plants roughly two-thirds (87/130) of the plants were wet digesters, while the remaining plants were dry processes (R-W-BECK 2004).

(2) Continuous systems versus fed batch systems

In a continuous system feedstock enters and digestate leaves the anaerobic digestion reactor continuously. In batch systems the reactor is filled at a certain moment and the digestate is collected after the digestion time. As a consequence, the biogas production in continuous systems is stable in time. In batch systems, the biogas production is high at the beginning of the process and decreases after that.

(3) One-stage versus two-stage (or multi-stage) anaerobic digestion systems

Two-stage systems are designed to take advantage of the fact that different portions of the overall biochemical process have different optimal conditions. By optimizing each stage separately, the overall rate can be increased (Joshua et al. 2008; Liu and Ghosh 1997). In the two-stage process, the first stage optimizes the hydrolysis of complex carbohydrates and the second stage the methanogenesis. The two-stage is more flexible than the one-stage process. However, it is more expensive and complex by requiring an additional reactor and process control systems. Due to the added costs the market share of two-stage systems is limited. Two-phase digestion has, so far, not been able to capture a sizeable market share (De Baere 2000). About 90% of the full-scale plants for anaerobic digestion of the OFMSW in Europe at this moment are based on one-stage systems. The large number of one-stage reactors is mainly due to the relatively simple design compared to two-stage or multi-stage systems, less frequent technical failures and lower capital costs. One-step wet systems are primarily designed to co-digest the source separated OFMSW with liquid substrates such as sewage sludge or manure. They are not typically used for the anaerobic digestion of just OFMSW (R-W-BECK 2004).

(4) Mesophilic versus thermophilic anaerobic digestion systems

The rate of methane production in an anaerobic digestion reactor increases with temperature until a relative maximum is reached at 35 - 37^{o}C (mesophilic condition) (Lettinga and Haandel 1993; De Mes et al. 2003). Traditionally, anaerobic digestion was mostly applied in the mesophilic temperature range (Hartmann and Ahring 2006). Thermophilic digestion is especially suited when the waste is discharged at a high temperature or when pathogen removal is an important issue (De Mes et al. 2003) . In thermophilic digestion high organic loading rates can be applied. In general, the higher the temperature the faster the process, but the thermophilic process may be harder to control and will need more biogas for heating to the required temperature. Thermophilic digestion may not be useful for all applications due to the fact that adaptation of micro-organism communities to the degradation of chlorinated aromatic compounds or dechlorination of specific xenobiotica cannot be achieved under thermophilic conditions (European Commission 2006).

Table 4.6 Technical data of the four most important anaerobic digestion technologies.

Technology	**Valorga**	**Dranco**	**Kompogas**	**Biocel**
Country of origin	France	Belgium	Switzerland	Netherlands
System	Semi-continuous	Semi-continuous	Semi-continuous	Batch
Total solid content of input (%)	30	15 - 40	High solids	30 - 40
Applied temperature	Mesophilic	Thermophilic	Thermophilic	Mesophilic
Mixing system	Reverse-circulation	Downward plug-flow	Horizontal plug-flow	None (only recirculation of percolate)
Retention time (days)	18 - 25	15 - 30	15 - 20	21
Biogas (m^3/ton wet material)	80 - 160	100 - 200	110 - 130	70
Digestate post-treatment	Incineration	Composting	Composting	Composting

Sources: Ten Brummeler (2000), De Mes et al. (2003) and Joshua et al. (2008).

In table 4.6, technical data are presented of representative dry one-stage anaerobic digestion technologies that are mostly used for MSW. Only the Biocel technology is a batch system and the others are semi-continuous systems. Based on the comparison of De Mes et al. (2003) the semi-continuous Valorga, Dranco and Kompogas technologies have comparable investment and treatment costs. Therefore, in our discussion about the technical aspects of anaerobic digestion technologies, we focus on two technologies: Biocel and Valorga, in which the first is a relatively inexpensive batch technology and the second a representative of the other semi-continuous technologies (Dranco and Kompogas).

Biocel technology

The Biocel technology is an anaerobic digestion process for OFMSW operated as a batch system with recirculation of percolate. The process scheme of the Biocel technology is given in figure 4.3. The process in the Biocel digester runs at mesophilic conditions and at a total solids content of about 30 - 40%. The first full-scale Biocel plant was built in Lelystad, the Netherlands, with a capacity of 50,000 tons OFMSW per year (about 150 tons/day) (Orgaworld Company 2006). The plant in Lelystad comprises 14 rectangular concrete digesters, with a volume of 720 m^3 per digester (6 * 6 * 20 m). The filling height of the digesters is 4 m; the effective digester volume is thus 480 m^3. The floors of the digesters are perforated with a chamber underneath for leachate collection. The leachate is recirculated and sprayed over the top of the digester content. This evenly distributes moisture and controls the temperature at 30 – 40 ^oC. The fresh OFMSW is intensively mixed with digested waste from previous batches before being loaded into the digesters. Biogas is collected and transported continuously to a biogas treatment system and subsequently to a generator. The retention time of the OFMSW in the Biocel digesters is about 21 days[30]. The system is fully computer-controlled with equipment to check the gas phase composition and pressure before opening the digester doors and to measure the moisture content, pH and temperature in the digesters. The mass balance of the processing of OFMSW in the Biocel system in Lelystad is presented in figure 4.5 (Ten Brummeler 2000).

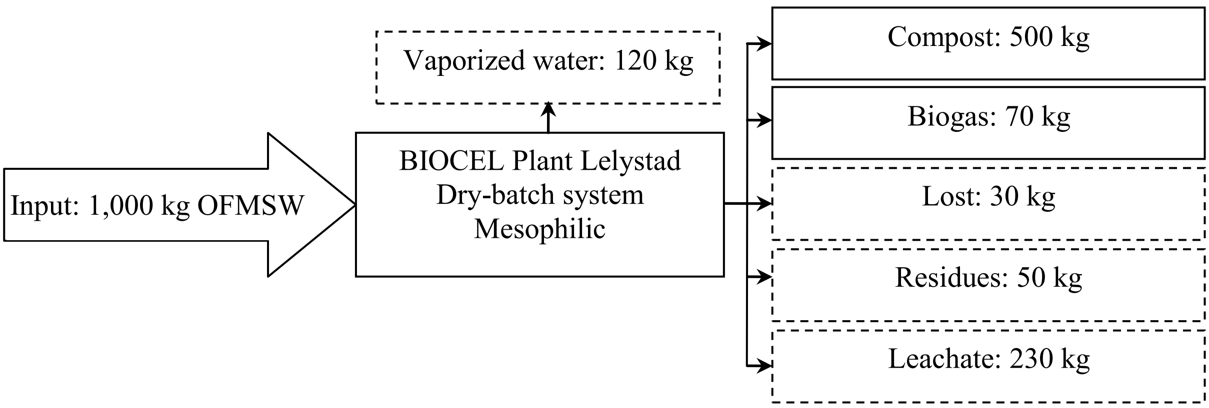

Figure 4.5 Mass balance of the Biocel plant in Lelystad, the Netherlands.
Source: Ten Brummeler (2000).

The biogas production of the Lelystad plant is 70 m^3/ton OFMSW (Joshua et al. 2008). There is no literature comparing the Biocel technology with other biological treatment technologies regarding heavy metal concentrations after treatment. In theory the heavy metal concentrations will not change very much in these biological processes. Some heavy metals might be removed with the leachate that is treated and discharged into the surface water or sewerage system. Another important characteristic of the digestate is the absence of pathogens. Some studies showed that mesophilic digestion could not completely reduce pathogens in the digestate (Ten

[30] Data collection on the survey at Lelystad Biocel AD plant in the Netherlands, October 27, 2006.

Brummeler 2000; De Mes et al. 2003; Hartmann and Ahring 2006). In Denmark, treatment of household waste at temperatures over 70 ^oC for 1 hour is required before the product can be used as fertilizer for consumable crops (Hartmann and Ahring 2006). However, the research of Ten Brummeler (2000) showed that there were no *S. typhimurium*, no *Pseudomonas solanacearum* and also no *Fusarium oxysporum* in the leachate after 21 days retention time in the Biocel process at mesophilic conditions.

There is no literature on the land use of the Biocel technology. Joshua (2008) estimated that the land use for the Biocel technology is 10 times higher than for other anaerobic digestion technologies like Valorga, Dranco or Kompogas. However, calculations based on the height of reactor and the digestion time of the technology show that the active height of Biocel is 4 m while the estimated active height of Valorga is about 12 m; the digestion time of Biocel is 21 days while the minimum digestion time of Valorga is 18 days. Therefore, the maximum land use for the Biocel digester is about 3.5 times higher than the land use for Valorga (land use is calculated only for operating the anaerobic digestion process, not for depositing residues). The area for the digester is about 20 - 30% of total area of the treatment plant. The total land use for Biocel is then about double compared to the Valorga technology. Assuming that a Biocel reactor with 4 m active height uses 20% of the total area of a treatment plant, the density of untreated MSW is 0.6 ton/m^3 and a complete treatment time (filling, anaerobic digestion, cleaning, post-composting) of 40 days, the treatment capacity is 43,800 tons of OFMSW per hectare per year. Economopoulos (2010) calculated the electricity use for anaerobic digestion of commingled MSW at 54 kWh/ton. With the Biocel technology the electricity requirement should be smaller due to less automated functions compared to the Valorga, Kompogas and Dranco technologies.

The Biocel technology can process commingled MSW. However, the feeding of commingled MSW with a bio-digestible fraction of 50% means that a Biocel system would need the double size which increases costs. In addition, the quality of digestate from unseparated MSW may be low and may not meet quality requirements.

The digested residue from anaerobic digestion technology can be dumped at a landfill, incinerated or composted. In the case of the Lelystad plant, digestate is composted by means of in-vessel composting technology to produce compost for agriculture. The composting process of the digestate from anaerobic digestion technology needs 7 - 14 days (Kim Oanh 2009; Orgaworld Company 2006).

Valorga technology

The Valorga technology is an anaerobic digestion process for OFMSW. It is a dry, semi-continuous process at mesophilic conditions. The difference between Biocel and Valorga is that the Valorga system is semi-continuous fed and uses a mixing system while Biocel is batch fed and applies recirculation of leachate to improve biological processes. The Valorga technology can be considered as more advanced. This causes higher investments costs compared to the Biocel technology. Biogas production from Valorga or other dry and semi-continuous technologies (Dranco and Kompogas) (80 -160 m^3/ton of wet weight) is higher than from the Biocel technology and the retention time in a Valorga system is approximately 18 - 25 days while this is approximately 21 days in a Biocel system (De Mes et al. 2003). The research of Joshua, Ruihong et al. (2008) showed that the capacities of Valorga plants varied from 10,000 to 720,000 ton/year. Based on data from a website, land use of the Valorga technology is about 1 m^2/ton[31] (or 10,000 tons/ha) for one batch retained in the plant for 40 days. If the number of operational days of the Valorga anaerobic digestion plant is 300 days/year (65 days are available for maintenance) then the land use is 75,000 tons OFMSW per year per hectare (10,000 tons

[31] http://www.mbt.landfill-site.com/AD/ad.html

capacity/ha * 300 day/year /40 day digestion time). The Valorga system needs about half the land as compared to the Biocel (75,000 vs. 43,800 ton OFMSW/ha/year). Similar to other anaerobic digestion technologies, the digestate from the Valorga technology can be composted, incinerated or deposited at a sanitary landfill. Figure 4.6 shows the mass balance of a Valorga plant based on OFMSW input.

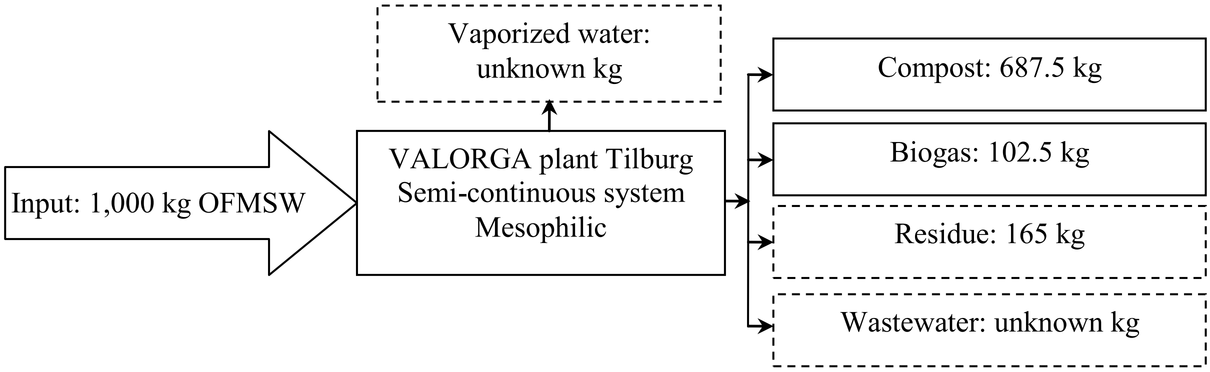

Figure 4.6 Mass balance of the Valorga plant in Tilburg, the Netherlands.
Sources: Laclos et al. (1997) and De Mes et al. (2003).

4.4.3 Financial, social and environmental aspects

The costs of anaerobic digestion technology includes: (1) The investment costs of digester, conversion biogas to electrical energy, composting of digestate and all infrastructure; (2) The costs of disposal of residues and marketing of valuable products, (3) The benefit from biogas (or electricity) and compost, and (4) Environmental costs and benefits. It is very difficult to compare technologies due to a lack of costing data. However, the experience of Orgaworld with the Biocel process showed that it is very competitive in terms of investment and operational costs (Bens 2007).

The number of anaerobic digestion plants has increased due to the fact that the technology satisfies the requirements of solid waste treatment and produces biogas and compost (De Baere 2006; Joshua et al. 2008). Costs analysis of anaerobic digestion technology in Europe showed that anaerobic digestion of MSW for different scales is increasingly competitive with composting (De Mes et al. 2003). The survey by R-W-BECK (2004) on Linde-BRV, Kompogas and Valorga systems led to the conclusion that the investment costs declined over the past decade by continuously applying process improvements.

The wet digestate from wet anaerobic digestion systems can be used as a liquid fertilizer in Germany and Switzerland. This is not permitted in all countries due to agricultural safety regulations. In that case it is separated in a wastewater and solid fraction after which the two fractions are further treated. This procedure has a strong effect on the costs of anaerobic digestion technology.

In an anaerobic digestion process, the odor potential is less than in composting as the process takes place in air-tight containers and the biogas is stored and used. The main odor problem occurs during unloading the biowaste from the trucks (similar to composting technology) and after opening the digesters and transporting and mixing the digested waste (different from composting technology) (Ten Brummeler 2000). Therefore, an odor collection and treatment system is added. Besides, in many cases, in-vessel composting is commonly used to process the digestate. This technology controls odor better than aerated static pile or windrow composting.

The method of anaerobic digestion processing usually preserves the nitrogen content and therefore it produces a soil conditioner with a higher fertilizing value than aerobic composts (Bidlingmaier et al. 2004).

4.4.4 Possibility to apply anaerobic digestion technology in Ho Chi Minh City, Viet Nam

MSW in HCMC has a relatively high content of OFMSW and moisture (50 - 60%) (CENTEMA 2008), so that high-rate anaerobic digestion and composting seem a better solution compared to disposal in a sanitary landfill. The biogas generated in anaerobic digestion can be converted to electricity and thermal energy. This is a strong argument for the application of anaerobic digestion as there is a rising demand for electricity particularly in the dry season. At the moment, the price of electricity (for both inhabitants and producers) in Viet Nam is low due to government subsidies. If the government would buy biogas-based electricity at the same or a higher price than fossil-fuel-based electricity and the regulations on environmental benefits and costs are applied, like in many developed countries, anaerobic digestion might be an economically attractive alternative for MSW treatment in HCMC. With respect to the quality and quantity of compost the anaerobic digestion process is comparable with aerobic composting and the compost can be used in organic fertilizer production.

Though anaerobic digestion technology is widely applied in developed countries, it is quite new in most developing countries. This is also the case in Viet Nam, where the anaerobic digestion technology of MSW has not been applied yet in practice. To select the most appropriate anaerobic digestion technologies for HCMC, the performance of the various technologies with respect to the criteria mentioned in section 4.2 should be assessed. The applicability of anaerobic digestion technologies depends particularly on characteristics, such as the solids retention time, the efficiency of biogas production, the quality of the digestate and the investment and operation costs.

As the ambient temperature in HCMC is close to the mesophilic temperature range, mesophilic anaerobic digestion is an obvious treatment method. Research results of Cuong and Hai (2006), Chi (2008), and Kim Oanh (2009) clearly showed the possibility to apply anaerobic digestion technology in Viet Nam. Dry systems are preferred to wet systems due to their simpler handling of the digestate. Therefore, our further elaboration of the application of anaerobic digestion in HCMC is limited to dry anaerobic digestion systems at mesophilic conditions (chapter 5 and 6). Both batch and continuous processes are deemed feasible. Nevertheless, thermophilic anaerobic digestion could also be an option if the extra income from biogas production can compensate the use of energy for heating the digester. Thermophilic digestion has advantages as compared to mesophilic digestion, such as an increased digestion rate, a higher biogas production, better pathogen removal, a shorter residence time, possibly better dewatering properties of the digestate. For reasons mentioned above two-stage systems seem not appropriate to the conditions of OFMSW treatment in HCMC.

4.4.5 Conclusions

Anaerobic digestion technology is a proven technique and is applied worldwide. Its success is based on (1) The increasing benefits of green electrical energy, (2) The exploitation of a potentially large source of still unused energy, (3) The value of the digestate as soil conditioner. However, its further spreading, especially in developing countries is still limited due to uncertainties regarding investment and operation costs of anaerobic digestion plants, a possibly disappointing energy yield, low energy prices, difficult access to energy markets, damaged reputation due to unsuccessful plants, lack of co-operation between relevant actors, and lack of information about and legal obstacles to the acceptance of certain (co-) composting products in agriculture. In Europe the net costs of MSW and biowaste treatment by means of anaerobic digestion are increasingly at the same level as aerobic composting (De Mes et al. 2003). The investment costs of a Biocel plant are about 40% lower than of other anaerobic digestion technologies (Joshua et al. 2008). The operation costs are also low due to the low amount of electricity that is required. However, the land use for a Biocel plant is higher than for continuous dry digesters (Joshua et al. 2008). The quality of biogas and the compost product of the Valorga, Dranco, Kompogas and Biocel technologies are more or less equal. The input of the systems has more influence on the quality of biogas and compost than the treatment technology (Bens 2007).

In Viet Nam anaerobic digestion of the OFMSW is not yet applied. However, given the high content of organic matter and moisture in the MSW, taking into account the high demand for electricity and considering the many limitations and problems of landfill and aerobic composting, anaerobic digestion technology should be considered an interesting technology. Although the dry-batch technology seems the most feasible concept, introduction in Viet Nam should be surrounded with much care, because the process operation is relatively complex as compared to for example windrow or aerated static pile composting. The system choice depends much on local conditions and circumstances.

4.5 Incineration technology

4.5.1 Introduction

The aim of this chapter is discuss thermal treatment technologies of MSW that may be successfully applied in developing countries. Therefore, as mentioned before, we leave pyrolysis and gasification aside and discuss incineration only. Incineration can be defined as thermal processing of solid waste based on chemical oxidation with a stoichiometric or excess amount of air with or without recovery of the combustion heat. The end products of incineration are hot combustion gases (flue gas), composed primarily of nitrogenoxides, sulphurdioxides, carbon dioxide and water vapor and non-combustible residue (fly and bottom ash) (Tchobanoglous et al. 1993, p 618). There are basically two waste incineration options: combustion without and with recovery of energy. The first option aims at reduction of the waste volume and the emissions from final waste disposal. In the second an additional goal is the recovery of energy from the combustion gases. In fact, energy can be derived from MSW in two forms: (1) directly, by burning waste as a fuel to produce steam, and (2) indirectly, through the conversion of wastes to fuel (oil and gas) or fuel pellets that can be stored for subsequent use. This chapter discusses the first form only. Incineration plants are the most expensive of the waste treatment technologies discussed here. Highly skilled personnel are required for careful operation and maintenance. Therefore, incineration technology is usually applied when other simpler and cheaper technologies are not suitable (Tchobanoglous et al. 1993, p.855). As incineration reduces the volume of the waste significantly, many countries use it as a means of reducing the required landfill capacity. The fraction of MSW subjected to incineration varies in the EU from nil in Greece to almost 100% in Switzerland (Den Boer et al. 2005). Below the most significant strengths and weaknesses of the two incineration options are summarized. Strengths and weaknesses of incineration technology are presented in table 4.7.

Table 4.7 Strengths and weaknesses of incineration technology.

Strengths	Weaknesses
Incineration without and with energy recovery - Reduction of the volume of MSW by incineration is up to 80 - 90% and reduction of weight up to 70 - 75% ; as a consequence incineration requires a small disposal area for residues as compared to landfill; - The residence time of waste in an incinerator is very short (maximal one hour) which contributes to a small footprint. The land requirement of incineration plants is small compared to other technologies; - The incineration system can be located inside or nearby (close to the discharge sources), which can reduce the transportation costs; - Incineration can destroy all toxic organic material and pathogens in an effective manner; - The emissions of incinerators to the atmosphere can be controlled effectively; - Ash residue is mostly non-putrescible or sterile and it can be used in a beneficial way; - Phosphate can be recovered from incineration ashes; - Incineration technology gains high CERs in CDM projects. In incineration plants without energy recovery these CERs are awarded for avoided methane emissions and in incineration plants with energy recovery additionally for produced energy through which some use of fossil fuel is avoided. *Incineration with energy recovery* - Incineration has a potential for energy production, which depends on the lower heat value of the treated waste and the applied technology;	*Incineration without and with energy recovery* - Investment and treatment costs are high compared to composting, anaerobic digestion and landfill; - Incineration is a complex technology which requires highly skilled staff in design, construction, operation and maintenance; - In particular the flue gas treatment needs advanced technology and highly skilled management to avoid pollution of the environment; - Incineration is less suitable for MSW with a low heat value; - Incineration is sensitive to a high moisture content in the waste; - In the case of wastes with a low heat value additional fuel may be needed to initiate and at times to maintain the incineration process; - Incineration leads to the loss of nitrogen in the wastes to the atmosphere; - Incineration leads to the conversion of ammonia or nitrate to nitrogen in the wastes to the atmosphere; it means that it lose N-containing nutrients in the incineration process. Besides it discharges NO_x, SO_2, maybe dioxins and furans. - Land is needed for the disposal of the fly ash and bottom ash, if the ash is not recycled; - For environmental reasons public acceptance of incineration facilities can be difficult to obtain.

References: Tchobanoglous et al. (1993, p.618-855), Cheremisinoff (2003, p.39-61), Tchobanoglous and Kreith (2002, p.13.8), World Bank (1999), Cheng et al. (2007), Den Boer et al. (2005) and Waste-C-Control (2011).

The incinerability of MSW can be defined based on the following factors: (1) Waste moisture content, (2) higher heat value of waste, (3), inorganic salts and (4) high sulfur or halogen content. The higher the waste moisture content, the more combustion heat is required to evaporate the moisture in the waste. If the moisture content is relatively low, the evaporation (drying) occurs simultaneously with the combustion. At high moisture content of the waste it may be necessary to supply extra heat value in the form of coal or another fuel. Drying as a pretreatment step may also be useful or even necessary. The higher heat value of the waste is an important factor of a thermal oxidation process. The higher heat value of the dry waste and the moisture content in combination determine the lower heat value of waste. Generally, a waste with a lower heat value less than about 6 MJ/kg is not suitable for auto-thermal incineration (Kreith 2002, p.13.8). According to Cheremisinoff (2003, p.43) MSW is combustible without addition of auxiliary fuel at a moisture content lower than 60% and an ash content lower than 25%. Waste rich of inorganic alkaline salts is less suitable for incineration as it creates a slag, which severely reduces the performance of the furnace. High sulfur or halogen content generates acid-forming compounds in the flue gases.

4.5.2 Technology

The incineration process of MSW includes four main steps: pretreatment, the combustion process, energy recovery (if opted for and feasible) and flue gas cleaning.

- Pretreatment aims at removing non-carbonaceous material, reducing the size of MSW and shredding or fine sorting. Some combustion technologies require a little or no pretreatment while other technologies need more pretreatment. The rejected residue is dumped at a residue landfill. For MSW with high moisture content as presently collected in HCMC, there are three main procedures. One is to co-combust materials with a high heat value, such as coal (Cheng et al. 2007), the second is incineration without energy recovery and the third one is incineration with electrical energy recovery, and used (a part of) the waste heat for drying the waste in an external drier.
- The combustion process converts MSW to inert components and hot gases. For incineration MSW may need resized and sufficient oxygen is required to fully oxidize the waste.
- Steam is generated by heat exchange with the hot flue gases. By means of a steam turbine and generator electricity and hot low-pressure steam are produced. Some countries in Europe produce energy mostly as heat like Denmark, Norway and Finland, while others like the Netherlands produce electricity mainly (Olofsson et al. 2005). It should be noted that energy recovery as heat is more efficient than as electricity with an efficiency of about 90% and 30%, respectively (Economopoulos 2010).
- Flue gas cleaning is a complex system. The type of the gas cleaning depends on the emission control standards.

The scheme of incineration technology is presented in figure 4.7.

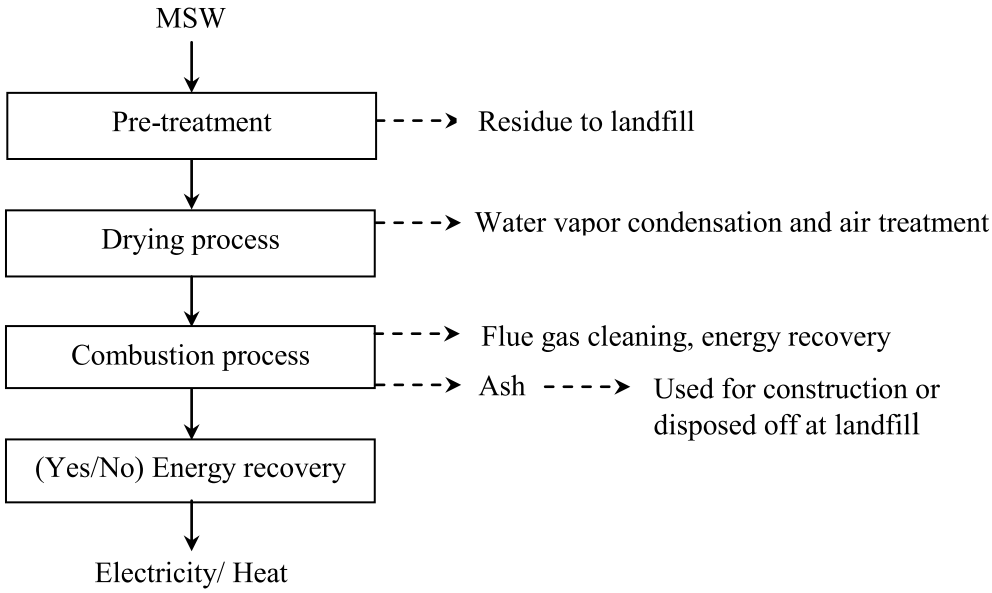

Figure 4.7 The scheme of waste-to-energy incineration technology with a pre-drying system.

An example of a mass balance for incineration is presented in figure 4.8. Depending on the composition and moisture content of MSW, the incineration needs on average 5.5 m^3 air to combust 1 kg MSW (Tchobanoglous et al. 1993, example 13-2, p.616). For increased energy efficiency the primary air can be preheated with flue gas (Cheng et al. 2007). In a mass burn incinerator, size reduction is applied before solid waste is placed in the hopper that feeds the incinerator. The bottom ash remaining after incineration amounts to 25 - 33% of total MSW input. About 2 - 5% of total MSW are recoverable metals from the ash.

A variety of incinerator types have been used for the combustion of waste. The grate system is one of the most crucial components of a mass burn furnace (Kreith 2002, p.13.34). A number of different types of grate designs are used. However, there are two main different grate types: the movable grate and the rotary grate[32]. World Bank (1999) showed that the mass burning principle with a movable grate is a feasible and well-proven technology. The rotary grate has a more limited use for the incineration of MSW.

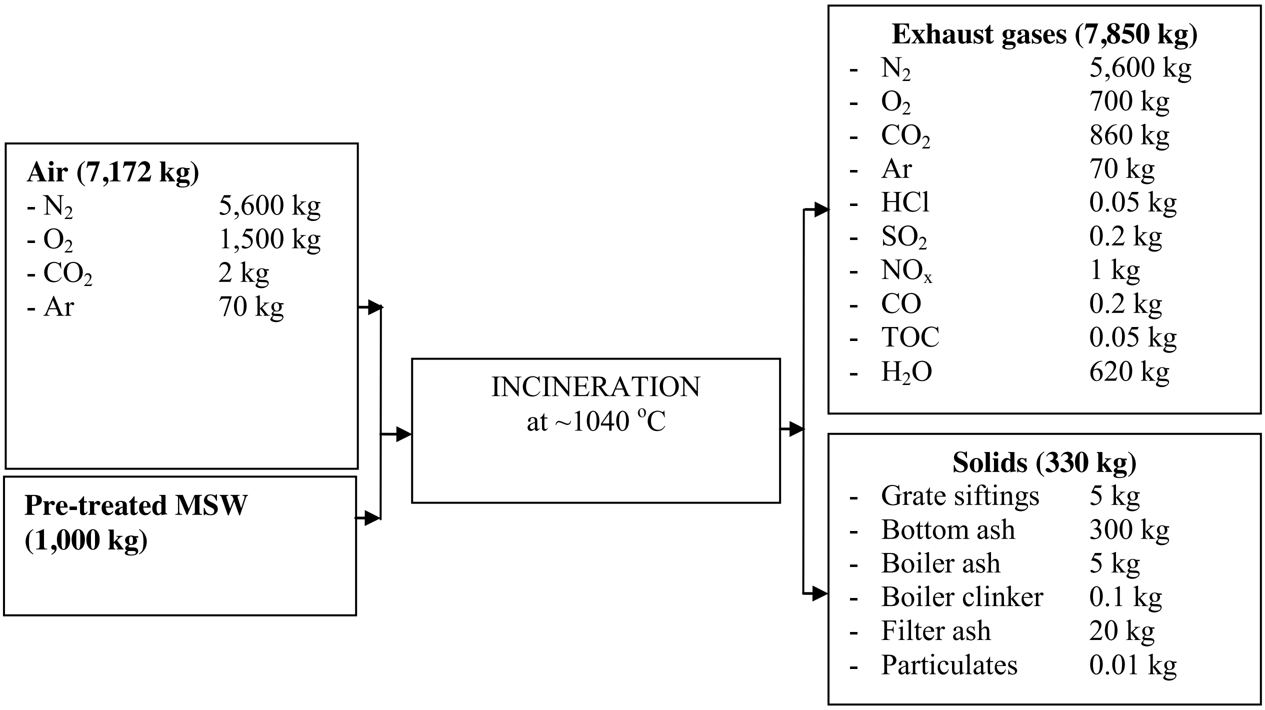

Figure 4.8 Mass balances for incineration.
Source: Biffaward (2007).
Note: Air need is 5.5m^3/kg.

The energy production from mass burning of MSW can vary widely, dependent on the characteristics of the MSW, the climate and the season. Mass burning is the oldest, simplest, and most widely used method of recovering energy from MSW. In European countries, mass burn incinerators usually range in capacity from 45 to 900 tons waste/day (Europen Environment Agency 2009)[33]. A typical plant would require about 45 tons of MSW to generate 1 megawatt (MW) of electricity of power for 24 hours (533 kWh/ton) (Cheremisinoff 2003, p.42). Since the landfill tipping fees and taxes in many countries tend to be high, mass burning has become an economically attractive alternative. In Europe incineration of MSW takes a large percentage of MSW treatment.

Chang (2001) reported an electricity output of 140 – 450 kWh/ton MSW for incinerators in Taiwan. Here, the waste moisture content was similar to HCMC. According to Dijkgraaf and Vollebergh (2004), about 580 kWh of electricity, 299 kWh of thermal heat, 1.6 kg aluminum and 34 kg iron were produced per ton of MSW with an incinerator with a capacity of 684,000 tons/year. In the research of Kaplan (2009) an electricity production from incineration of about

[32] Mass-burn incineration technology is presented in website: http://ce540.groups.et.byu.net/syllabus/termpaper/1999-W/teng.pdf
[33] http://www.eea.europa.eu/publications/EMEPCORINAIR/group09.pdf

470 - 930 kWh/ton MSW was reported. Economopoulos (2010) found that incineration plants of MSW produced 640 kWh/ton MSW and consumed about 175.4 kWh/ton MSW. The same publication states that the capacity of treatment in terms of land use is 15,000 - 63,000 tons MSW/ha/year.

As mentioned above, incineration can be applied with and without energy recovery. Depending on the legal requirements of a country, the heat value of the waste and the intention to produce energy, a technology can be selected. For environmental reasons, waste incinerators without energy recovery are not allowed in Europe anymore. However, in many other countries, both types of incinerators can be used. The difference between the two technologies lies in the equipment for energy recovery. Therefore, the investment costs for plants without energy recovery are lower. In countries where the waste to be combusted has a high moisture content (> 40%) and the lower heat value is less than about 6 MJ/kg the regular incineration technologies will not suffice. To maintain the combustion process a certain amount of additional fuel has to be added, the grate design has to be adapted and/or an external drier has to be used to reduce the moisture content before the MSW is fed to the combustion chamber.

A study by Cheng et al. (2007) on power generation through the combustion of wet MSW (50% moisture, average lower heat value is 4.4 MJ/kg) in Changchun (China) in combination with lignite (coal) showed that the efficiency of the electricity generation process over the combined heat value of MSW plus coal was equal to only 14.6%, but the efficiency based on the heat value of the coal only was about 30%. As an efficiency of 30% is a regular value for electricity generation from coal, it may be inferred that the energy from the MSW was more or less completely needed for the evaporation of the moisture in the waste. This is an important conclusion as it shows that auto-thermal combustion may require special measures though which waste is pre-dried using heat from the flue gas. The option of co-feeding thermal power plants with MSW was not taken further detailed in this thesis as it was considered outside its scope.

As mentioned above incineration of MSW with a high moisture content of about 50% could also be achieved if the plant were provided with extended means to recover heat from all available sources including the heat of condensation of a part of the moisture. Such extended means could include an external waste pre-drier that brings down the moisture content of the waste before it is being fed to the furnace to less than 40%. This drier should be heated by low-pressure steam from the steam turbine and heat from steam condensers. Such extra equipment for heat recovery would increase the capital costs of the plant but it would avoid the supply of extra fuel to a high degree. The capacity of electricity generation from waste with this high moisture content in this type of plant is lower than in regular MSW incinerators fed with relatively dry MSW.

4.5.3 Financial, social and environmental aspects

MSW incineration is an advanced waste treatment technology. It is a technology associated with high investments, high operation costs and high skills for operation and maintenance. However, if the waste has a sufficient heat value the generated thermal energy can be utilized to (partially) compensate for the investment and operation costs.

Similar to other technologies, treatment costs of incineration decrease with scale. Therefore, World Bank (1999) has proposed that individual incineration units should have capacities of at least 240 tons/day. Incineration plants are not flexible with regard to the waste input. If the flow of feedstock is higher than the design capacity, the incineration plant is unable to treat the extra supply. If it is lower, the treatment costs per ton increase.

Incineration with energy recovery gives three types of valuable products: electricity, heat and possibly metals recovered from the bottom ash. Compared to other conversion technologies, the advantages of incineration are: significant reduction in volume or amount of waste (about 90% in volume and 70% in weight) which reduces land use of waste disposal, significant production of energy depending on the heat value of the MSW, reduction greenhouse gases (0.4 - 1.5 MT CO_2/MWh) compared to sanitary landfill (2.3 MT CO_2/MWh) (Kaplan et al. 2009). In general, about 20 - 30% of the input becomes ash and must be landfilled, which adds costs for transportation and dumping. In some countries like the Netherlands and Switzerland, the ash is used as construction material. Based on Olofsson, Sahlin et al. (2005), in Europe the total revenue from incineration with energy recovery is in range 14 - 57 €/ton input (equal to 20.7 - 84.4 USD/ton). Most revenue comes from the generated heat (0 - 54 €/ton input) and a smaller part from the electricity (0 - 14 €/ton input). It should be noted in this respect that the heat value of MSW in Europe is usually rather high due to a low moisture and high combustible matter content. This high heat value is reached by waste separation at source during which a considerable part of wet food waste is removed from the feedstock for the incinerators.

Incineration reduces the environmental risks associated with MSW. An incineration plant always includes an air cleaning system that reduces the emissions to the atmosphere (HCl, SO_2, NO_x, dioxins, furans), so that the standards of the local government are reached. The wastewater discharged from the pre-treatment step amounts to about 2.5 m^3/ton MSW (Daskalopoulos et al. 1997). Incineration requires less land compared to other technologies.

4.5.4 Possibility to apply incineration technology in Ho Chi Minh City, Viet Nam

Incineration is an expensive technology that finds only very limited application in Viet Nam. Until now, Viet Nam has applied it only for hazardous hospital waste and some types of industrial solid waste, at a very small scale. The capacity of the largest incinerator in Viet Nam, at the moment, is 21 tons/day. Currently, all incinerators in Viet Nam are implemented without energy and metal recovery. Incineration technology of MSW still needs to be adapted to applications in developing countries like Viet Nam for the following reasons:

- Incineration is a modern technology manufactured in countries like Germany, US and Japan and exported over the world. The investment costs of incineration plants are high. Besides, the construction and operation of an incineration plant requires highly skilled staff that is not always available in developing countries. Chinese scientists claim that MSW incinerators constructed in China are significantly cheaper than the ones imported there (Cheng et al. 2007).
- The heat value of MSW in Viet Nam is low due to a relatively low content of paper, cardboard and plastics and high moisture content. Waste with a low heat value has a higher net treatment costs than waste with a high heat value. An example given by World Bank (1999) showed that waste with a lower heat value of 6 MJ/kg has 30% higher net treatment costs than waste with a lower heat value of 9 MJ/kg. If the heat value is still lower than 6 MJ/kg as is the case in Viet Nam, the treatment costs will increase even more either due to the need to supply fuel or extra investments in heat recovery.

As shown above three approaches to incineration of MSW in HCMC could be adopted: (1) co-combustion of MSW with a high-energy and low-cost fuel (like coal), (2) incineration without heat recovery and (3) incineration with energy recovery and the application of pre-drying of the waste. With the low and varying heat value of the commingled MSW in Viet Nam the second option might require incidental co-firing of fuel. The second and third options are adopted in this thesis as possibilities for the incineration of MSW in HCMC.

The overall heat balance of these options looks as follows. Assuming the dry matter, moisture and inert fractions of the waste as respectively 0.4, 0.5 and 0.1 and the higher heat value of the dry matter equal to 20 MJ/kg, the gross available heat of combustion is equal to 0.4 * 20 = 8.0 MJ/kg MSW (Kiely 1996, p.638-639).

In an incinerator without energy recovery this heat is required to evaporate the available water (0.5 kg/kg waste). Such a layout requires a special furnace grate. All produced heat is lost with the flue gas and the hot ashes.

In an incinerator with energy recovery in the form of electricity the high-pressure steam from the boiler is used to generate electricity and the resulting low-pressure steam is used for pre-drying of the waste. Assuming efficiencies of the boiler and the generator of respectively 78% and 30%, the gross electricity output is 8.0 * 0.78 * 0.30 = 1.87 MJ/kg MSW (Chang and Huang 2001; Tchobanoglous et al. 1993, p.661). Accordingly 8.0 * 0.22 = 1.76 MJ/kg MSW is lost with the bottom ash, in the combustion chamber, the flue gas cleaning and in the exhausted flue gas. The remaining heat amounting to 8.0 – 1.87 – 1.76 = 4.37 MJ/kg MSW is available in low pressure steam of the turbine and can be (partly) used for evaporation of the water. The heat required for heating and evaporation of water from the waste amounts to about 2.7 MJ/kg water. At a moisture content of 50% the drying heat amounts to 0.5 * 2.7 = 1.35 MJ/kg MSW. This calculation shows that sufficient heat for drying of the waste is available. The gross electricity output in this example is 1.87 MJ/kg MSW or 519 kWh/ton MSW. Taking into account the electricity consumption of the plant itself of 175 kWh/ton MSW (Economopoulos 2010), the net electricity output would be 519 – 175 = 344 kWh/ton MSW. In this thesis it is assumed that the average electricity generation from MSW in HCMC amounts to 323 kWh/ton MSW.

4.5.5 Conclusions

Incineration of solid waste is an important element in many modern integrated waste management systems (Tchobanoglous et al. 1993, p.611). Traditionally, incinerators were used only to reduce the volume of waste. Today, incinerators generate energy as an important by-product. Incinerators represent an alternative to traditional energy sources (fossil fuels), but their potential environmental impact is an important consideration. With new technologies, the removal of harmful contaminants of the flue gases is well possible and is a prerequisite for satisfying emission standards. Incineration is without any doubt a very efficient way for eliminating pathogens.

Incineration is a complex technology that requires: (1) High capital and operation expenditures and (2) Highly skilled staff who can be scarce in developing countries. The possibility to apply incineration technology in HCMC is increasing due to: (1) The pressing need of an efficient technology for volume reduction of the strongly growing amount of MSW; (2) The increasing scarcity of land for MSW treatment; (3) Incineration may produce electricity and heat. This pleads for this technology since there is an urgent need of electricity in HCMC. It must be realized that the net energy output in HCMC might be less than in countries where the heat value of the waste is much higher. It is estimated that the net electricity output could be approximately 323 kWh/ton MSW; and (4) If incineration projects are registered for CDM, a high number of CER units may be earned.

4.6 Landfill technology

4.6.1 Introduction

Landfill disposes of solid waste by burial and is the oldest form of waste treatment. Historically, landfills have been the most common method of solid waste disposal and will stay important in the future. Landfill can deal with all materials in the solid waste stream. It also offers a final disposal route for residues from other waste management options, such as mechanical-biological pre-treatment or incineration. In a landfill, biological conversion of organic matter generates biogas. Until recently three types of landfills were distinguished: open dumps, controlled dumps and sanitary landfills. Presently, the bioreactor landfill is an additional option. The process of recirculation of leachate in the bioreactor landfill accelerates the biological conversion process, so that more biogas is produced in a shorter time of digestion compared to the sanitary landfill. The aim of this technology is to enhance the production of biogas and reduce the generation of leachate.

A sanitary landfill is a controlled method of solid waste disposal. Sanitary landfill is an accepted technology in Europe and the United States but is still new in many developing countries. A professional design of a sanitary landfill avoids the environmental problems of open dumps, such as smoke, odor, unsightliness, and problems associated with insects, rodents and birds. A well-designed and operated sanitary landfill prevents groundwater pollution, provides for gas (methane) venting or recovery, has a leachate collection and treatment system, provides gas and leachate monitoring wells.

There are many sub-types of sanitary landfills, such as the so-called secure landfills for hazardous wastes, mono-landfills for particular types of wastes, such as combustion ash, asbestos, and other similar wastes, and landfills for MSW. Most landfills over the world are designed for commingled MSW. In MSW landfills, limited amounts of non-hazardous industrial wastes and sludge from water and wastewater treatment plants are usually accepted. Strengths and weaknesses of landfill technology is presented in table 4.8.

Table 4.8 Strengths and weaknesses of landfill technology.

Strengths	Weaknesses
- Landfill is a flexible and relatively simple technology that can be applied for all types of solid waste; consequently it is an unavoidable element in waste management systems; - Depending on legal requirements and local conditions landfill may be a good option in terms of costs and required operation skills; - It is common technology for MSW treatment developed through upgrading of the traditional open dumping method. Therefore, solid waste decision makers usually accept landfill rather easily.	- Landfill technology requires much land compared to other technologies and it occupies the land during a long period; - Landfills discharge odor, noise and air pollution (especially greenhouse gases); - A landfill site remains a source of contamination until it is recovered; - As a consequence of the preceding weaknesses sitting of landfills is often very difficult; - The convenience of landfill tends to discourage the development of innovative more sustainable waste management options.

References: Cheremisinoff (2003, p.96-125), Tchobanoglous et al. (1993, p.361-538), O'Leary and Tchobanoglous (2002, p.14.15), Veolia (2010), Townsend et al. (2008), R-W-BECK (2004) and Waste-C-Control (2011).

4.6.2 Technology

Two modern types of landfills for MSW, the sanitary landfill and the bioreactor landfill are discussed here.

Sanitary landfill

The sanitary landfill is an engineered landfill that includes waste disposal, landfill gas extraction, ground water monitoring and leachate treatment. The waste stabilization is controlled until the biological, chemical and physical degradation is completed. It aims at risk-free disposal of MSW. The most important facility in a sanitary landfill is the landfill cells. They are large holes where MSW is deposited. Design and construction of a landfill cell include: impermeable bottom layer, subsurface sides, intermediate layers and top cover. Inside each landfill cell, there is a collection system that collects leachate at the bottom of the cell and pumps it to the wastewater treatment plant. Leachate is the liquid that has percolated through solid waste and contains dissolved and suspended materials. The amount of leachate depends on the water balance of the landfill. At the production side of the balance is the water released from the waste during degradation and rainwater entering the landfill during the time the cells in use are still not covered. On the consumption side are the water consumed in biological reactions, the water leaving the waste mass as water vapor and the water held up in the waste until the moisture holding capacity is reached. The composition of leachate depends on the composition of MSW, biological processes and impact factors, digestion time, etc. Leachate contains a high amount of organic matter that may pollute groundwater, soil, surface water and also the air. The technology to treat leachate is complicated and costly. Each landfill cell is connected to a biogas collection system. Biogas can be collected and used during a short or long period depending on the quantity and quality of biogas. Collected biogas is transported to a biogas cleaning system before it can be converted to electricity. Biogas can also be used to produce heat. If the quality of biogas is lower than the quality requirement of the electric generator or the amount is small, biogas is burned at flare. The equipment related to biogas collection, cleaning and electricity generation is complicated and costly. A landfill site includes several additional facilities, such as: roads, drainage system, weighing station, offices, electricity and water supplies, etc. The details of the layout of landfills can be found in Tchobanoglous (1993; 2002). Figure 4.9 presents the structure of a sanitary landfill cell.

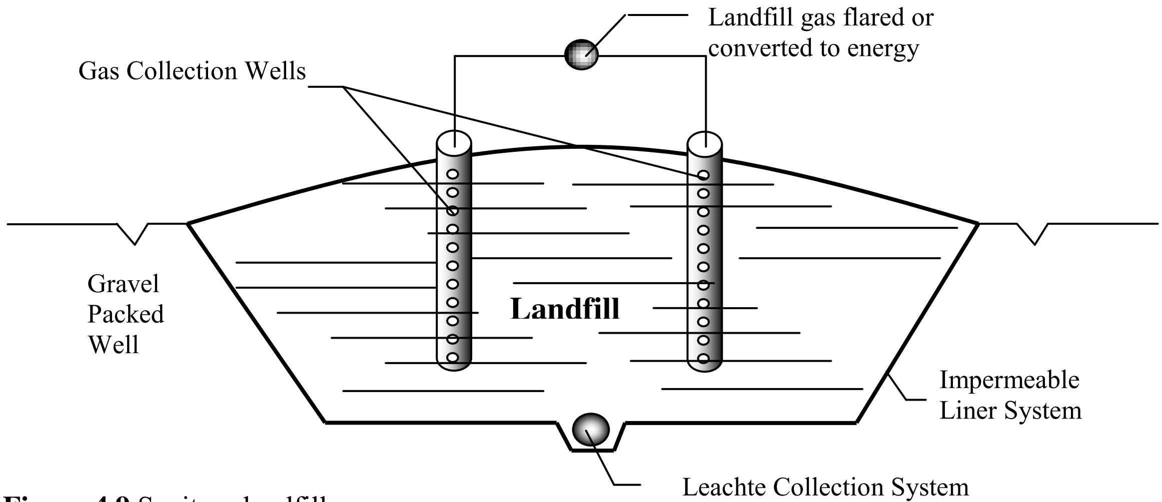

Figure 4.9 Sanitary landfill.

Products of a sanitary landfill

According to O'Leary and Tchobanoglous (2002, p.14.15), the theoretical amount of biogas that would be expected under optimum conditions from rapidly and slowly biodegradable organic wastes in a landfill varies from 750 to 936 and 874 to 999 m^3/ton of dry biodegradable organic solids converted, respectively. Organic matter that can be digested within 5 years is called rapidly biodegradable organic solid. If the digestion takes from 5 to 50 years the organic solid waste is called slowly biodegradable. Under normal conditions, the biogas production in landfills increases and reaches a peak at about 2 years after disposal and subsequently tapers off slowly, continuing in many cases for 25 years or more.

Based on the findings of Veolia (2010)[34], a landfill with a capacity of 800,000 tons/year will produce on average 13,000 m^3 biogas/hour during 25 years of operation. About 10,000 m^3 biogas/hour can produce 10 MW electricity. This means that from every ton of MSW dumped at a sanitary landfill, 142 m^3 of biogas is produced during the operation time of 25 years. Within

[34] http://www.biogas-bouqueval.veoliaenvironnement.com/features/history.aspx

the first 10 years the recovered volume of biogas is 109 m^3/ton (77% of the total biogas production) and can be converted to 109 kWh of electricity. As apparently most biogas is produced during the first 10 years, the collection and electricity generation is often limited to those first 10 years (Veolia 2010). For the remaining 15 years, biogas is collected and burned due to the low quality and quantity. The Eastern Research Group and the MGM International Group (2008) found for a landfill of MSW in Brazil with 44% organic waste content at an average temperature of 18^{o}C, a methane production of about 72 m^3/ton. If the volume of methane in biogas is estimated at about 50%, the biogas production is about 144 m^3/ton, which is similar to the data given by the Veolia Environment Group.

After a digestion time of 25 years, a sanitary landfill can be opened and the digested residue collected for composting purposes (if the product satisfies requirements of heavy metals and toxic compounds) and the land can be reused. A survey by Xu et al. (1999) including 19 landfill sites in Australia in 1999 showed that the size of the landfills ranged from 12 to 100 ha, with a median surface area of 35 ha.

Bioreactor landfill

In a bioreactor landfill enhanced microbiological conversion processes transform and stabilize the biodegradable organic waste within 5 to 10 years after disposal, compared to 25 to 50 years in sanitary landfills. This is achieved by means of leachate recirculation, addition of biosolids, nutrients, or air injection (in aerobic bioreactor landfills). During the recirculation of leachate, water (or a suitable type of wastewater) may be added to reach a moisture content of 45 to 60%, optimal for biological processes, and this moisture is spread more homogeneously than in sanitary landfills. Via leachate recirculation also the temperature and other impact factors can be controlled, such as the C/N ratio, pH and inoculation. As a consequence the costs of leachate treatment in bioreactor landfills are lower or sometimes nil. The environmental impacts of bioreactor landfills are lower than those of sanitary landfills. In a bioreactor landfill, the volume of solid waste decreases quickly due to rapid biodigestion. The obtained empty air space at the top of bioreactor may be filled again with extra MSW, thus increasing the capacity of the landfill.

The benefits of bioreactor landfills as compared to sanitary landfills are: (1) Less leachate treatment; (2) Reuse of air space due to the rapid biological process; (3) High biogas recovery efficiency; and (4) Less post-closure monitoring costs; and (5) Less landfill space is required due to a more rapid degradation process.

Bioreactor landfills require higher investment and have higher operation costs per ton of waste compared to sanitary landfills. It is not advisable to dump non-organic residue from separation processes and ash from incineration plants in a bioreactor landfill. Therefore, bioreactor landfills cannot fully replace sanitary landfills in a solid waste management system. Nowadays, bioreactor landfill technology is gaining popularity in North America and Europe, and has been demonstrated widely.

Technique and operation of bioreactor landfills

Bioreactor landfills can be classified into 3 types (Townsend et al. 2008):
(1) *Anaerobic bioreactor landfill*. In anaerobic bioreactor landfills leachate is recirculated to control moisture of MSW in the optimum range of the anaerobic digestion process of 45 - 60%. If there is not sufficient leachate to supply moisture, other sources of water or suitable wastewater can be added. A higher amount of biogas is produced in a shorter time as compared to traditional landfills. In principle, an anaerobic bioreactor landfill has a high biogas production

rate during the first 2 years and the collection is finished at the end of the fifth year (ITRC 2006; Yazdani et al. 2007).

(2) *Aerobic bioreactor landfill*. In aerobic bioreactor landfills the main biological process is aerobic conversion, which is different from sanitary landfills. Leachate is recirculated and also air is injected into the mass waste by a vertical and horizontal well system to promote aerobic activity and accelerate waste stabilization. Aerobic bioreactor landfills become stable more rapidly than anaerobic systems and can recover volume (airspace) faster (Reinhart et al. 2002). Aerobic bioreactor landfills do not produce biogas and cause less direct greenhouse gas emissions.

(3) *Hybrid (Aerobic-Anaerobic) bioreactor landfill*. This is a combination of aerobic and anaerobic processes that accelerates waste degradation by employing sequential aerobic and anaerobic treatment.

Anaerobic bioreactor landfill technology had been proven in many countries, such as: the United States, Canada, Japan, Australia, Malaysia and Bangladesh, while aerobic and combined aerobic and anaerobic bioreactor landfills are not much applied yet. Therefore, in this chapter, we discuss anaerobic bioreactor landfills only. Anaerobic bioreactor landfills are divided into two types: as-built and retrofit bioreactor landfills. In the as-built bioreactor landfill, the leachate recirculation and water addition system is implemented during the placement of MSW. In the retrofit bioreactor landfill, the construction and operation of the leachate recirculation and water addition systems are installed after the disposal of MSW. Therefore, the leachate recirculation and water addition in a retrofit setting are limited compared to as-built bioreactor landfills. In this paper, we discuss as-built anaerobic bioreactor landfills only. Figure 4.10 shows the scheme of anaerobic bioreactor landfill.

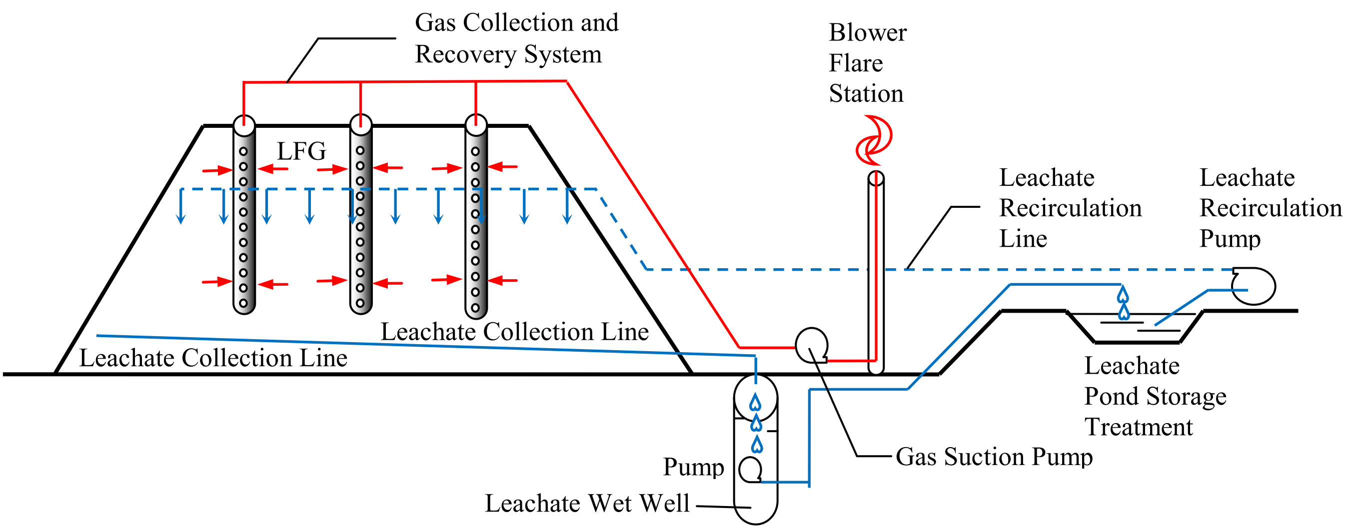

Figure 4.10 Anaerobic bioreactor landfill.
Based on: U.S EPA, 2010[35].

The figure shows that the design of the anaerobic bioreactor landfill is similar to the sanitary landfill. The difference is the way of leachate recirculation of the bioreactor landfill. Leachate is collected from the bottom of the bioreactor landfill and pumped to the leachate pond for storage. In this pond leachate may or may not be treated before being distributed onto the top of the waste in a landfill cell. As the flow rate of biogas is higher compared to the sanitary landfill, the biogas

[35] www.epa.gov

collection system has a bigger capacity. When the quality or quantity of biogas is low, biogas is burnt at flare.

Products of a bio-reactor landfill

The potential benefits of anaerobic bioreactor landfills are: (1) Increase of the energy recovery potential due to fast digestion leading to an increased volume of biogas collected in a shorter period of collection. During the first two years of collection the volume of collected biogas is about 30 -100% higher than from a sanitary landfill (Yazdani et al. 2007). According to data of Veolia (2010) the volume of recovered biogas is about 142 - 217 m^3/ton MSW during the first two years after disposal; over the first five years the biogas production is in the range of 185 - 282 m^3/ton. After the second year biogas is still collected but flared due to the low quality and quantity; (2) Rapid settlement results in an increased air space recovery which is up to 30% of total volume of the bioreactor landfill within 2 years (Townsend et al. 2008). Rapid settlement can shorten the required lifetime of a landfill which results in higher land use efficiency and lower costs for post-closure monitoring compared to the traditional landfill (5 - 10 years vs. 25 - 50 years) (ITRC 2006); (3) Leachate can be treated inside the bioreactor landfill. Therefore, the costs of leachate treatment can be reduced. This is important as the costs of leachate treatment in Viet Nam account for 30% of the total treatment costs of landfills (DONRE HCMC 2009); (4) Reduction post-closure maintenance and risk due to rapid stabilization. The expenditures for post-closure are low due to short duration of maintenance. It is estimated that the reduction amounts to about 40 - 50% of total costs of post-closure monitoring based on the post-closure time reduction (Yazdani et al. 2007); (5) Landfills are cited as an important source of greenhouse gases. However, anaerobic bioreactor landfills have a more efficient biogas collection system, so that less greenhouse gas is discharged; (6) Bioreactor landfills are more sustainable. Most biodegradable matter in bioreactor landfills can be digested to produce biogas, which can be converted to green energy. The residue can be used as compost in agriculture or landfill cover material or is suitable for several other purposes.

Although bioreactor landfills have much potential compared to traditional landfills, there are some disadvantages, such as: (1) The higher costs of bioreactor landfills as compared to traditional landfills; (2) A lack of regulations related to bioreactor landfills, especially a lack of incentives (Angelidaki et al. 2006); (3) The control of the moisture content in bioreactor landfills at 45 - 60% requires not only leachate recirculation but sometimes also addition of extra water or suitable wastewater. Therefore, water must be available at the landfill site. The volume of added water may be high, which can be costly if there is no suitable wastewater available; (4) Bioreactor landfills need high operator skills which are not always available in low-tech countries; (5) Higher requirements regarding geo-technical stability; and (6) Extra equipment is needed for leachate collection and recirculation. During the time leachate is outside of the cell, it may cause emissions of odor and greenhouse gases.

4.6.3 Financial, social and environmental aspects

Literature data about costs of landfills are rare due to the fact that most investment and construction occur continuously during the time of operation. Only the costs for the start-up investment are available. By and large, treatment in bioreactor landfills is more expensive than treatment in sanitary landfills.

Methane emissions and leachate problems (leakage and treatment) are the main environmental issues in landfills. Presently, landfills are estimated to account for 12 - 15% of the total greenhouse gas emissions on a global basis (R-W-BECK 2004). The Global Warming Potential (GWP) of MSW is estimated at 2.323 ton of CO_2 per ton of MSW landfilled, in which the methane emission, expressed as CO_2 is 2.130 tons CO_2 per ton of MSW and the CO_2 emission is

0.193 tons CO_2 per ton MSW (O'Leary and Tchobanoglous 2002, p.14.16). Landfill gas (expressed in volume percentages) includes methane (45-60%), carbon dioxide (40-60%), nitrogen gas (2 - 5 %), oxygen (0.1 - 1.0 %), ammonia (0.1 - 1.0%), sulfides, disulfides and mercaptans (0 - 1.0%), hydrogen (0 - 0.2 %), carbon monoxide (0 - 0.2) and trace constituents (0.01 - 0.6%) (O'Leary and Tchobanoglous 2002, p.14.17).

The potential impacts of landfill gas not only relate to emissions to the atmosphere but also to explosions due to landfill gas migration and accumulation in confined spaces, flash fires in open spaces, asphyxiation of people and fauna in confined spaces, vegetation and crop stress and loss due to displacement of soil oxygen in the plant-root zone, nuisance effects, visual impacts, noise from generators, water pollution, corrosion of equipment and health effects (Daskalopoulos et al. 1997).

The environmental impacts of landfills depend on the design of the landfill, method of operation and the nature of the waste deposited. The operation of landfill sites needs efficient monitoring during a long time. The new design of landfills as bioreactor landfill allows more energy recovery and has less environmental impacts due to shorter operation and post-closure time, and also faster biogas production and improved recovery.

4.6.4 Possibility to apply landfill technologies in Ho Chi Minh City, Viet Nam

In HCMC at present, sanitary landfills receive commingled MSW and non-biodegradable rejects from the solid waste separation process of composting. In our scenarios for the future it is assumed that there will be in addition landfill bioreactors and so-called residue landfills. The latter are destined to receive rejects from composting, anaerobic digestion and incineration plants. The design and operation of landfills in HCMC should especially be adapted to the weak soil structure, the high level of groundwater and the tropical weather. Leachate treatment and air emission control at landfills must comply with the governmental emission standards. Biogas collection for electricity production is a priority, since there is a lack of electricity and HCMC aims to earn credits from the CDM program. The potential waste heat produced from electricity production from the incineration of biogas will probably not be used in HCMC. If, however, the supply would be continuous, some industries could use heat energy in their production processes.

MSW in HCMC has a high percentage of organic material and the weather is suitable for biological conversion but the moisture content is much higher than in Western Europe (Veolia 2010). Therefore, it is expected that the conversion rate of the organic fraction in waste is high but the production of biogas per ton of wet MSW relatively low. The average density of MSW in landfills is about 0.85 tons/m^3 (DONRE HCMCg 2006; Veolia 2010). In the case of HCMC, the height of the sanitary landfills varies between 23 and 33 m (DONRE HCMCg 2006). Each hectare of sanitary landfill cells can hold about 180,000 tons of MSW.

There are some reasons to apply landfill in HCMC, among that landfills are a flexible and in under some conditions a relatively cheap technology compared with other technologies like composting, incineration or anaerobic digestion. It suitable for commingled MSW. Besides, sanitary landfill technology has been applied in Viet Nam and in HCMC, therefore, local expertise is available to design, construct and operate the sites. In addition, the planned areas for landfills in HCMC have a low soil quality; therefore, the agriculture farm had been resulted in low efficient. However, landfill technology become less interesting due to: HCMC is a densely populated city and large stretches of land as needed for continued application of landfill become more and more scarce. New sites would have to be located at even larger distances from the city center. The two planned treatment zones (Phuoc Hiep and Da Phuoc) are located at weak geological sites. This raises the costs for design, construction and operation of landfills. Landfill is a long-term treatment. The risk of failure of the technology and/or occurrence of natural accidents is relatively great, since the period they can occur is prolonged. Besides, landfills limit the possible profits from valuable products present in MSW such as: iron, aluminum, plastic, glass, and yield only a moderate amount of energy.

4.6.5 Conclusions

Worldwide landfill is still the first choice in MSW treatment as the strengths of other technologies do not outweigh those of landfill and it is most suited to the conditions of the poorest regions. In many places like European countries, however, the role of landfills is reduced step-by-step due to economic, social and environmental concerns.

Landfill has long been applied in HCMC. Although a second technology (composting) has been introduced in 2009, landfill continues to play an important role in the MSW treatment system. As bioreactor landfills have specific advantages such as more efficient land use, lower environmental impacts and higher production of biogas, this technology will be included in our scenarios for future solid waste management in HCMC. With regard to its future application the main aspects to be considered are:

- Technical aspects: geological and climate conditions, the composition of the MSW, the demand of the produced biogas and the discharge requirements of the local government;
- Environmental aspects: prevention of environmental damage due to leachate leakages, landfill gas and odor emissions, collapse of landfill embankments and explosions and control of disease transmission;
- Economic aspects: the investment, operation and maintenance costs and the financial benefits of biogas and compost end product need to be investigated,
- Social aspects: the acceptance by the government and local citizens; the high land requirement and the practical possibilities of biogas utilization.

4.7 General conclusions

Several technologies are available to treat MSW. The main ones are composting, anaerobic digestion, incineration and landfill, that all have their strengths and weaknesses. These have been summarized in table 4.9 based on the considerations given in this chapter. The choice of one or more proper technologies in a situation under study depends to a high extent on local conditions.

Table 4.9 Strengths and weaknesses of four MSW treatment technologies in HCMC, Viet Nam.

Technology	Strengths	Weaknesses
Composting	- Local experiences and technologies available in Viet Nam. - Large market for compost. - Compost use represents recovery of C, N, P, etc. - Opportunity for collecting recyclable waste (resource sustainability). - Creates jobs for low-education people (the MSW separation process requires a lot of labor). - Cheap technology compared to anaerobic digestion and incineration.	- High land use compared to other three technologies. - High moisture content in MSW produces odor emissions and leachate - Greenhouse gas emissions. - Consumes about 30 - 35 kWh/ton input - May yield low quality of compost due to impurities in input (commingled MSW). - About 25% of total commingled MSW input residues discharged to landfill.
Anaerobic digestion	- Anaerobic digestion process compatible with high moisture content in MSW (while this is a problem with composting technology). - Area requirement lower than for composting. - Odor problems minimized. - Yield of valuable products: biogas, electricity and compost. Net production of electricity is 160 - 400 kWh/ton input. - Opportunity for collecting recyclable waste (resource sustainability). - Creates jobs for low-education people.	- No experience in anaerobic digestion technology for MSW in HCMC, VN. - Biogas-based electricity not competitive in Viet Nam as electricity is cheap and no subsidy is given for green energy. - May get less biogas product and low quality of compost due to impurities in input (commingled MSW). - About 25% of total commingled MSW input is discharged to landfill. - Higher investment, operation and maintenance costs compared to composting and landfill.
Incineration	- Suitable for uncompostable MSW. - Significantly reduces volume/amount of MSW (about 80 - 90% in volume and 70 - 75% in weight). - Lowest land requirement compared to three other technologies. - Environmental impact comparable to other technologies. - Possibility of energy recovery from wastes dependent on lower heat value of wastes and efficiency of energy recovery equipment.	- No experience at large-scale in HCMC, Viet Nam. - Energy yield in HCMC very low due to the high moisture content of the MSW. - High volume of ash (about 25% (w) of total commingled MSW input). - Possibility of harmful emissions to the atmosphere. - No possibility to collect recyclable waste. - The highest investment costs compared to the other three technologies.
Landfill	- Local experiences and technology available in Viet Nam. - Capacity can be increased step by step. - Possibility to improve biogas production and reduce greenhouse gas emissions and landfill lifetime by using the bioreactor landfill.	- High land use requirement. - Greenhouse gas and other emissions to atmosphere cannot be avoided. - Possibility of leachate leakages. - Leachate treatment technologies are still not efficient in Viet Nam. - No possibility to collect recyclable waste. - No resource recovery (N, P).

The treatment capacities of these technologies per unit of land (ha) are reviewed in table 4.10.

Table 4.10 Land use requirements of solid waste treatment technologies.

Technology	Land use proposed in references	References
Aerated Static Pile Composting	20,000 tons MSW/ha/year	Renkow et al. (1993)
In-vessel composting	30,000 tons MSW/ha/year	
Batch anaerobic digestion	43,800 tons MSW/ha/year	Estimated based on Chapter 3 and data about the Biocel process
Continuous anaerobic digestion	75,000 tons MSW/ha/year	Estimated based on data from websites (http://www.mbt.landfill-site.com/AD/ad.html)
Incineration with energy recovery	15,000 – 63,000 tons MSW/ha/year 40,000 - 100,000 tons MSW/ha/year 112,000 tons MSW/ha/year	Economolous (2010) From website: http://www.epem.gr/waste-c-control/database/html/WtE-01.htm Assumed for HCMC. Taking into account that the amount of MSW strongly decreases after drying process and new generation of incineration plant need less land.
Incineration without energy recovery	80% of incineration with energy recovery.	Estimated in this thesis
Sanitary landfill	180,000 tons/ha for sanitary landfill cell	DONRE HCMCg (2006)
Landfill bioreactor	15-30% higher than sanitary landfill cell	Townsend et al., (2008)
Residue landfill	1.2 times of sanitary landfill	Estimated in this thesis

Departing from these four main technology groups and applying criteria of technical appropriateness, environmental performance, social manageability and economic affordability eight technologies have been pre-screened whose application would be feasible in HCMC. These sub-types are (1) Aerated static pile composting, (2) In-vessel composting, (3) Batch anaerobic digestion, (4) Continuous anaerobic digestion, (5) Incineration with energy recovery, (6) Incineration without energy recovery, (7) Sanitary landfill and (8) Bioreactor landfill (anaerobic).

For a further selection of mixtures of most appropriate technologies in Viet Nam a further detailed analysis of performance with respect to costs and revenues under the local circumstances would be required. As costs are an important criterion the pre-screened technologies are assessed on this criterion in chapter 5.

Chapter 5
Costs analysis of municipal solid waste treatment technologies in developing countries

5.1 Introduction

This chapter presents an overview of the costs of the treatment options selected for the future municipal solid waste management system of HCMC. In order to obtain a clear picture of the situation and the input data for cost calculation, it first reviews the most important characteristics of the present waste management system and the waste to be treated (5.1.1, 5.1.2). Then, it explains the aim of the chapter and lists the technological options for waste treatment (5.1.3). In section 5.1.4 the input data and method of costs calculation are described. In the following sections the treatment costs and the capacity-cost functions of the proposed feasible technologies are estimated (5.2: composting; 5.3: anaerobic digestion; 5.4: incineration and 5.5: landfill). Finally, section 5.6 summarizes the main outcomes of the chapter. This chapter constitutes an essential database for the computation of the waste management scenarios presented in chapters 6 and 7.

5.1.1 Municipal solid waste management in Ho Chi Minh City

Collection, transfer and treatment of municipal solid waste

Commingled MSW in HCMC is collected and transported directly or via transfer stations to the two main treatment zones of the City. Small trucks with a capacity of 2 to 3 tons are used in small streets. They collect MSW at the discharge sources and bring it to transfer stations. From the transfer stations, big trucks, with a capacity of 7 - 12 tons transport the MSW to the treatment zones. Also big trucks collect MSW directly from discharge sources alongside the larger main streets and transfer it directly to the treatment zones. The two MSW treatment zones of HCMC are Phuoc Hiep and Da Phuoc. Phuoc Hiep treatment zone is located in Phuoc Hiep Commune, Cu Chi District, at approximately 48 km from the center of HCMC. Da Phuoc is located in Da Phuoc Commune, Binh Chanh District, at about 24 km from the city center. Phuoc Hiep and Da Phuoc are available for landfill or treatment facilities of MSW or a combination of treatment plants and landfill.

The average transport costs to transport MSW to Phuoc Hiep and Da Phuoc, paid by the Government, are about 21 cent USD and 27 cent USD/ton MSW per km transport route respectively (DONRE HCMCa 2009)[36]. The costs to transport MSW from the City to treatment zones depend on the transport distance and the time of transportation (during the day or night). Currently there are three sanitary landfills in the Phuoc Hiep treatment zone named Phuoc Hiep 1, Phuoc Hiep 1a and Phuoc Hiep 2 and a composting plant named Vietstar. Phuoc Hiep 1 and Phuoc Hiep 1a landfills are closed and Phuoc Hiep 2 is in use. The Vietstar Composting plant started to operate in December 2009. At this plant the incoming commingled waste is separated into four main fractions: (1) biodegradable organic MSW which is composted, (2) plastic recyclable waste, (3) other recyclable wastes and (4) residue dumped at the landfill. This plant provides important experiences and data that are used in this thesis for the assessment of other technologies (see also section 5.1.2).

The three landfills and the composting plant cover about 200 ha of the total Phuoc Hiep treatment zone of 660 ha. The Da Phuoc treatment zone has currently only one sanitary landfill,

[36]For short distances the government wants to compensate by setting high unit cost (27 cent vs. 21cent USD/ton).

covering 107 ha of the total area of 640 ha. The actual planned land use[37] for MSW treatment plants and landfills is about 276 and 233 ha for the Phuoc Hiep and Da Phuoc treatment zones, respectively. The rest is used for green land. Both treatment zones are situated at a low level, have a weak soil structure and a high groundwater level. This has caused and will cause in the future difficulties regarding designing and operating landfills and treatment installations. Accordingly, the investment and operation costs for new installations at those sites will be relatively high.

Quang (2008) showed that the budget of HCMC in 2007 was 228,679 billion VND (equal to 14.3 billion USD). This amounts to about 1 - 2 % of the city budget, in which the expenditure for treatment is about 70%. Treatment costs (total cost for landfill MSW but not including land cost) at Phuoc Hiep 2 landfill are 20 USD/ton. The treatment fee (the cost that the government pays to the owner) at the Da Phuoc landfill is 16.4 USD/ton and at the Vietstar Composting factory 5 USD/ton (DONRE HCMCb 2010). Since March 2011, the treatment fee at Vietstar Composting has risen to 12 USD/ton (DONRE HCMC 2011).

Recovery of useful products from waste

Householders, collectors and waste pickers have already separated a part of the recyclable waste from the commingled MSW before it is received at the landfills. The recyclables are sold to informal recycling factories that process them to marketable products. This practice has strengths and weaknesses. Sorting recyclable wastes out of the MSW reduces transport and treatment costs, creates jobs for people, increases the income for collectors and contributes to the viability of the recycling sector. The Vietstar Company is able to extract about 0.4 ton raw PE material per ton collected PE plastic waste. The price of the raw PE material was about 450 USD/ton in 2009. These relatively high benefits make PE plastic waste a major financial factor in the treatment of MSW. Besides, the average price of a mixture of other recyclable wastes without plastics was about 50 USD/ton[38]. Apart from benefits to the recycling sector the present practice of separation of recyclables at source causes serious economic, safety, environmental and health problems. The recycling factories are small and old. Backward technologies cause environmental problems, especially air and water pollution. Few investments are done in waste treatment and prevention. Due to the waste separation at source, it is less recyclable wastes are available at central treatment plants, such as Vietstar, which reduces the profitability of such plants. This situation will continue in the coming years; therefore, the amount of recyclable waste at the central treatment sites will stay low.

Biogas is one of the products from anaerobic digestion. It can be converted to electricity and sold to the state electricity network or to industrial zones. A part of the produced biogas can be used to produce thermo-energy. Economopoulos (2010) and Electrigaz (2010)[39] show that 1 m^3 biogas with 50 - 60% (volume) methane content can be converted to 1.7 - 2.1kWh electrical energy (the overall conversion efficiency is 30 - 33%). At present, biogas production in Viet Nam occurs mostly at small scale. Recovery of landfill gas for electricity production is found only at the Go Cat Sanitary landfill. The waste heat from co-generation of electricity can be used for drying and disinfection of compost. Lack of electricity is not only a problem in rural or sub-urban areas but also in cities in Viet Nam, especially during the dry season. This offers an opportunity to apply

[37] These 2 treatment zones are planned (by HCMC' government) used for at least 20 years.

[38]The collected recyclable material is separated into 2 types in Vietstar Composting plant: one is PE plastic waste from which raw PE material is processed and another is a mixture of recyclable waste (without PE). The PE plastic waste is processed inside the Vietstarcomposting plants and produce raw PE material with a price of 450 USD/ton. The other mixture of recyclable waste (glass, metals, etc) is not processed inside the plant and is sold to the recycling sector at 50 USD/ton.

[39]Data from website: http://www.electrigaz.com.Download date 17/9/2010.

WTE (Waste to Energy) technology. However, the present price of electricity is low (4 cent USD/kWh) in Viet Nam at the moment, due to subsidy from the government for the production of electricity. The government is now considering attracting investors to the electricity production. Therefore, the price of electricity is assumed to increase to 8 cent USD/kWh which is equal to the production price.

Viet Nam is an agricultural country with potential high needs for compost, especially since the quality of soil in Viet Nam is decreasing quickly due to inadequate management. It requires large amounts of compost to compensate for the loss of many years in the past. The survey at the Vietstar Composting factory in 2010 showed that the compost demand was so high, that all their compost could be immediately sold. Compost is sold as raw compost or processed to organic fertilizer. There are some composting plants with post-processing installations to produce organic fertilizer. In the post processing, compost is granulated and mixed with nutrients (N, P, K) and active microorganisms in different ratios, based on the requirements of agriculture for different soils and crops. The price of this fertilizer is 2 - 5 times[40] higher than of raw compost but the cost of the fertilizer process is also high. Therefore, Vietstar composting plant has not invested in a post-processing installation. The amount of compost that can be produced from MSW is about 20% (weight) of the total raw MSW. In 2010 the raw compost price was in the range of 30 - 35 USD/ton (Vietstar Company 2010). A survey of Giac Tam and co-workers showed that the annual production of manufactured organic fertilizer in the South-East region amounts to 250,000 tons. Due to constraints in the supply of manure and stronger awareness of the need to apply organic matter to soils, the demand for commercial manufactured fertilizer is expected to grow (Giac Tam et al. 2006).

As presented in Table 5.1, the total estimated need for organic fertilizer in the South-East region of Viet Nam, based on application rates that would sustain cultivated soils, is large: 25.8 million tons of manure per year. This figure refers to the agronomic needs of the most important crops. The need would even be larger if also minor crops would be included. The effective demand, however, is relatively small: 2.26 million tons of manure per year. This represents only about 9% of the agronomic need. This demand is presently satisfied by approximately 2 million tons of manure and 0.25 million tons of commercially manufactured organic fertilizer.

Table 5.1 Need and demand of organic fertilizers and supply of compost in the South-East of Viet Nam.

	Perennial crops	**Annual crops**	**Total**
Cultivated area in S.E. region (1000 ha)	728	893	1,621
Estimated need of manure (1000 tons/year)	12,558	13,230	25,788
Estimated demand of manure (1000 tons/year)	452	1,809	2,261
Urban-waste based compost supply (1000 tons/year)	-	-	192
Required replacement of manure by compost (%)	-	-	7

Source: Giac Tam et al. (2006).

Notes:

- *"Need of manure" means the amount of organic fertilizer which is needed to improve the soil in order to get a good performance.*
- *"Demand of manure" means what farmer effectively buys for their soil.*

The low actual demand is due to the small percentage of farmers that utilizes organic fertilizers and the low application rates (Giac Tam et al. 2006). The manure in Viet Nam is mostly fresh and only occasionally digested pig manure (see chapter 2). But the application of fresh pig manure damages the environment and public health. To safely increase fertilizer application,

[40]Huu co limited company, website: http://www.humixvn.com.Download date 17/9/2010.

manure should be matured or processed. It may be concluded therefore that technologies that produce compost of a good quality have a high priority.

5.1.2 Characteristics of municipal solid waste in Ho Chi Minh City

In HCMC in 2008, on average 5,800 tons of commingled MSW was collected per day. The increase of the MSW amount during the last 10 years was 6 - 8 %/year (DONRE HCMCb 2009). The average MSW discharge is about 0.81 kg MSW per capita per day (294 kg/capita/year). The amount of MSW in HCMC is equal to 57 % of the per capita MSW in European countries (518 kg/capita/year) (EUROTAS 2007). The discharged amount of MSW in the province of HCMC varies considerably: from about 0.3 kg per capita per day in rural areas to about 1.2 kg per capita per day in urban areas (CENTEMA 2008).

The organic fraction of MSW of HCMC is big and amounts to about 80% (CENTEMA 2008). Due to the high moisture content of the waste, separation of fractions after collection is relatively difficult as is experienced at the Vietstar Composting plant. The organic fraction collected from the separation process at the Vietstar Composting plant is only about 60 % of the total weight of the waste (Chi 2008; Vietstar Company 2010). In the collected organic fraction, the moisture content is about 65 % while the moisture content in commingled MSW is about 55 % (CENTEMA 2008). There are food markets in HCMC that produce only biodegradable organic waste, which could be collected separately and transported directly to Composting or anaerobic plants. In order to reduce the transportation costs, the government uses compress trucks to increase the transported amount per truck. However, the compressed MSW is difficult to separate at the Composting plant and the fraction of organic waste obtained as input to the Composting process in this way is lower than if the waste were collected without compressing.

About 5 % of the wet weight of MSW consists of nylon, plastic, glass, metal and paper (Vietstar Company 2010; CENTEMA 2009; DOSTE HCMC 2006). For commercial reasons the recyclable materials are separated into two types in the separation process at composting plants in Viet Nam. PE plastic waste is collected and processed to raw plastic material for the plastic industry or oil industry. At the moment, there is a high demand for raw plastic material. In May 2010 the Vietstar Composting plant showed that there was not enough raw plastic material to satisfy market demand. The percentage of collected recyclable PE plastic waste is about 3.2 % of total MSW input to the plant and the percentage of raw plastic material which is produced from recyclable PE plastic waste is about 40% of the amount of collected recyclable PE plastic waste (Vietstar Company 2010). The other type of recyclable material (glass, paper, metals, etc.) is collected and sold to the recycling sector. These non-plastic recyclables amount to about 1.8 % of total MSW input.

The residue (the rejected material which could not be composted) of the MSW separation process at the Vietstar Composting plant is collected and transferred to the Phuoc Hiep landfill. Since control of illegal discharges is not strict, MSW in HCMC contains undesirable components such as industrial waste and sludge, glass and rock, syringes, hazardous wastes, etc. (CENTEMA 2008). These unwanted contaminants cause problems in the treatment of MSW.

5.1.3 Aim of this chapter

The government of Viet Nam and of HCMC in particular, is questioning: (1) which technologies are appropriate, (2) what amount of MSW should be transported to each treatment zone in the current situation and in the future? As shown above two technologies to treat MSW in Viet Nam are currently in use: composting and sanitary landfill. The two sanitary landfills and the composting factory in HCMC are all state of the art technologies. The Phuoc Hiep 2 landfill is a 100% local enterprise. Its design is a modification of the Go Cat landfill, originating from the

Netherlands. The Da Phuoc sanitary landfill is a 100% US investment as is the Vietstar composting factory (2010). In other places of Viet Nam, there are many locally designed, constructed and equipped landfills and composting factories. It may be concluded that Viet Nam has sufficient expertise on design, construction and operation of sanitary landfills and aerated static pile composting factories. However, bioreactor landfills, in-vessel composting, anaerobic digestion and incineration technologies as described in the previous chapter are still new and need the support of foreign expertise.

Incineration technology has been applied for about 10 years. In HCMC there are some companies that can construct incineration plants. However, incineration is only applied on a small scale with installations that have a maximum capacity of 21 tons/day (DONRE HCMCa 2010), based on simple technology and applied for hazardous wastes only (hospital and industrial hazardous waste). Viet Nam has not much experience on off-gas treatment to abate the emission of NOx, dioxin and furans. There is no incineration of wastes with energy recovery in Viet Nam; therefore, Viet Nam has no experiences with the production of electrical energy from the combustion of solid wastes. Ash from incineration processes can be used to produce cement and construction material (Viet 2009).

Anaerobic digestion is a relatively new technology in Viet Nam. Some foreign companies (from the United States, Italy, Germany, etc.) introduced their anaerobic technologies in Viet Nam. However, there is no proof yet that these technologies will be appropriate for application in HCMC with its typical MSW characteristics and climate (high temperature, high humidity, etc.). This is the reason why after about five years and many deliberations HCMC's government could not yet decide for possible application of anaerobic technologies. However, Viet Nam has been operating a sanitary landfill with biogas recovery. Therefore, experiences in storage and use of biogas, and in production of electricity from biogas are available. Many industries in HCMC are potentially interested in waste heat, such as paper mills, wood processing, agriculture processing (drying of agricultural products), etc. However, the heat is not used due to: (1) absence of much waste heat at the moment, (2) the industries are far from the heat source (Go Cat Sanitary landfill), (3) the price of electricity in Viet Nam is still low, (4) there is no support activity for using this green energy.

HCMC is a crowded city with a fast economic and population development causing high demands for land. Therefore, the planned areas for solid waste treatment are located far from the urban zones and the geology of these soils is poor which leads to high costs of transport and landfill. The typical socio-economic characteristics of HCMC, such as limited budget for MSW treatment, lack of environmental experts, cheap labor, and high demand for recycled products, etc, should be taken into account in the selection of MSW treatment options. Based on technical, environmental, social and economic criteria and taking the conditions of HCMC into account, 9 feasible technologies for MSW treatment were selected (chapter 4 of this thesis). These technologies are aerated static pile composting, in-vessel composting, batch anaerobic digestion, continuous anaerobic digestion, incineration with energy recovery, incineration without energy recovery, bioreactor landfill, sanitary landfill and residue landfill. Some new technologies, such as pyrolysis, gasification, etc., are not included, because they are not or hardly applied on a practical scale yet and are in fact still in the development stage. This chapter makes an inventory of the costs of the aforementioned 9 technology options.

This chapter focuses on cost analysis of treatment options. As mentioned above 9 technologies can be applied in HCMC. This study also discusses the products from waste treatment and their markets. Depending on the technologies, there are 7 types of products, namely: recyclable waste, compost, biogas, electricity, heat energy, aluminum and iron. Figure 5.1 shows the framework of the chapter.

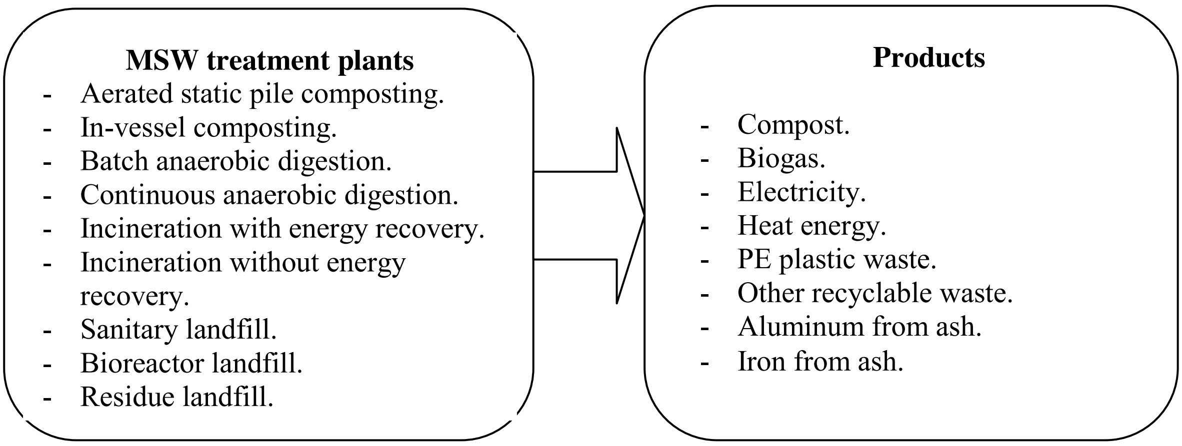

Figure 5.1 The framework of the cost analysis in this thesis.

Figure 5.2 presents a graphical overview of the options for treatment of MSW in HCMC at the two treatment zones considering transportation, treatment technologies, products and markets for products.

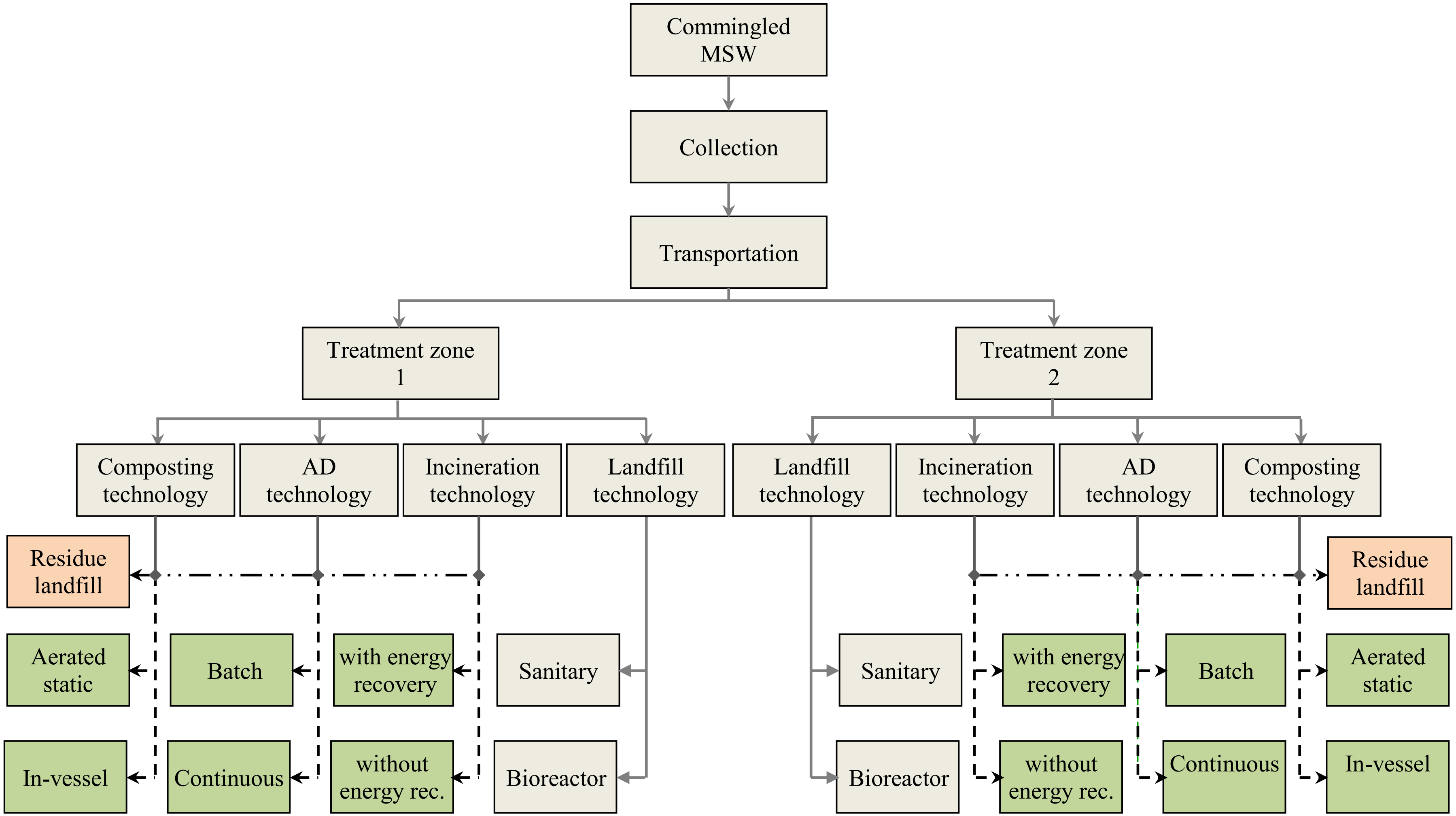

Figure 5.2 Possibility to apply the municipal solid waste treatment technologies in Ho Chi Minh City, Viet Nam.
Note: ⟶ *Commingled MSW flow,* - - -➔ *OFMSW flow,* —··➔*Residue flow*.

5.1.4 Method and assumptions for the calculation of costs and benefits of treatment technologies

For the calculation of the costs of the various options the following method and assumptions have been taken into account. The MSW which is transported to treatment zones and then to the treatment plant is wet commingled MSW. Table 5.2 summarizes the input data cost analysis. The input data were collected from literature references applied average value.

Table 5.2 Input data for costs analysis.

Parameters	Values
Characteristics of MSW in HCMC	
Moisture content of raw MSW.	55%
Organic fraction in raw MSW.	80%
Collected biodegradable organic matter.	60%
Moisture content of organic fraction.	65%
Plastic recyclables in MSW.	3.2%
Non-plastic recyclables in MSW.	1.8%
Residue (rejects) from compost, anaerobic digestion.	25%
Residue (rejects) from incineration	10%
Products from MSW treatment	
Amount of compost from composting or anaerobic digestion	20% of comminged MSW input to the plants.
Amount of biogas from batch anaerobic digestion, continuous anaerobic digestion, sanitary landfill and Bioreactor landfill.	36 - 42; 48 - 96; 87 - 95; 100 - 109 m^3 biogas/ton comminged MSW input to the plants.
Amount of PE plastic waste.	3.2% of comminged MSW input to the plants.
Amount of raw PE material.	40% of amount of PE plastic waste.
Amount of other recyclables recovered.	1.8% of comminged MSW input to the plants.
Amount of ash from incineration.	10% of comminged MSW input to the plants.
Amount of aluminum recovery from ash.	0.88 kg/ton comminged MSW input to the plants.
Amount of iron recovery from ash.	15.4 kg/ton comminged MSW input to the plants.
Cost	
Costs of land in HCMC.	0 USD as land for public facilities is free of charge.
Market price of raw PE material.	450 USD/ton
Assumed electricity price.	0.08 USD/kWh
Market price compost.	30 – 35 USD/ton
Costs of leachate treatment.	Included in the overall costs.
Base year of cost analysis.	2009
Design lifetime of installations (composting, anaerobic digestion and incineration).	20 years
Number of effective working days of installations.	300 days/year.
Interest rate on capital.	5%/year

Investment costs of a MSW treatment plant include construction and equipment costs. Fixed cost includes mortgages and interest on borrowed investment capital, depreciation, repair and maintenance of fixed assets, and insurance. Operation cost includes cost of labor, materials and operation of equipment. The costs of land are not included as in HCMC land for public facilities are free of charge. The costs of composting, anaerobic digestion or incineration plants do not include the transport and dumping cost of residues. The market prices of utilizable products from waste processing are as indicated in table 5.2: compost: 30 – 35 USD/ton; electricity: 0.08 USD/kWh; raw PE: 450 USD/ton. It has been assumed that in incineration plants, about 10% of the total MSW input will be converted to ash and that this ash can be utilized as raw material for construction. This material is free of charge, so that no financial benefits or costs for ash processing are taken into account. The residue from composting/ anaerobic digestion to be deposited at a landfill is about 25 % of the MSW input. Besides, due to the high moisture content, 5 - 10% of total weight of MSW input will be separated as leachate. The prices of energy, fuel, electricity, chemicals and labor are the 2009 market prices in Viet Nam converted to USD. All the cost data borrowed from references are converted to USD with the exchange rate of 2009 and the history of the inflation rate up to 2009[41].

5.2 Cost analysis for composting technology

The composting process consists of 5 important treatment steps: (1) pretreatment of the input material (the MSW separation process), (2) main treatment: biological process, (3) possible post-treatment or post-composting step, (4) leachate treatment, and (5) treatment of the off gases of the composting process. Step 1 and 3 are more or less the same for aerated static pile static pile and in-vessel composting. However, step 2, 4 and 5 are quite different. The biological process in in-vessel composting takes place in a closed box where the environmental impact factors regarding the biological conversion process, leachate production and air emissions are well controlled.

5.2.1 Aerated static pile composting

MSW in HCMC is collected and transferred to the 2 treatment zones and subsequently to the aerated static pile composting plant. The mass balance and the scheme of aerated static pile composting in HCMC is presented in figure 5.3 and figure 5.4, respectively.

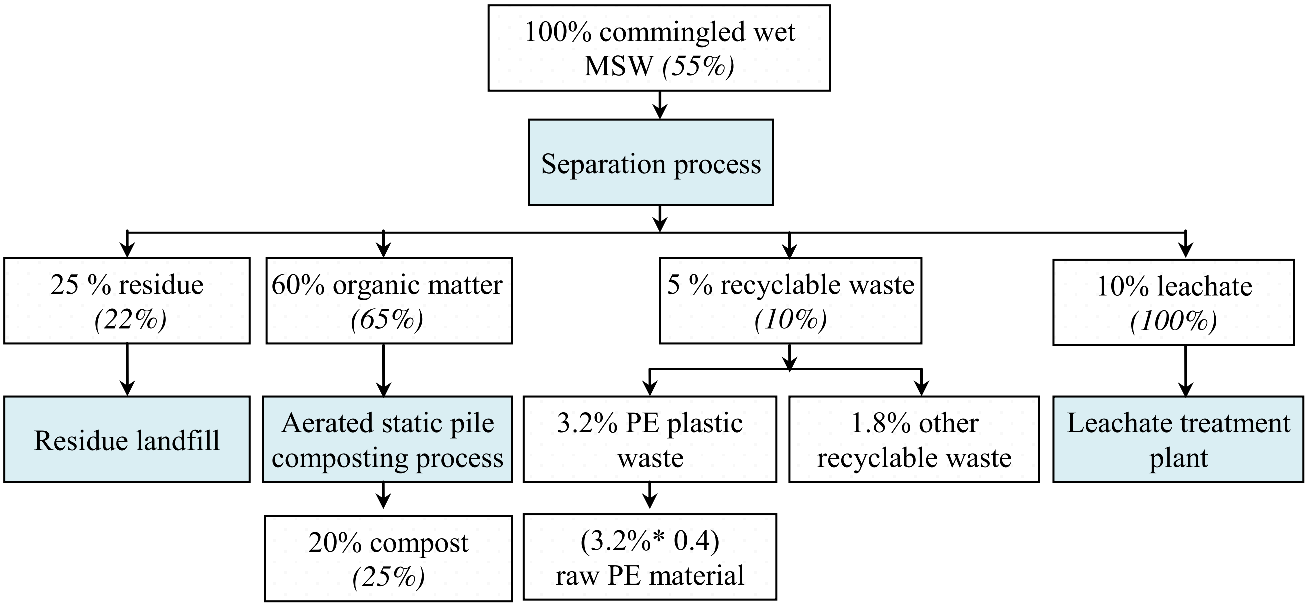

Figure 5.3 Mass balance of aerated static pile composting plant in Ho Chi Minh City.
Note: the percentages between brackets indicate the moisture content.

Before MSW gets into the aerobic biological conversion process, MSW is separated into different fractions, including: (1) 60% of MSW input is organic matter (moisture content is about 65%); (2) 10% of MSW input is leachate; (3) 25 % of MSW input is residue (moisture content about 22%); and (4) 5% of MSW input is recyclable waste (moisture content about 10%). The collected organic matter is biologically converted in the aerated static pile process to produce compost. The amount of compost is about 33% of the amount of collected organic matter input to the biological conversion process or about 20% of the amount of total MSW input.

[41] Inflation rate download from http://www.inflationdata.com. Download date 17/9/2010.

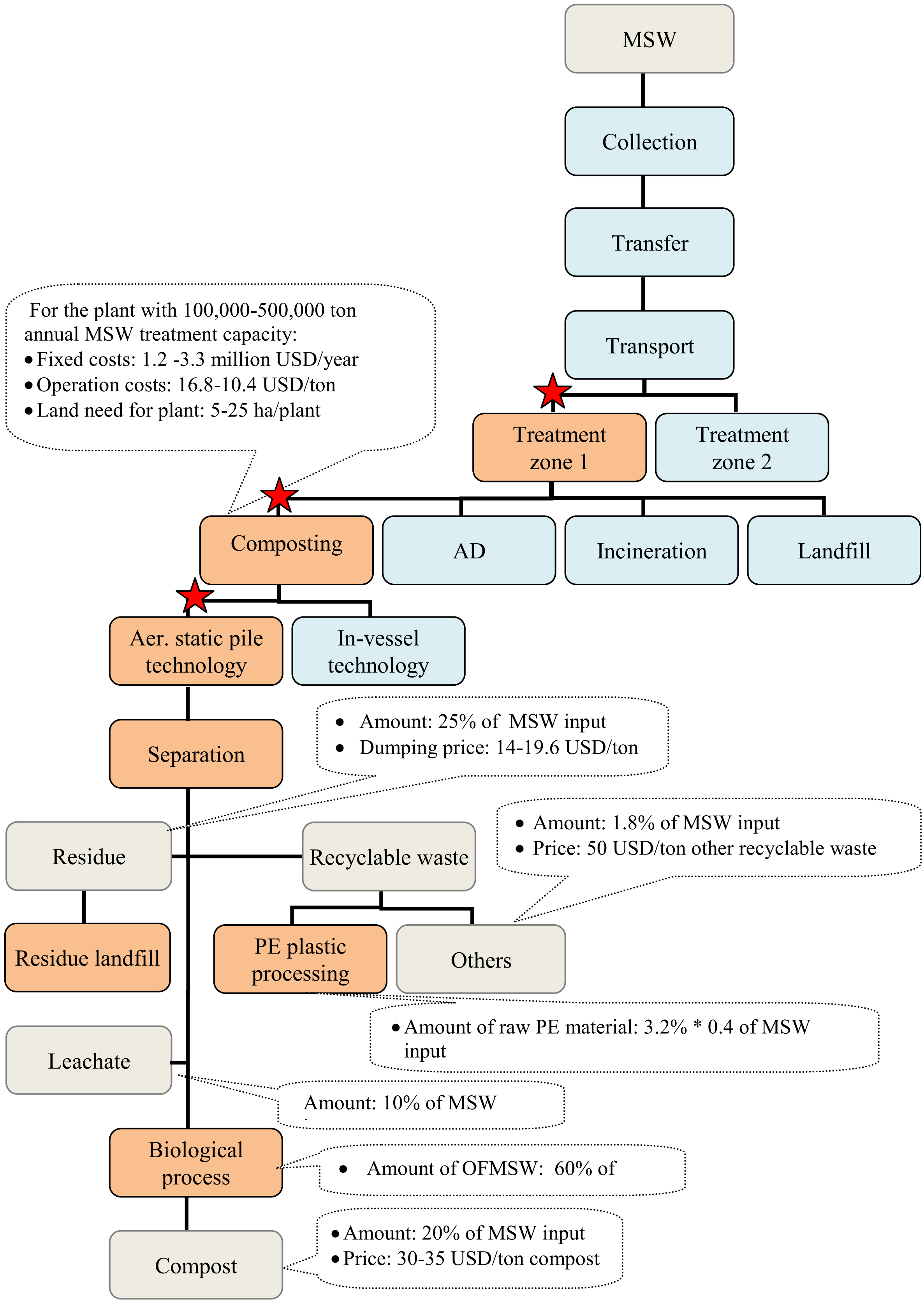

Figure 5.4 The aerated static pile composting scheme in Ho Chi Minh City.
Note: ★ are points of decisions for options.

Aerated static pile composting technology is a simple technology compared to in-vessel composting. Therefore, the investment cost of aerated static pile composting is lower, especially in the case of HCMC where land is free of charge. However, aerated static pile composting requires more labor, more land and produces lower quality compost than in-vessel composting. Moreover, although this technology is adapted to the environmental requirements of Viet Nam, compared to in-vessel composting this technology produces more pollution and therefore causes more problems regarding social acceptance.

The investment, fixed and operation costs of aerated static pile composting plants of commingled MSW in Europe at different capacities are presented in Table 5.3. The operation costs of aerated static pile composting plants are relatively high (74 - 79% of total treatment costs). This is caused by the fact that low technology requires relatively much labor and the labor costs in Europe are high. Cost data of composting plants from literature shows a wide variation. It shows that treatment costs per ton decrease at a larger capacity. However, at treatment capacities over 500,000 tons MSW/year, the costs are more or less constant and become independent from the capacity. The treatment costs (USD/ton MSW) of the composting plant with a capacity of 500,000 ton MSW/year are about 71% of the costs of the plant with capacity of 100,000 ton MSW/year.

Table 5.3 Literature review on costs of aerated static pile composting at different capacities in industrialized countries.

Costs	**Capacity (1000 tons commingled MSW/year)**				
	100	200	300	400	500
Investment costs (million USD)	29.3	42.7	53.3	66.7	80.0
Fixed costs (million USD/year)	2.23	3.26	4.06	5.09	6.61
Operation costs (USD/ton)	64.0	54.7	50.7	48.7	48.0
Treatment costs (USD/ton)	86.3	71	64.2	61.4	61.2

Source: Economopoulos (2010).
Note: Country of data: Greece. The input MSW is commingled MSW with 28.3% of biodegradable organic matter. The costs of handling residues and benefits from products are not mentioned in the paper.

The costs of proposed composting plants in HCMC are estimated based on the costs of current composting plants in HCMC and in Viet Nam. The costs of composting plants in Europe are also taken into account in order to compare the costs of composting plants in Viet Nam and in Europe and also to compare the costs of composting and the costs of other MSW treatment technologies, like anaerobic digestion, incineration and landfill. In this study, the general costs analysis for composting plants in HCMC is based on the actual costs of the Vietstar composting plant in HCMC that was built in 2008 and started operation in December 2009. The total investment costs of the Vietstar project were 36 million USD at a total capacity of 1,200 tons MSW/day or 400,000 tons MSW/year (DONRE HCMCa 2009). The Vietstar composting plant is currently in the demonstration period and is running at about 30% of its full capacity. Therefore, some data is not available yet. Consequently, the calculations of the energy and material consumption are based on technical data of the Nam Dinh composting plant and the Thuy Phuong composting plant in Hue City, where more or less the same technology is applied. The data on recycled materials in this research is based on the recycling percentages of Vietstar. Based on the investment costs of the Vietstar plant and operation costs from other sources, the operation costs are calculated at 11.2 USD/ton commingled MSW input (about 18.7 USD/separated organic matter MSW) and the fixed costs at about 2.75 million USD/year (2,292 USD/ton installed capacity of MSW input) for an aerated static pile composting plant with a capacity of 400,000 tons commingled MSW/year (Table 5.4). This operation costs figure includes the costs of processing organic MSW, leachate treatments, PE plastic removal and processing, odor treatment and maintenance. But it does not include the costs to deposit the residue. In the case of HCMC, the costs to transport residue from the composting plant to the residue landfill is very little and we will ignore it in the treatment costs of the residue due to the fact that composting plants and residue landfill are located within the same treatment zone.

Comparison of the operation costs of composting in Viet Nam (Vietstar, 11.2 USD/ton, 400,000 ton/year) and in Greece (48.7 USD/ton, 400,000 ton/year) shows that costs in Viet Nam are about 30% of those in Greece. This can be ascribed to Vietnamese conditions of (1) low labor costs, (2) low costs of electricity and fuel due to subsidy from the government, (3) less environmental control, and (4) less strict requirements to compost quality. Besides, the fixed costs in HCMC are also low (54% of the costs in Greece) since: (1) the land for solid waste treatment is free of charge, (2) the interest on loans for investment in solid waste treatment plants in Viet Nam is low (5%/year or less) in agreement with the policy of HCMC to encourage the development of environmental protection projects, and (3) low local cost for construction and for buying some of the equipment.

Table 5.4 presents the estimated capacity-cost data for aerated static pile composting in HCMC. These data were obtained by applying the ratios of the fixed and operation costs between Viet Nam and Greece at a capacity of 400,000 tons MSW/year also to the other capacities. Operation costs of aerated static pile composting in Europe are high (74 - 79% of total cost, table 5.3) due to high labor cost. As labor cost in HCMC is lower, we assume for operation cost the ratio of 60 - 65% of the total cost. There is additional cost for dumping the residue after the separation process at the composting plant. The amount of residue is estimated to be about 25% of total MSW. The costs to dump residue are not included in the treatment costs given in table 5.4. It is discussed in the section 5.5.3 about "Residue landfill" of this chapter.

Table 5.4 Estimated costs of aerated static pile composting plants for different capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons wet commingled MSW/year)**				
	100	200	300	400*	500
Fixed cost (million USD/year)	1.21	1.76	2.20	2.75	3.30
Operation cost (USD/ton)	16.8	14	12.1	11.2	10.4
Treatment cost (USD/ton)	28.9	22.8	19.4	18.1	17

Note:
- ** Calculated costs of Vietstar composting plant in HCMC.*
- *The costs to dump residue are not included in the treatment costs given in table 5.4.*

Table 5.5 shows the estimated income of composting plants in Viet Nam. It is shown that the benefit of PE is comparable to the benefit of compost.

Table 5.5 Estimated income of aerated static pile composting plants per ton of municipal solid waste input

Descriptions	**Amount**	**Unit price**	**Income** (USD/ ton MSW input)
Compost	20 % of total MSW input	30-35 (USD/ton compost)	6 -7
Raw PE material	3.2% * 0.4 = 1.28% of total commingled MSW input	450 (USD/ton plastic)	5.8
Other recyclable waste	1.8 % of total input	50 (USD/ton recyclable material)	0.9
Total income			12.7 - 13.7

Source: Vietstar (2010).

The income of a composting plant consists of the benefits from selling compost and recyclables. The amount of compost is about 20 % of total amount of MSW input. PE plastic waste constitutes 3.2% and other recyclables (paper, glass and metals) 1.8% of the total commingled MSW input (see mass balance of aerated static pile composting in HCMC) (Vietstar Company 2010). As mentioned above, the Vietstar composting plant processes collected PE plastics waste to raw PE material (40%), and sells them to the market (Vietstar Company 2010).

5.2.2 In-vessel composting

In-vessel and aerated static pile composting systems have similar treatment chains, so that the mass balance of in-vessel composting plants is similar to the one for the aerated static pile composting plant (figure 5.3). Figure 5.5 presents the scheme of MSW in an in-vessel composting process.

In a comparison between in-vessel and aerated static pile composting four costs factors should be considered, namely: (1) the costs of an in-vessel composting plant will be higher at the same capacity than the costs of aerated static pile composting; (2) the operation costs of in-vessel composting may be higher or lower dependent on electricity, fuel price and labor costs, (3) compost quality from in-vessel composting is higher, because the compost has a more homogeneous structure, a higher degree of maturity and a lower pathogen abundance. This may result in higher benefits, better marketability and better compliance with the expected higher standard requirements for compost quality in the future and (4) better control of air pollution and leachate emissions.

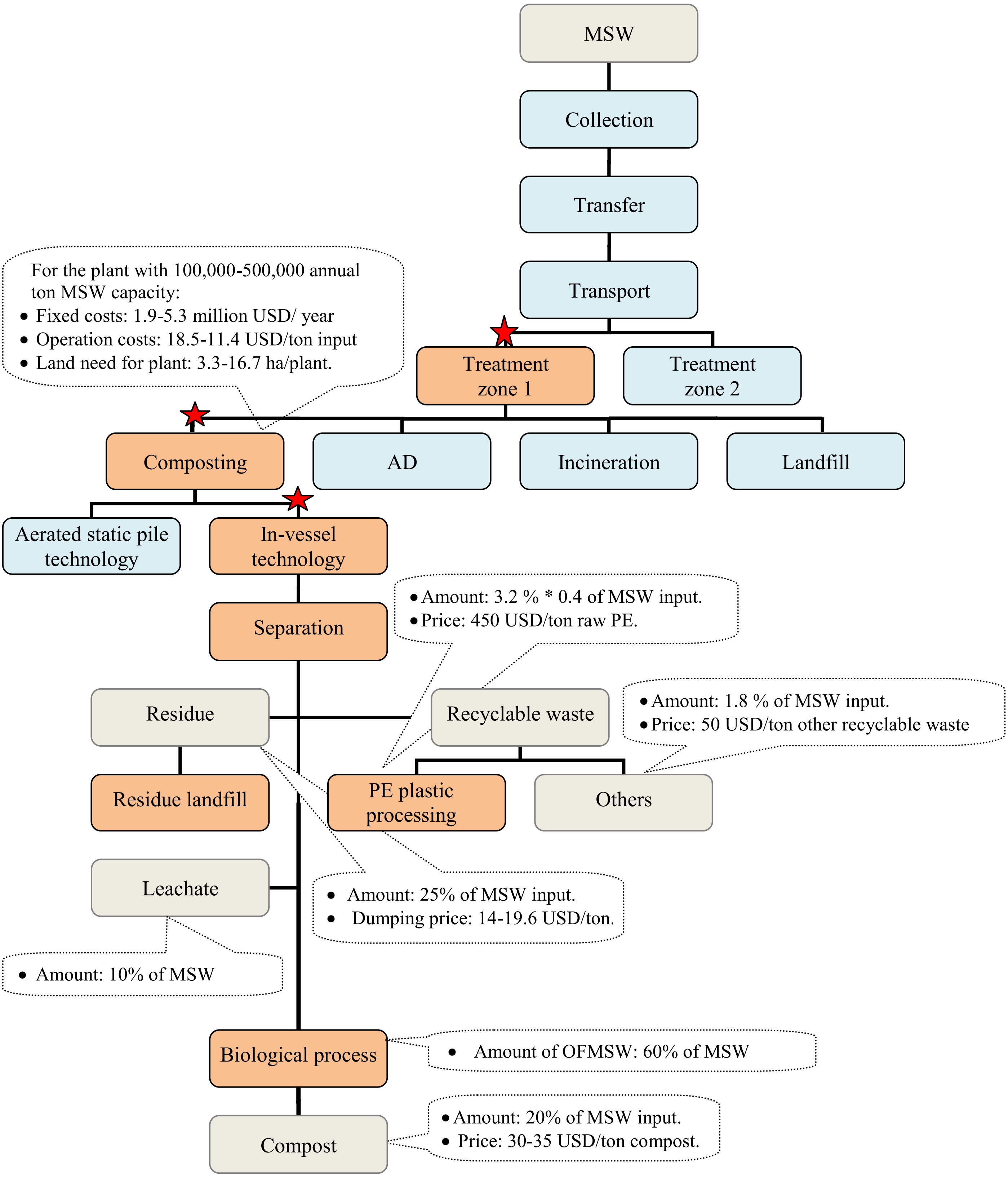

Figure 5.5 The in-vessel composting scheme.

Note: ★ *are points of decisions for options*

In Viet Nam, the first in-vessel composting plant, Vu Nhat Hong, was set up around the year 2005. However, this plant stopped operation due to inadequate technology. Therefore, for calculations, the data of Vu Nhat Hong could not be taken into account.

The costs for different scales of in-vessel composting in the USA and Europe are presented in Table 5.6. Similar to the case of aerated static pile composting plants, the costs analyses of in-vessel composting plants vary. In comparing costs for the same treatment capacity, Davis and Kincaid (1996) showed that the fixed costs of in-vessel plants are 140% of the fixed costs of aerated static pile plants. WRAP (2009) also showed that the gate fee of an in-vessel composting plant is equal to 140% of that of an aerated static pile composting plant (38£ and 23£/ton). It means that the treatment costs of in-vessel composting are 40% higher than aerated static pile composting. Tsilemou (2006) showed that the investment costs of in-vessel composting is about double compared to aerated static pile composting plant at the same capacity (9,4 and 4,5 million Euro for the plant with 100,000 tons OFMSW/year capacity).

Table 5.6 Literature review on costs of in-vessel composting at different capacities in industrialized countries.

Descriptions	**Capacity (1000 tons OFMSW/year)**		
	30	**100**	**165**
Investment (millions USD)	-	13.4	-
Fixed costs (millions USD/year)	1.13	1.02	6
Operation costs (USD/ton)	68.7	84.6	32.3
Treatment costs (USD/ton)	106.4	94.8	68.7
Countries	US	Europe	US
Source:	*Renkow et al (1993)*	*Tsilemou and Panagiotakopoulos (2006)*	*Renkow et al. (1993)*

Notes:

- *Renkow et al (1993) studied yard waste with 18% TS.*
- *In Tsilemou (2006) the treatment costs did not include the dumping of residues and benefit from products. MSW input is source separated organic waste in Europe.*

In the case of HCMC, the equipment must be imported resulting in higher transport costs and higher installation costs due to foreign expertise requirement, while the construction costs in Viet Nam are lower and land use is free of charge. We will use a factor 1.8 between the fixed costs of the aerated static pile composting in HCMC and the fixed costs of an in-vessel composting plant in HCMC. Davis and Kincaid (1996) showed that the operation costs of in-vessel composting are slightly lower than aerated static pile composting. In the case of HCMC, labor cost for aerated static pile composting is low, but the labor cost for in-vessel composting is high due to the need of appropriate expertise. In-vessel composting requires more electrical, energy and maintenance. Therefore, we multiply the operation costs aerated static pile composting cost in HCMC by a factor 1.1 to obtain the operation costs of in-vessel composting in HCMC. Renkow, Safley et al. (1993) found that the operation costs of an in-vessel composting plant are about 65% and 47% of the total treatment costs at capacities of 30,000 and 165,000 tons/year respectively. The operation cost percentage of the total treatment cost decreases with increasing capacity of the plant. The estimated data for HCMC shows that the operation cost percentage of the total treatment cost is in the lower part of the range mentioned (65 - 47%) due to lower labor, electricity and energy costs. Estimated costs of in-vessel treatment for HCMC are presented in Table 5.7. Similar to aerated static pile composting technology, the dumping cost of residue (25% of total commingled MSW) is not included. The costs to dump residue are not included in the treatment costs given in Table 5.7 and are discussed in the section 5.5.3 about “residue landfill” of this chapter.

Table 5.7 Estimated costs for in-vessel composting plants of different treatment capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons commingled MSW/year)**				
	100	**200**	**300**	**400**	**500**
Fixed costs (million USD/year)	1.94	2.82	3.52	4.40	5.28
Operation costs (USD/ton)	18.5	15.4	13.3	12.3	11.4
Treatment costs (USD/ton)	37.8	29.5	25.0	23.3	22.0

Note:
− The costs to dump residue are not included in the treatment costs given in table 5.7.

The income of in-vessel composting may be slightly higher than with aerated static pile composting. In-vessel composting may produce high-quality compost, and it can be assumed that this will yield benefits if the demand for higher quality compost increases. Because in-vessel composting is less polluting to the environment, it can be located near communities, which could reduce the transportation costs. If land use is a limiting factor in selecting the technology or if land use costs are calculated also, in-vessel composting has an advantage over aerated static pile composting. However, at the moment, the income of in-vessel composting is estimated and aerated static pile composting is assumed to be equal since the price of compost is the same and the land use is free of charge. The income of in-vessel composting from PE plastic and other recyclable wastes is the same as for aerated static pile composting.

5.3 Cost analysis for anaerobic digestion technology

Amongs the various anaerobic digestion technologies a high-solid (dry) continuous flow and a batch technique have been selected for MSW treatment in HCMC (chapter 4). The capacity-costs relationships for these two techniques are presented below.

5.3.1 Continuous anaerobic digestion technology

Figure 5.6 presents a flow scheme of the continuous anaerobic digestion technology proposed for HCMC. In this technology no moisture is added to the digestion process and the digestate can be readily aerobically composted. Similar to composting, the MSW is transported to the continuous anaerobic digestion plant. The MSW is separated to collect the organic matter for the anaerobic digestion process. The separation process in anaerobic digestion plant (both batch and continuous) is similar to that of the composting plant, in which the biodegradable fraction sent to the anaerobic digestion process is about 60% of total MSW input. The recyclable waste is collected and recycled at the site or sold. 3.2 % of the total MSW input is PE plastic waste and 1.8% is other recyclable waste. The leftover residue is discharged to a landfill with about 25% of MSW input to the plant. The leachate flow is amount to about 10% of total MSW input. The digested material from anaerobic digestion process is composted (aerobically) to produce compost. There are two products from the anaerobic digestion technology: biogas and compost. The mass balance of the continuous anaerobic digestion technology is more or less similar to that of the aerated static pile composting plant (figure 5.3).

The costs for different capacities of continuous anaerobic digestion technology in highly industrialized countries are presented in Table 5.8. Treatment costs of continuous anaerobic digestion technology per ton of MSW decrease with increasing plant capacity. The treatment costs of the continuous anaerobic digestion technology in many references are in the range of 80 - 123 USD/ton OFMSW respectively for plants with a capacity of 30,000 - 500,000 tons OFMSW/year. In Europe, the investment costs per ton designed capacity are in range of 265 – 690 USD/ton OFMSW (317- 814 USD/ton OFMSW in 2009) (De Mes et al. 2003). The investment costs of the continuous anaerobic digestion plant given by Economopoulos (2010) (67.6 million USD) for a plant of a capacity of 100,000 tons OFMSW/year are more or less similar to the investment costs given by De Mes et al., (2003).

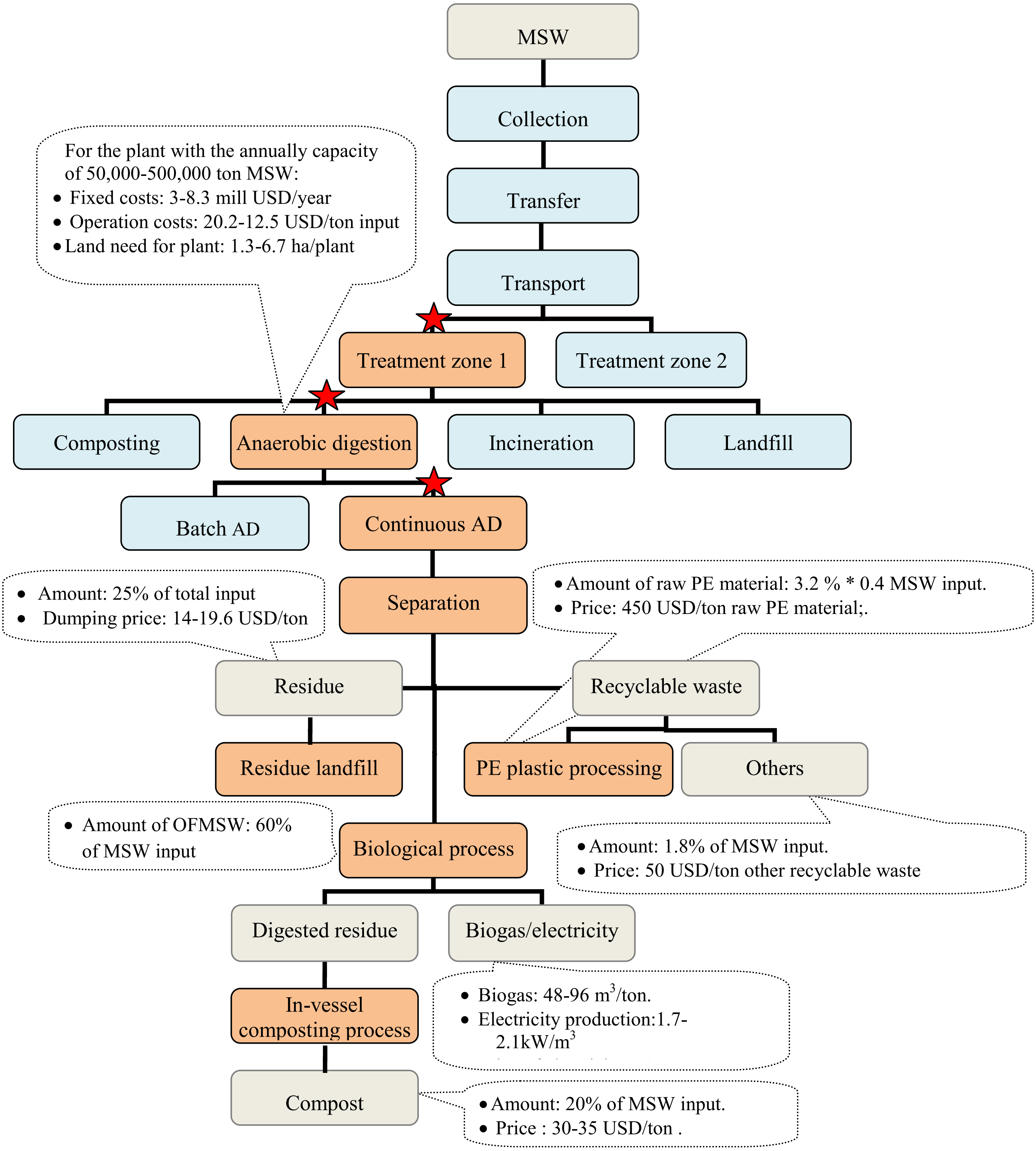

Figure 5.6 Continuous anaerobic digestion scheme.
Note: ★ *are points of decisions for options.*

Table 5.8 Literature review on costs of continuous anaerobic digestion at different capacities in industrialized countries.

Descriptions	Capacity (1000 tons OFMSW/year)		
	30	**77**	**100**
Investment cost (million USD)	20.4	39.2	62
Fixed costs (million USD/year)	1.56	2.99	4.72
Operation costs (USD/ton)	71.4	52.6	68.7
Total treatment costs (USD/ton)	123.4	91.4	115.9
Countries	Netherlands	Australia	Netherlands
Source	*De Mes et al.(2003)*	*Clarke (2000)*	*De Mes et al.(2003)*

Note: These costs are based on OFMSW. It is the same as the 60% organic matter coming from the MSW from HCMC. This means per ton of commingled MSW from HCMC that the costs are substantial lower.

Economopoulos (2010) compared the investment costs of an continuous anaerobic digestion plant and an aerated static pile composting plant at the same capacity of 100,000 tons OFMSW/year, and shows that the investment costs of the continuous anaerobic digestion plant are 2.3 times higher than those of the composting plant. Continuous anaerobic digestion technology application in HCMC would need imported technology and equipments. A continuous anaerobic digestion plant needs to be combined with a small composting plant to compost the digested material after the anaerobic digestion process. In view of the bad odor coming from the digested material, in-vessel technology is assumed for the post-composting plant. Therefore, we use the factor of 2.5 based on the investment cost of aerated static pile composting plant in HCMC to estimate the fixed (investment) cost of continuous anaerobic digestion in HCMC. For the operation costs, we take the factor of 1.2 compared to aerated static pile composting plant in HCMC. The estimated costs of continuous anaerobic digestion technology are presented in Table 5.9. The cost of dumping residues is not included in the estimation of the treatment costs given in this table. These costs are discussed in the section 5.5.3 about "residue landfill" of this chapter.

Table 5.9 Estimated costs of continuous anaerobic digestion plants for different capacities in Ho Chi Minh City.

Descriptions	Capacity (1000 tons commingled MSW/year)				
	100	**200**	**300**	**400**	**500**
Fixed costs (million USD/year)	3.0	4.4	5.5	6.9	8.3
Operation costs (USD/ton)	20.2	16.8	14.5	13.4	12.5
Treatment costs (USD/ton)	50.4	38.8	32.9	30.6	29

Note:

- *The costs to dump residue are not included in the treatment costs given in table 5.9.*

References show that the biogas production of continuous anaerobic digestion technology is about 80 - 160 m^3/ton OFMSW (average 120 m^3/ton). MSW in HCMC is commingled waste from which 60% is effectively separated as biodegradable organic matter input to the anaerobic plant. Therefore the biogas production from commingled MSW is about 60% of the reference data which means about 48 - 96 m^3 biogas/ton commingled MSW input to the anaerobic digestion plant (average: 72 m^3/ton MSW). Economopoulos (2010) and Electrigaz (2010) show that 1 m^3 biogas with 50 - 60% methane content can be converted to 1.7 - 2.1 kWh (the overall conversion efficiency is 30 - 33%). Therefore, the electricity production is about (1.7 - 2.1)* (48 - 96)= 82 - 202 kWh/ton commingled MSW (average: 142 kWh/ton MSW). Heat energy is about the double amount of the electrical energy; therefore it is about 164 - 404 kWh heat energy/ton commingled MSW (average: 284 kWh/ton MSW). Because of the high moisture content in collected organic matter, compost product is only 20% of total MSW input. The income from a continuous anaerobic digestion plant is presented in Table 5.10.

Table 5.10 Estimated income from continuous anaerobic digestion plant per ton of municipal solid waste input.

Descriptions	**Volume/Amount**	**Unit price**	**Income** (USD/ ton MSW input)
Electricity	(48 - 96) m^3 biogas/ton ≈ (82 - 202) kWh/ton MSW	8 (cent USD/kWh)	6.6 - 16.2
Heat	(164 - 404) kWh/ton MSW	0 (USD/kWh)	0
Compost	20% of total MSW input	30 - 35 (USD/ton compost)	6 - 7
Raw PE material	3.2% * 0.4 of total MSW input	450 (USD/ton plastic)	5.8
Other recyclable waste	1.8 % of total MSW input	50 (USD/ton recyclable material)	0.9
Total			19.3 - 29.9

5.3.2 Batch anaerobic digestion technology

The scheme for batch anaerobic digestion technology in HCMC is presented in Figure 5.7. Similar to the scheme of Continuous flow plants the collected MSW is transported to treatment zone 1 and/or 2 and then to the batch anaerobic digestion plant. The mass balance (percentages of OFMSW, collected biodegradable organic matter, residue, recyclable waste, compost) of the batch anaerobic digestion technology is similar to aerated static pile composting (Figure 5.3). The differences between continuous anaerobic digestion and batch anaerobic digestion technology are: (1) the investment costs of continuous anaerobic digestion are 40% higher than for batch anaerobic digestion (Joshua et al. 2008; De Mes 2003), (2) the continuous anaerobic digestion process is more complicated and requires more energy and technical skills, (3) the digestion time of continuous anaerobic digestion process is shorter, and (4) continuous anaerobic digestion technology produces more biogas and may produce a higher quality of compost made from the more homogeneously digested MSW. In both cases, depending on the requirements, the biogas can be converted into electricity or heat or both.

Comparison of data of the operation costs (Table 5.11) shows that the operation costs (USD/ton) at higher batch anaerobic digestion capacity is higher (the case of the Netherlands- De Mes, 2003) than at lower batch anaerobic digestion capacity (the case of Switzerland- Edelmann, 2000). Normally the opposite is true. Reasons for the higher operation costs (USD/ton) at higher capacity may be: (1) the treatment reported is combined treatment of anaerobic digestion and composting of the digestate to produce compost. At high capacity (in the Netherlands, Biocel process) the more expensive in-vessel technology was used for composting of the digestate, while in Switzerland for small-scale installations the cheap windrow composting technology was applied; (2) dramatic changes of the monetary exchange rate; (3) different ways of cost calculation.

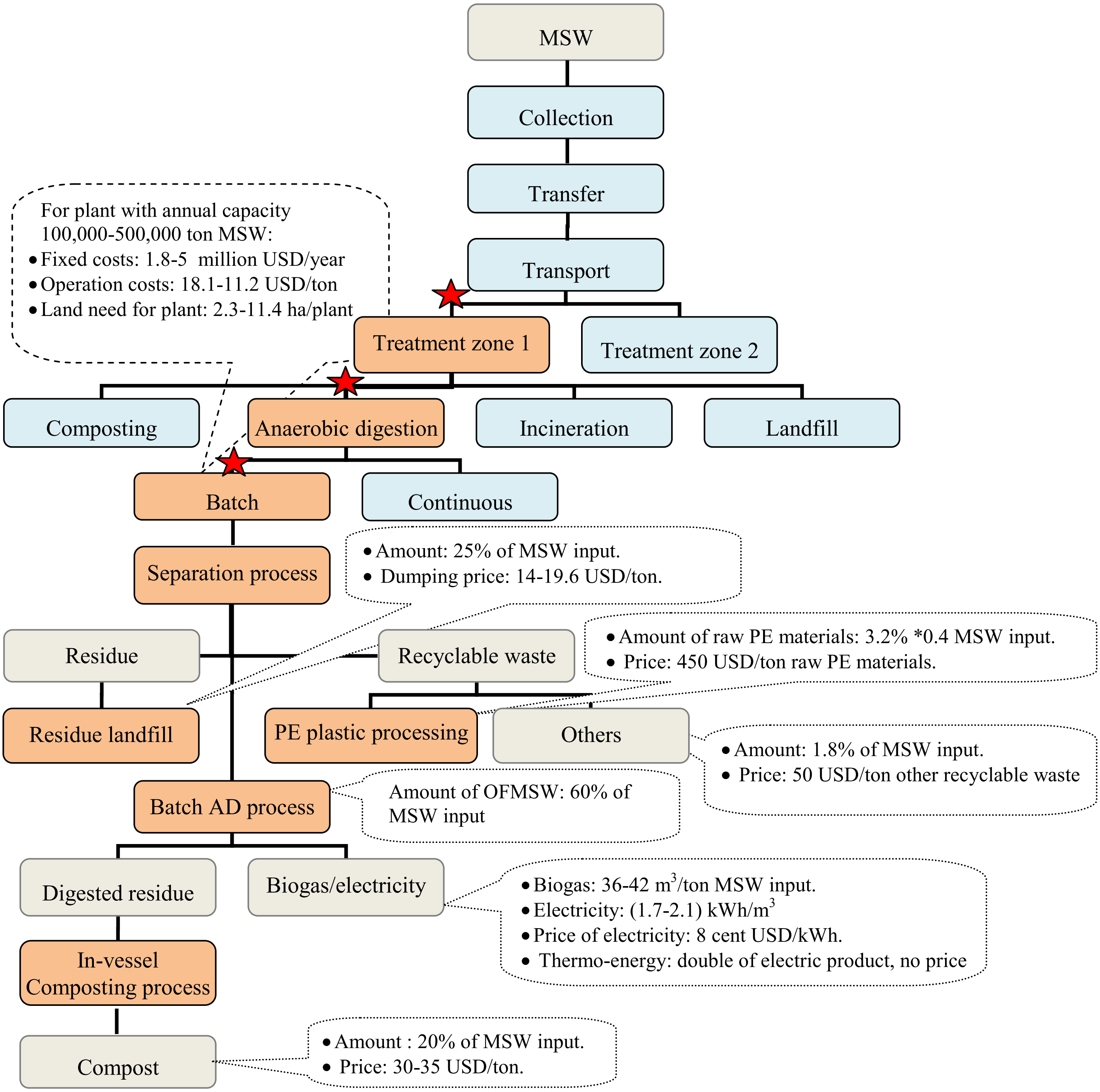

Figure 5.7 Batch anaerobic digestion scheme.
Note: ★ *are points of decisions for options*.

Comparing treatment costs of small-scale plants shows that the anaerobic digestion treatment costs in Viet Nam are about 34 % of the anaerobic digestion treatment costs in Switzerland (Table 5.11). It should be taken into account that in Viet Nam second hand equipment was used, with a lifetime for the system of 5 years, while the plant in Europe was brand new with a lifetime of 20 years.

De Mes (2003) showed that the capital cost for commingled MSW batch anaerobic digestion facilities is higher than that for source separated MSW by about 8 - 9%.

Table 5.11 Literature review on costs of batch anaerobic digestion technology at different capacities in industrialized countries.

Descriptions	**Capacity (1000 tons OFMSW/year)**		
	6	10	100
Investment costs (millions USD)	-	-	37.1
Fixed costs (million USD/year)	0.014	0.76	2.83
Operation costs (USD/ton)	37.8	44	87.6
Total treatment cost (USD/ton)	41.2	120	115.9
Country	Viet Nam	Switzerland	The Netherlands
Source	*Kim Oanh (2009)*	*Edelmann et al.(2000a)*	*De Mes et al.(2003)*

Notes:

- *Kim Oanh (2009) estimated the costs of batch anaerobic digestion combined with windrow composting treating 20 ton/day and a 5- year lifetime, with all equipment second hand at market prices in HCMC, Viet Nam.*
- *Edelmann (2000) presented thermophilic digestion in the batch technology combined with windrow composting in Switzerland.*
- *De Mes (2003) presented anaerobic digestion digestion combined with in-vessel composting in the Netherlands.*

Joshua et al.(2008) reported that the investment cost of a Biocel plant (batch anaerobic digestion technology) is equal to about 60% of the investment of other technologies like Dranco, Kompogas or Valorga (continuous anaerobic digestion technology) at the same treatment capacity. The investment costs of Dranco, Kompogas or Valorga are comparable and amount to about 400 €/ton designed digester capacity (≈ 620 USD/ton in 2009) (De Mes et al. 2003, , p 84). This number included a 30% share for CHP (Combined Heat and Power generator) in the investment costs. Therefore, the investment cost of the Biocel technology will be about 240 €/ton digester capacity (371 USD/ton digester capacity in 2009). De Mes, Stams et al. (2003) showed that the average treatment costs of source separated OFMSW in Biocel, Dranco and Valorga systems are comparable at about 75 €/ton in 2003 (equal to about 116 USD/ton in 2009). As the investment costs of Biocel are lower than the investment costs of the Valorga technology (Joshua et al. 2008), the operation costs of the Biocel system are higher possibly due to higher labor and land cost. In HCMC labor is cheap, municipal land is free of charge for public infrastructure at the moment. Therefore, different from the data of De Mes et al., the operation costs for batch anaerobic digestion in HCMC could be lower than for the continuous anaerobic digestion technology. Here, the fixed and operation cost for an batch anaerobic digestion plant in HCMC are assumed to be 60% and 90% of the respective costs of the continuous anaerobic digestion technology. Estimated costs of batch anaerobic digestion plants for different capacities are presented in table 5.12.The costs of dumping residue are not included in the treatment costs given in this table. The costs to dump residue are discussed in the section 5.5.3 about "residue landfill" of this chapter.

Table 5.12 Estimated costs of batch anaerobic digestion plants for different capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons commingled MSW/year)**				
	100	**200**	**300**	**400**	**500**
Fixed costs (million USD/year)	1.82	2.64	3.30	4.13	4.95
Operation costs (USD/ton)	18.1	15.1	13.1	12.1	11.2
Treatment costs (USD/ton)	36.3	28.3	24.1	22.4	21.1

Note:

− The costs to dump residue are not included in the treatment costs given in table 5.12.

Similar to the data of continuous anaerobic digestion, the biogas production in batch anaerobic digestion technology is about 59 – 70 m^3/ton OFMSW which is about 36 - 42 m^3 biogas/ton of commingled MSW in HCMC. Therefore, the electricity production is about 61 - 88 kWh/ton MSW (1 m^3 biogas ~ 1.7 - 2.1 kWh) and heat production 122 - 176 kWh/ton MSW. Table 5.13 shows the estimated income of a batch anaerobic digestion plant.

Table 5.13 Estimated benefits of a batch anaerobic digestion plants per ton of municipal solid waste input.

Descriptions	**Volume/Amount**	**Unit price**	**Income (USD/ ton MSW)**
Electricity	36 - 42 m^3 biogas/ton MSW ≈ 61 – 88 kWh/ton MSW	8 (cent USD/kWh)	4.9 - 7
Heat	122 – 176 kWh/ton MSW	0 (cent USD/kWh)	0
Compost	20 % of total MSW input	30 - 35 (USD/ton compost)	6 - 7
Raw PE material	0.4 * 3.2% of total MSW input	450 (USD/ton plastic)	5.8
Other recyclable waste	1.8 % of total MSW input	50 (USD/ton recyclable material)	0.9
Total			17.6 – 20.7

5.4 Costs analysis for incineration technology

As shown in chapter 4 there are three ways to combust high moisture solid waste:
1. Incineration with electricity production by means of a boiler, steam turbine and generator;
2. Incineration without electricity production;
3. Incineration of MSW with electricity production by co-combustion of a high-calorific fuel like coal.

The high moisture content puts special requirements to the drying of the waste before and during the combustion process. As the heat value is low, measures have to be taken to make optimal use of the available heat. Here, the first two options are adopted in the technology comparison for HCMC. The third technology is not discussed because it is not relevant in industrialized developed countries.

5.4.1 Incineration with energy recovery

For combustion of MSW it is not necessary to separate the MSW into fractions. Depending on the type of waste, some activities may be needed to make the incineration process possible. The input material needs to have a suitable particle size. Therefore, separation of big objects from the MSW is needed. Also leachate is separated to reduce the moisture content of the waste and increase the heat value. Due to the fact that the waste is wet and the heat value low, the heat in the low-pressure steam from the boiler and turbine is used for drying the MSW in an external drier. Further, condensation of the water from the drying gases results in a water phase that contains volatile fatty acids, which has to be treated. The cost to treat leachate and water condensation is included in the cost analysis of incineration with energy recovery.

The mass balance of an incineration plant is presented in figure 5.8. It is estimated that out of the total commingled MSW mass arriving at the incineration plant 10% is separated as residue (rejected large objects) (with 20% moisture content) and 5% as leachate[42]. The remaining 85% MSW is fed to the combustion chambers. As incineration plants are capable of processing all sorts of waste except non-combustibles and very large objects, the amount of rejects that have to be shunted to a landfill is rather small (10%). The moisture content of the rejects is low due to the fact that most of them are inorganic materials, such as: concrete waste, rock, etc. The pretreated MSW has a moisture content of 56%, which is dried to a moisture content of 35 % before being fed to the combustion chamber (see chapter 4). These activities reduce the amount of MSW to 57% of total commingled MSW. The amount of ash is assumed to be 33% of the amount of MSW to get into the combustion

[42] Due to the short retention time of the incoming MSW in the incineration plant the initial leachate removal is only 5%.

box of the incineration plant (Biffaward 2007; World Bank 1999). Therefore, the amount of ash is about 19% (= 0.33 * 57%) of the initial commingled MSW input to the plant MSW.

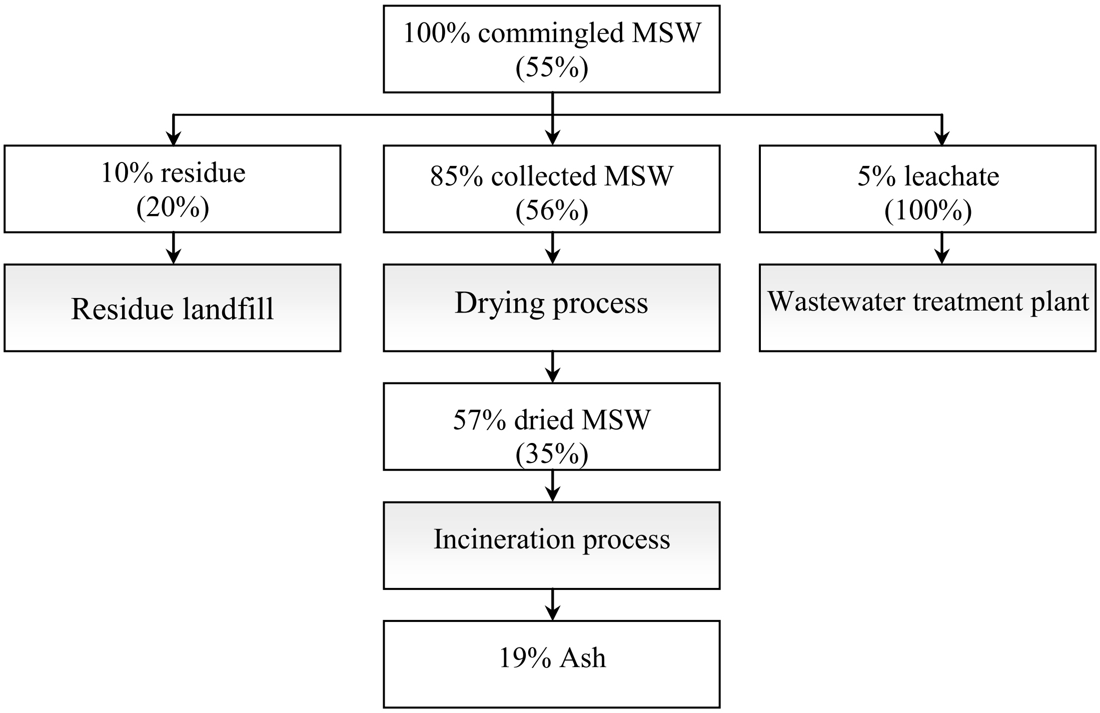

Figure 5.8 Mass balance of an incinerator in Ho Chi Minh City.
Note: the percentages between brackets indicate the moisture content.

Figure 5.9 shows the scheme for incineration of MSW in HCMC.

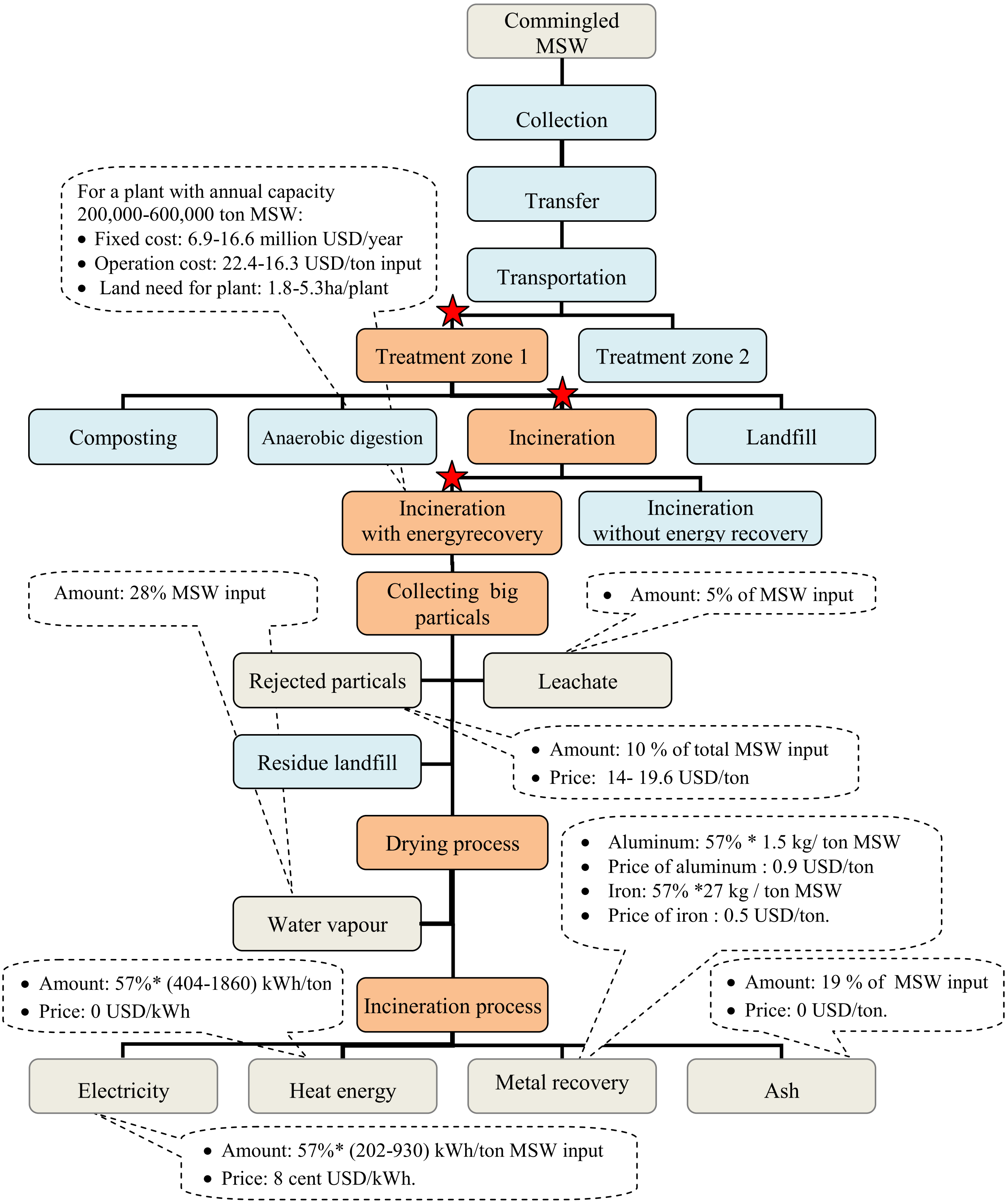

Figure 5.9 Incineration with energy recovery scheme in Ho Chi Minh City.
Note: ★ are points of decisions for options.

Table 5.14 presents the costs in dependence of the treatment capacity of incineration plants with energy recovery. These costs are obtained from Perkoulidis et al. (2010). Rabl and co-workers (2008) found respectively a cost of 69.7 and 66.6 USD/ton at capacities of 300,000 and 500,000 ton/year of waste fed to an incinerator, which is similar to the costs of Perkoulidis.

We assume that, after the pretreatment and the drying process, the MSW fed to the incinerator has the same calorific value as the MSW in Europe: about 9 - 11 MJ/kg (DEFRA 2007). In addition, the fixed and operation costs of incinerators depend on the air pollution regulations and local discharge regulations (World Bank 1999). In case of Viet Nam, we take the same pollution discharge standards as mentioned by Perkoulidis et al. (2010).The costs to dump residue are not included in the treatment costs given in table 5.14. The costs to dump residue are discussed in the section 5.5.3 about "residue landfill" of this chapter.

Table 5.14 Literature review on costs of incineration with energy recovery at different capacities in industrialized countries.

Descriptions	**Capacity (1000 tons MSW/year)**				
	200	300	400	500	600
Investment costs (million USD)	110.5	153.4	193.1	230.8	266.5
Fixed costs (million USD/year)	8.42	11.7	14.7	17.6	20.3
Operation costs (USD/ton)	27.3	24.3	22.4	21.1	19.9
Treatment costs (USD/ton)	69.4	63.3	59.2	56.3	53.7

Source: Perkoulidis, 2010.

Note: the costs are for raw MSW before removal of 10% rejects. The costs to dump residue are not included in the treatment costs given in table 5.14.

As incineration plants in Viet Nam have to be imported from Europe, the US or Japan, the costs of incineration with energy recovery plants in Viet Nam are calculated based on the costs in Europe taking into account that:

- The land use is free which reduces the investment costs. However, the investment costs for HCMC will increase due to import costs and expert training costs. Therefore, we assume the same investment costs as in the highly industrialized countries.
- The mass flow of MSW in HCMC that is fed to the incinerator is reduced due to the separation of rejected objects, leachate and the water that is removed in the drying process. We assume that the residue of large pieces in European MSW for which the data of table 5.14 holds is also 10% and that as a consequence the amount of MSW to be incinerated is 90% of the raw MSW. Therefore, regarding this aspect, we apply a correction factor of 57%/0.90 = 0.63 to the investment costs of the incineration plant. This factor expresses the capacity reduction due to the lower mass flow of the commingled MSW (original collected waste) that goes to the incineration plant in HCMC (see mass balance in figure 5.8).
- The investment costs of an incinerator system in Viet Nam will be higher compared to the case of Europe. Due to, it is included the additional investment costs of extra measures for external waste drying, vapor condensation and treatment of the condensate. Take into account the amount of MSW in the case of Viet Nam to get into the drying process and subsequent incineration process are 85% and 57% of the initial amount of MSW. It is assumed that the investment costs of incineration system in Viet Nam are about 1.3 times of Europe.

Overall, the investment costs of an incinerator (including a drier) in HCMC per ton of incoming commingled MSW = investment cost in Europe * 0.63 * 1.3 = investment costs in Europe * 0.82. This factor is assumed to be independent from plant capacity. Besides that, to calculate the benefit, the amount of product is calculated based on the amount of MSW that is fed to the incineration process after drying, which is 57% of the total commingled MSW.

Similar to investment cost, the operation costs for an incinerator in HCMC is estimated based on the operation costs of European installations, taking into account:

- The labor costs for the incineration process in HCMC is lower but costs for experts and maintenance are higher. Therefore, taking this aspect into account, we assume the same labor costs.

- Similar to investment costs, we take into account the additional operation costs of the drying process, (including also the treatment of the off-gases of the dryer and the recovery of heat from the treatment of the off-gases of the dryer) and the treatment of the leachate. Take into account the amount of waste to the dryer is higher than the amount of waste to the incineration process. We assume that these additional operating costs are 30% of the operating costs of the incineration process, augmented with a factor 1.3.
- The actual amount of MSW fed into the incineration process in HCMC and Europe are 0.57 and 0.9 times the received raw MSW respectively. We take therefore a correction factor of 0.57/0.90 = 0.63. In general, the operation costs in HCMC (USD/ton commingled MSW) are assumed to be equal to the operation cost in Europe multiplied by 1.3 * 0.63 = 0.82.

Table 5.15 shows the estimated costs for incineration plants in HCMC. Here, it is assumed that ash is reused and therefore not dumped and that the costs of ash processing are equal to the benefits of reuse. Therefore no costs for ash processing are taken into account. The costs to dump residue are not included in the treatment costs given in table 5.15.

Table 5.15 Estimated costs of incineration with energy recovery in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons commingled MSW/year)**				
	200	300	400	500	600
Fixed costs (million USD/year)	6.9	9.6	12.0	14.4	16.6
Operation costs (USD/ton)	22.4	19.9	18.3	17.3	16.3
Treatment costs (USD/ton)	56.8	51.8	48.4	46.1	44.0

Note:

− The costs to dump residue are not included in the treatment costs given in table 5.15.

In the Netherlands, the average electricity and heat production of incinerated MSW in all incinerators with energy production, including old and new incinerators, is about 362 kWh/ton and 1,364 MJ/ton commingled MSW, respectively (Statistic Yearbook of the Netherlands 2008). Dijkgraaf and Vollebergh (2004) showed in a case study of new incineration technology with 648,000 tons MSW incinerated/year, an electricity production of 580 kWh/ton, thermal heat of 299 kWh/ton, 1.6 kg of aluminum/ton and 34 kg of iron/ton MSW. Rabl et al. (2008) showed that electricity and heat production from waste in the incinerator was 202 and 607 kWh/ton waste. Aluminum and iron recovery from the ash was 1.5 and 20.2 kg/ton waste. COWI (2000) showed that the electricity production from incineration of MSW was about 470 - 930 kWh/ton MSW incinerated. Based on the references above, the electricity production from MSW is in the range of 202 - 930 kWh/ton incinerated.

Table 5.15 shows the benefits of the incineration process to energy recovery. As was shown in chapter 4 on the basis of an energy balance, the expected electricity output on the basis of the wet waste of HCMC would be in the order of 340 kWh/ton MSW. Using the output data of regular MSW incinerators from literature, which range from 202 to 930 kWh/ton, and taking into account that in HCMC the dried waste is only 57% of the initial flow of waste, the expected electricity production would be in the range of 115 - 530 kWh/ton of commingled MSW [(202 - 930) * 0.57]. Here, the average value in this range of 323 kWh/ton is adopted as expected electricity output of the incinerators in HCMC. Depending on the needs the energy from incineration can be converted into electricity or heat. In the case of HCMC, there is no market for heat at the moment and given the high moisture content of the waste the heat in the low-pressure steam from the turbine must be used for the drying process. Therefore, no financial benefits are expected from heat generation.

In Viet Nam the benefit from electricity production is low due to the low current electricity price. However, in the future if the subsidy stops, the electricity cost is expected to increase and be in line with the cost in regional countries like Philippine (18.1 cent USD/kWh)[43], Singapore (22 cent USD/kWh)[44]. The market costs of recycled aluminum and iron in HCMC in 2009 are 0.9 and 0.5 USD/kg, respectively[45].

Table 5.16 Estimated income of incineration with energy recovery in Ho Chi Minh City per ton municipal solid waste input.

Descriptions	**Units/ton MSW**	**Unit price**	**Income** (USD/ ton MSW input)
Electricity	115 – 530 kWh/ton	8 cent USD/kWh	9.2 - 42.4
Heat	230- 1,060 kWh/ton	0	0
Aluminum recovery	0.86 – 0.91 kg/ton	0.9 USD/kg	0.77- 0.82
Iron recovery	11 - 19 kg/ton	0.5 USD/kg	5.7- 9.7
Total			15.7 – 52.9

5.4.2 Incineration without energy recovery

This technology is cheaper than an incinerator with energy recovery since it needs no investment in an energy recovery system. However, there are no beneficial products. In the incinerator without energy recovery, it may not be necessary to invest in an external drying process. Therefore, the amount of MSW that is fed to the incineration process is high, namely about 85% of total MSW input to the plant. The mass balance of incineration without energy recovery is given in figure 5.10. Similar to incineration with energy recovery, in the incineration without energy recovery plant, big pieces are removed first (about 10% of total MSW input) and disposed at the residue landfill. The amount of leachate removed is assumed to be 5%.

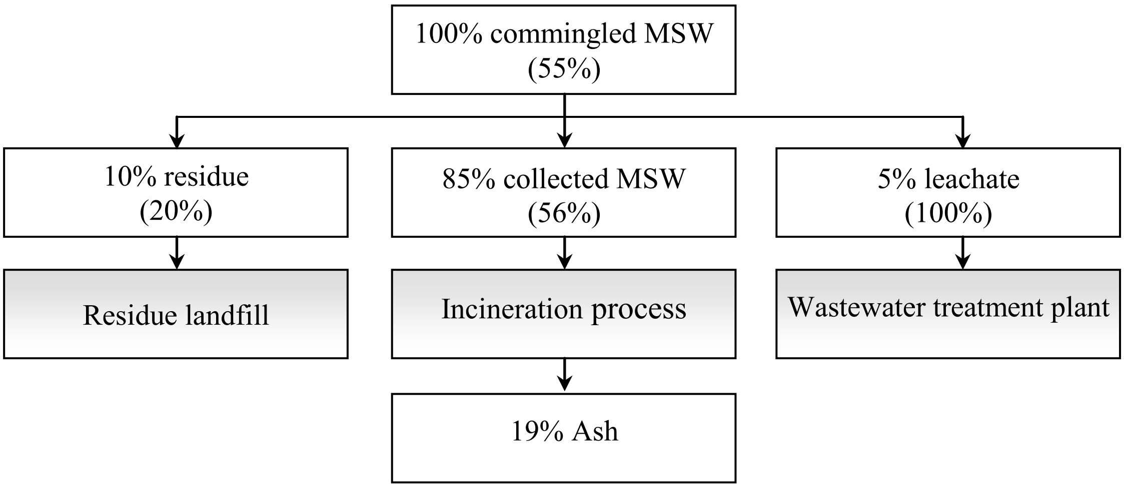

Figure 5.10 Mass balance of incinerator without energy recovery.
Note: the percentages between brackets indicate the moisture content.

A flow chart for incineration without energy recovery technology is given in Figure 5.11. As mentioned previously, 85% of the MSW input with a moisture content of 56% is fed into the combustion chamber. We assume that the energy production is sufficient for the incineration itself. Some Diesel fuel is needed for starting the combustion and possibly also in periods the heat value of the waste is too low for self-combustion. In HCMC, the ash is used as construction material and is free of charge.

[43] Data from web page of Manila Bulletin Publishing Corporation in 2011 (http://www.mb.com.ph), download date: 31/5/2012.
[44] Data from web page of Singapore Power in 2010 (http://www.singaporepower.com), download date: 18/11/2010
[45] Survey market cost of Aluminum and Iron on August 2009 (These costs respectively with the lowest quality of Aluminum and Iron).

Literature reviews on costs analysis of incinerators without energy recovery are very rare and outdated due to the fact that in many developed countries, especially European countries, it is not allowed to build these plants anymore. Probably some of the existing incinerators without energy recovery are still in operation. It is difficult to compare the costs of incineration with and without energy recovery, since the latter is an old treatment technology and incineration with energy recovery is a new environmentally more sustainable technology. From an environmental point of view, the incineration without energy recovery must be adapted to the discharge standards for air emission control. Therefore, in general, the combustion and exhaust gas technology of incinerators without energy recovery is similar to incineration with energy recovery. The difference is that the investment costs of incinerators with energy recovery includes the costs of the system to recover energy and sometimes the drying system. Operation costs of incinerators without energy recovery are lower than that of incinerators with energy recovery due to lower labor and maintenance costs, especially for the energy recovery system and drying system.

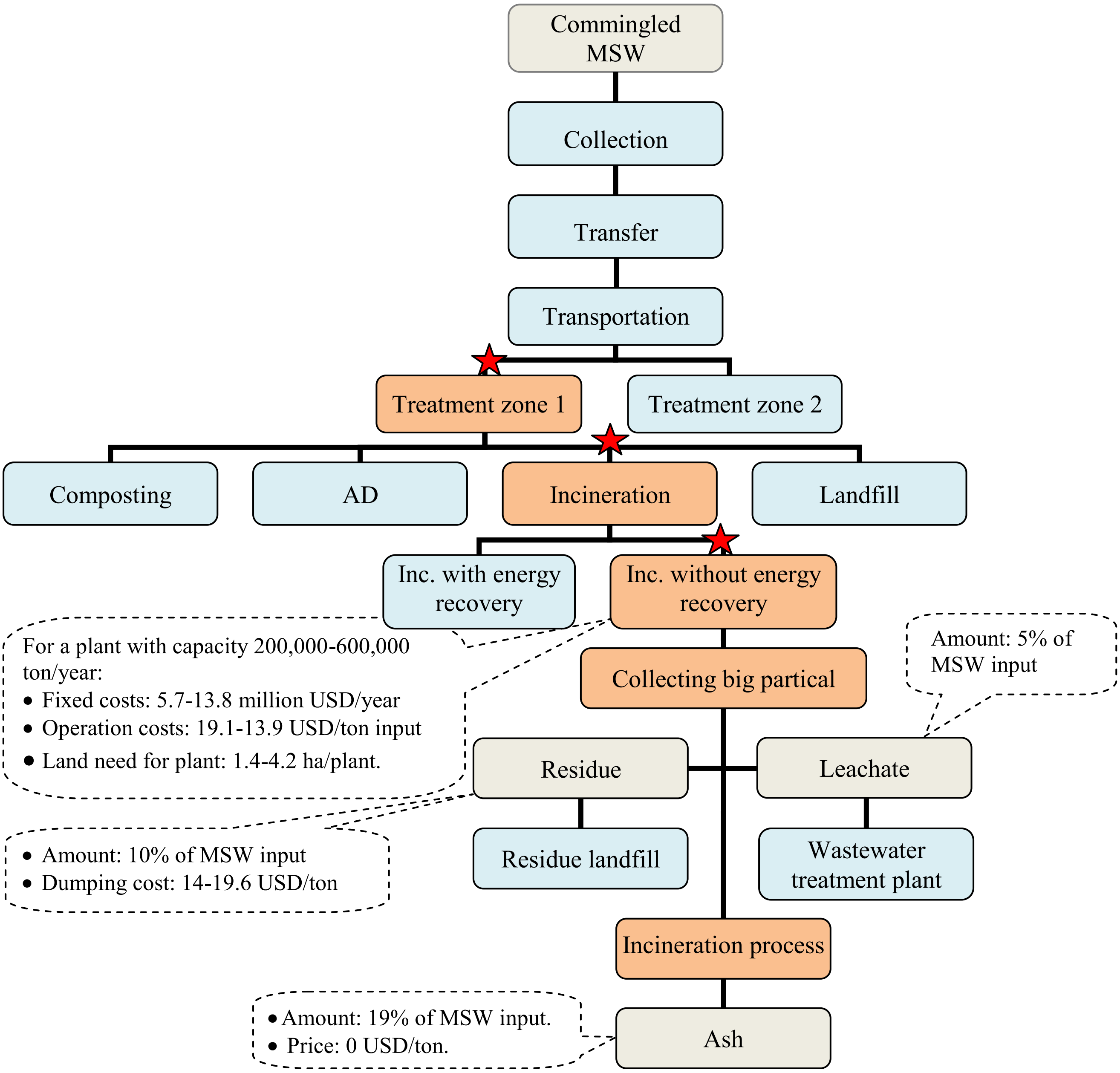

Figure 5.11 Incineration without energy recovery.
Note: ★ *are points of decisions for options.*

The investment costs of incineration without energy recovery in HCMC is calculated based on the investment cost of incineration with energy recovery in HCMC, taking into account that:

- The land use is lower due to the fact that no land is required for the drying process in an Incineration process without energy recovery plant. Therefore, we assume that the land use is 0.8 times the land use of an incinerator with energy recovery and drying system;
- The investment costs for an incinerator without energy recovery in highly industrialized countries is assumed to be 0.72 times the investment costs of an incinerator with energy recovery;
- For this type of incinerator the investment costs in Viet Nam are 0.85/0.9 of this investment. (In Viet Nam 85% of the raw MSW goes to the incinerator without energy recovery and in Europe this is 90%). Thus investment costs for an incinerator without energy recovery in Viet Nam, for the type of waste produced in HCMC is 0.72 * 0.85/0.9 = 0.68 times the investment costs for an European incinerator with energy recovery, all related to the amount of commingled MSW collected in HCMC.

Operation costs of incineration without energy recovery are lower than those of incineration with energy recovery, because this type of incineration has no drying and energy recovery system. Therefore, we take for the operation costs of this technology a factor 0.7 of the operation cost of European plants with energy recovery. Table 5.17 shows the estimated costs for incineration plants without energy recovery in HCMC. Here, it is assumed that ash is reused and therefore not dumped and that the costs of ash processing are equal to the benefits of reuse. Therefore no costs for ash processing are taken into account. The costs to dump residue are not included in the treatment costs given in table 5.17

Table 5.17 Estimated costs of incinerators without energy recovery for different capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons commingled MSW/year)**				
	200	**300**	**400**	**500**	**600**
Fixed cost (million USD/year)	5.7	8.0	10.0	12.0	13.8
Operation cost (USD/ton)	19.1	17.0	15.7	14.8	13.9
Treatment cost (USD/ton)	47.7	43.5	40.7	38.7	36.9

Note:

– The costs to dump residue are not included in in the treatment costs mentioned in table 5.17.

The technology of incineration without energy recovery has no energy benefits but may have benefits from ash if it can be sold as raw material. In the case of HCMC, ash can be used as construction material. However these benefits are neglected in the comparison of the various treatment technologies.

5.5 Cost analysis for landfill technology

In this chapter the costs of three types of landfills are estimated: the sanitary landfill, the bioreactor landfill and the residue landfill. A sanitary landfill is a biological treatment process with biogas as the main product. A bioreactor landfill is a sanitary landfill with recirculation of leachate through the waste masses in order to accelerate the biological process. More biogas is produced in a shorter time compared to the regular sanitary landfill. A residue landfill is also a sanitary landfill but it is used to dump residue (non-biodegradable matter) from separation processes in MSW treatment. It produces less polluted leachate than a sanitary landfill and very little biogas which is not recovered as energy product.

5.5.1 Sanitary landfill

In the calculation of the sanitary landfill option, we assume that the sanitary landfill receives MSW only and not the less biodegradable residues from separation processes. The mass balance of a sanitary landfill is shown in figure 5.12. During the time MSW is kept at the collection point at the landfill before being transported into dumping cells, MSW produces leachate. The amount of leachate is estimated at 5% of total MSW input. This leachate will be collected and treated at the wastewater treatment plant together with leachate from dumping cells.

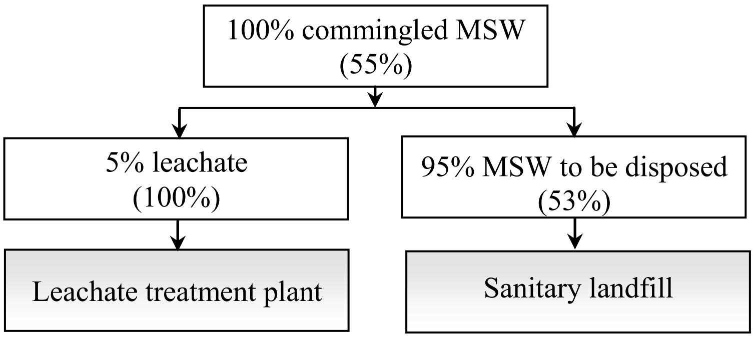

Figure 5.12 Mass balance of the sanitary landfill.
Note: the percentages between brackets indicate the moisture content.

Figure 5.13 shows the place of landfill in the totality of technology choices in waste management.

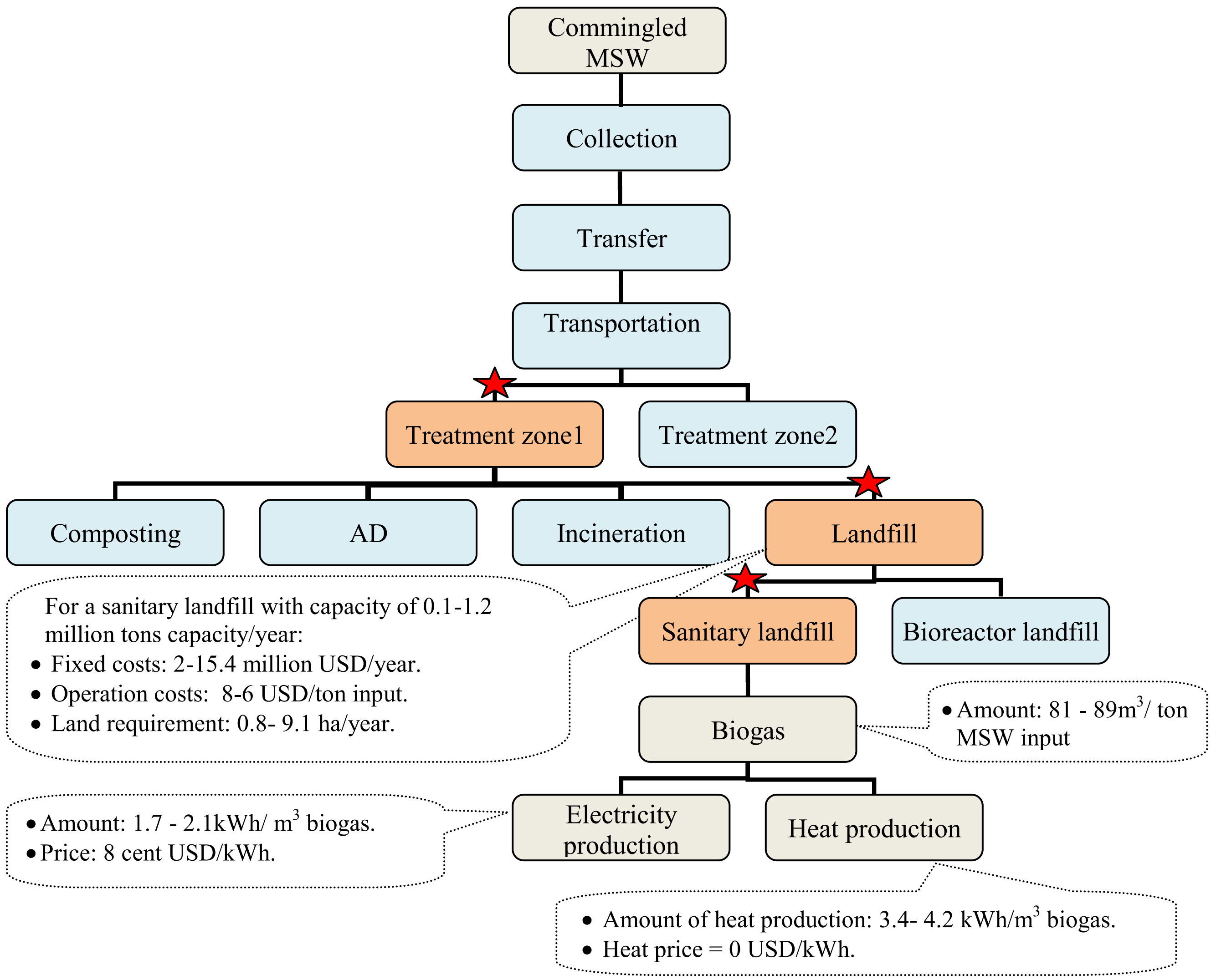

Figure 5.13 Sanitary landfill scheme.
Note: ★ *are points of decisions for options.*

In the case of landfill treatment (both sanitary landfill and bioreactor landfill) costs include the costs of land use, construction, operation, landfill cover, biogas collection and treatment, leachate treatment, maintenance and aftercare. The applied technologies must adapt to the pollution discharge standards of the local government. The BDA Group (2009) showed that the treatment costs for sanitary landfills in Australia were 94, 56 and 38 USD/ton for small, medium and large scale plants, respectively. Small, medium and large-scale are defined as plants having a treatment capacity less than 10,000, from 10,000 - 100,000 and more than 100,000 tons/year, respectively (Table 5.18). The data shows that the treatment costs are strongly depending on the capacity of the landfill.

Table 5.18 Literature review on costs of Sanitary landfill at different capacities in Australia.

Descriptions	**Capacity (1000 tons MSW/year)**		
	10	**10-100**	**>100**
Fixed costs (million USD/year)	-	-	-
Operation costs (USD/ton)	-	-	-
Treatment costs (USD/ton)	94	56	38

Source: BDA group (2009).

The costs analysis of Phuoc Hiep 2 sanitary landfill in HCMC with a capacity of 1.1 million tons/year is presented in the last column of Table 5.19. The costs are high compared to other sanitary landfills in Viet Nam due to the weak geological structure of the soil it was built on. The costs of sanitary landfills in Australia were higher than in HCMC. In Australia the costs include costs of land, while costs of management, labor, materials and aftercare are much higher.

The capacity of the two currently operational sanitary landfills in HCMC is about 3,000 tons/day (equal to 1.1 million tons/year/landfill). These are relatively high capacities compared to most landfills in the US, Europe, Australia, etc. However, the total capacity of the two landfills together (2.2 million tons/year) is just enough to serve the current requirements of HCMC. If no other MSW treatment technology will be adopted, all the MSW must be deposited at new landfills. We take the current sanitary landfill size as a unit to calculate the costs of bigger sites. Basing ourselves on the actual costs of Phuoc Hiep landfill and the capacity – costs curve of landfills in Australia (BDA group 2009), we obtained the estimated costs of sanitary landfills in HCMC (Table 5.19).

Table 5.19 Estimated costs of sanitary landfills for different capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons commingled MSW/year)**				
	100	**300**	**500**	**800**	**1,100***
Fixed costs (million USD/year)	2.0	5.55	8.5	12.4	15.4
Operation costs (USD/ton)	8.0	7.5	7.0	6.5	6.0
Treatment costs (USD/ton)	28	26	24	22	20

*Note: * the actual data of Phuoc Hiep 2 landfill in HCMC (DONRE HCMCi 2009).*

In order to calculate the biogas production from sanitary landfills, the following aspects should be taken into account:

- The sanitary landfill is provided with a collection system for recovery of biogas and electricity generation system;
- The biogas will be collected during 15 years after depositing the waste;
- In a standard landfill with biogas recovery 30% of the produced biogas is lost;
- Biogas production in the post-closure period is lost (after year 15).

The benefit from sanitary landfills is biogas production, which is about 109 – 120 m^3 biogas/ton input after 15 years of deposition time in Europe (Veolia 2010; Eastern Research Group and MGM International Group 2008; Dijkgraaf and Vollebergh 2004). The moisture content of MSW in this case (in Europe) is about 35%. If 1 m^3 biogas with methane content of 50 - 60% can be converted to 1.7 - 2.1 kWh electrical energy, the electricity production is about 185 - 252 kWh/ton input. The MSW deposited into the sanitary landfills in HCMC has an estimated moisture content of 53% (figure 5.12), so that the dry matter content is 47%. It means that the dry matter in MSW in the references is about 65%. We take into account waste with a high organic fraction compared to our references, so we estimate with the factor 1.1 (=gas production/ton of dry matter in HCMC/gas production per ton of dry matter in literature). Therefore, we estimate the biogas production from MSW in HCMC to be 87 - 95 m^3/ton commingled MSW [(109 - 120) * 47/65 * 1.1]. Electricity production is 148 - 200 kWh/ton. The production of heat energy is twice as much [(148 - 200) * 2 = 296 - 400 kWh/ton].

Table 5.20 Estimated income from the energy production from sanitary landfills in Ho Chi Minh City per ton of municipal solid waste input.

Descriptions	**Volume/Amount**	**Unit price**	**Income** (USD/ tons MSW input)
Electricity	87 - 95 m^3 biogas/ton ≈ 148 -200 kWh/ ton	8 cent USD/kWh	11.8 - 16.0
Heat	296 – 400 kWh/ton	0	0
Total			11.8- 16.0

5.5.2 Bioreactor landfill

Typical for a bioreactor landfill is recirculation of leachate to enhance the stabilization rate of biodegradable matter. This recirculation of leachate may result in a lower overall leachate generation than in sanitary landfills without leachate recirculation. Excess leachate is stored in a reservoir and from time to time sent to a post-treatment plant. Apart from leachate recirculation also other measures have been tested and applied in landfill bioreactors, such as air injection and inoculation of nutrients or inoculate, but these are not part of the technology discussed here. The mass balance of the bioreactor landfill is similar to the one for sanitary landfill (figure 5.12).

In general, construction, equipment and maintenance of bioreactor landfills are more complex and more expensive as compared to sanitary landfills. However, in the bioreactor landfill organic matter is degraded faster and accordingly more biogas is generated and it is produced faster than in a traditional sanitary landfill. The total biogas production from anaerobic bioreactor landfill after a period of 10 years is 30 - 100% higher than the biogas production from a sanitary landfill (Townsend et al. 2008). Based on Veolia (2010) biogas production from European bioreactor landfills is about 185 - 282 m^3/ton of MSW within the first 5 years. Literature showed that the biological process in a bioreactor landfill is completed within 5 - 10 years (Yazdani et al. 2007; ITRC 2006), where a traditional sanitary landfill needs 25 - 50 years. The fast digestion of organic matter rapidly reduces the volume of the deposited MSW. As a consequence bioreactor landfills have the possibility to reuse airspace, which means that the volume that has become available through the compaction of the waste mass is filled up with fresh waste. The volume of a bioreactor landfill that can be reused (again for bioreactor landfill) within 2 years is about 15 - 30% of the total volume (Townsend et al. 2008). An additional benefit of bioreactor landfills is reduced loss of CH_4 to the atmosphere. A flow chart of the bioreactor landfill is presented in figure 5.14.

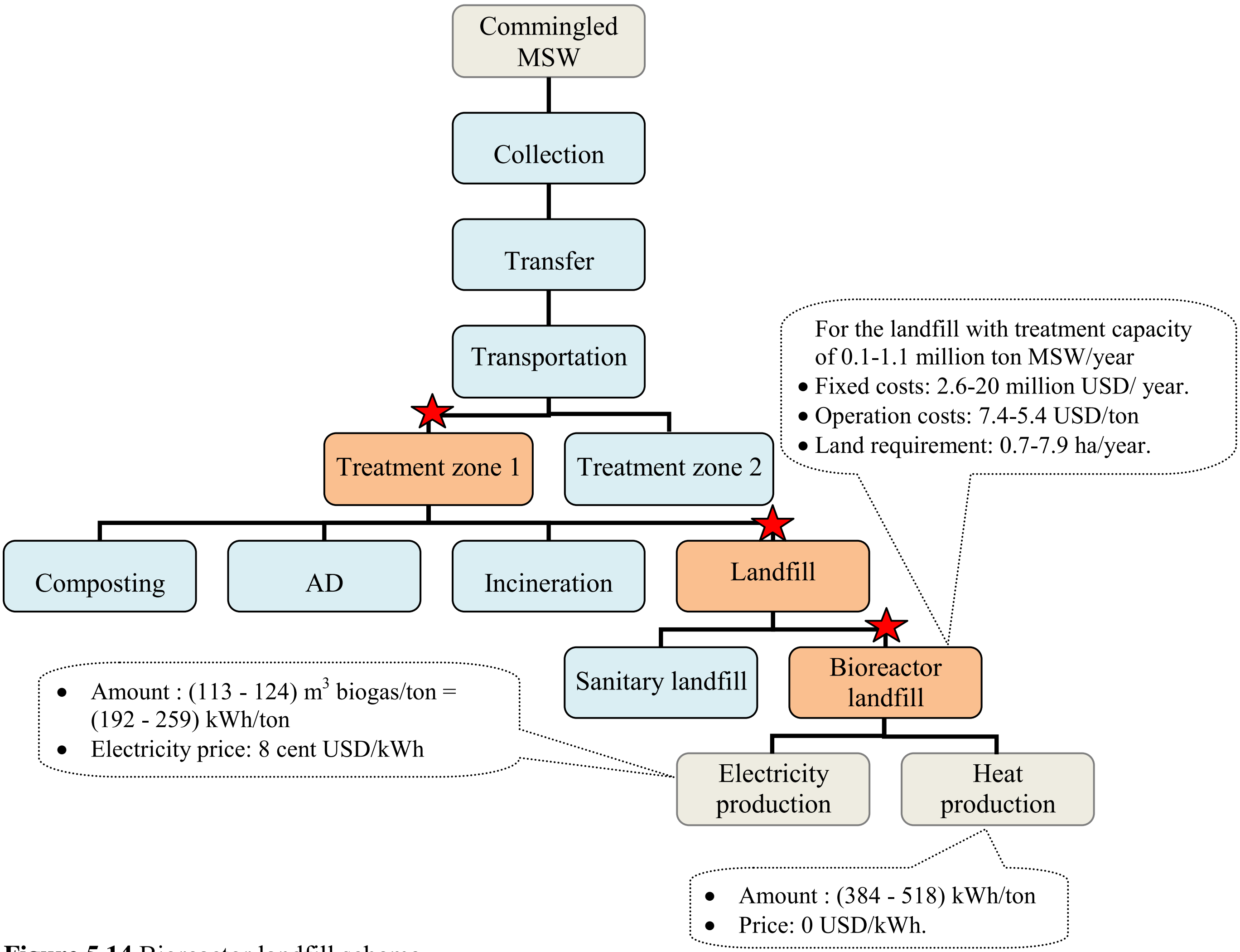

Figure 5.14 Bioreactor landfill scheme.
Note: ★ *are points of decisions for options.*

Bioreactor landfills have higher investment and operation costs as compared to traditional landfills but require less monitoring over the shorter period of aftercare. The use of bioreactor landfills may lead to revenues gained from airspace recovery and biogas utilization, and to avoided costs on leachate treatment (Berge et al. 2009). The costs analysis of different types of bioreactor landfills with different capacities are shown in Table 5.21.

Table 5.21 Literature review on costs of Bioreactor landfill at different capacities in industrialized countries.

Descriptions	**Capacity (1000 tons/year)**	
	78	**194**
Type of bioreactor landfill	Semi-aerobic	Anaerobic
Investment (million USD)	2.7	-
Fixed costs (million USD/year)	0.21*	-
Operation costs (USD/ton)	8.1	-
Treatment costs (USD/ton)	10.8	6 - 30
Countries	Malaysia	US
Source:	*Chong et al.(2005)*	*Yazdani et al.(2007)*

Note: Treatment costs of a case study in the US are the net treatment costs (including the income of biogas product sale).

Berge et al.(2009) and Yazdani et al.(2007) compared the costs of traditional sanitary landfills and different types of bioreactor landfills which showed that the fixed costs of the latter is 14 - 30% higher than of traditional sanitary landfills. Therefore, based on data of sanitary landfills in HCMC, we estimate that the fixed costs for a bioreactor landfill are a factor 1.3 higher than the fixed costs of a sanitary landfill. Bioreactor landfills have lower operation costs than sanitary landfills due to reduced leachate treatment costs (Berge et al. 2009). Therefore, we take a factor 0.9 to estimate the operation costs of bioreactor landfills based on sanitary landfills. With these factors, we estimate that the overall MSW treatment costs with bioreactor landfills are about 18% higher than sanitary landfills. This figure seems reasonable as it lies within the range of 9 – 19% that Berge et al. (2009) mentioned for the extra treatment costs of bioreactor landfills in comparison with traditional sanitary landfills. The estimated costs for different capacities of bioreactor landfills in HCMC are presented in table 5.22. The costs of leachate treatment are included in the mentioned costs.

Table 5.22 Estimated costs of bioreactor landfills for different capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons commingled MSW/year)**				
	100	**300**	**500**	**800**	**1,100**
Fixed costs (million USD/year)	2.60	7.22	11.05	16.12	20.02
Operation costs (USD/ton)	7.4	6.8	6.3	5.9	5.4
Treatment costs (USD/ton)	33.4	30.8	28.4	26.0	23.6

In the research of Yazdani et al. (2007) and Townsend et al. (2008) reported a 30 - 100% higher biogas production compared to a traditional sanitary landfill. In our calculation for HCMC we assume a 30% higher biogas production (or electricity production). Therefore, the biogas generation is 113 - 124 m^3 biogas/ton (87 - 95 m^3 biogas/ton * 1.3). Electricity and heat production from bioreactor landfills are equal to 192 - 259 kW electricity/ton [(113 - 124) * (1.7 - 2.1)] and (384 - 518) kW heat energy/ton [(192 – 259) * 2], respectively. Although, there is a benefit from air space recovery but we assume that this is not much and it equal to the cost of open and close the landfill and also the extra cost of pollution control due to this activity. Therefore, we do not take it into account. The estimated income of a bioreactor landfill in HCMC is presented in table 5.23.

Table 5.23 Estimated income from the energy production in bioreactor landfills in Ho Chi Minh City per ton of municipal solid waste input.

Descriptions	**Volume/Amount**	**Unit price**	**Income** (USD/ ton input)
Electricity	(113 - 124) m^3 biogas/ton = (192 - 259) kWh/ton	8 cent USD/kWh	15.4 - 20.7
Heat	(384 - 518) kWh/ton	0	0
Total			15.4 - 20.7

5.5.3 Residue landfill

The residue landfill is specially designed for rejects (residues) from the separation processes of MSW, not for raw (commingled) MSW. Figure 5.16 shows the flow chart of the residue landfill. The residue landfill is applied in combination with composting, anaerobic digestion and incineration plants. The residue landfill has more or less the same design as a sanitary landfill. However, a residue landfill has a simpler biogas collection system and no biogas cleaning system nor a generator. All collected biogas is burned at flare. The leachate collection system is also simple as the deposited residue contains little moisture and very little organic matter. Therefore, the residue landfill is designed with a small or even without a leachate treatment system. Where applicable its leachate may be treated together with the leachate from other treatment technologies. In order to limit transport costs the residue landfill should be located near the plants from which it receives waste. It is assumed that 25% of the raw MSW received at the composting and anaerobic digestion plants and 10% of raw MSW at incineration plants will be deposited in the residue landfill.

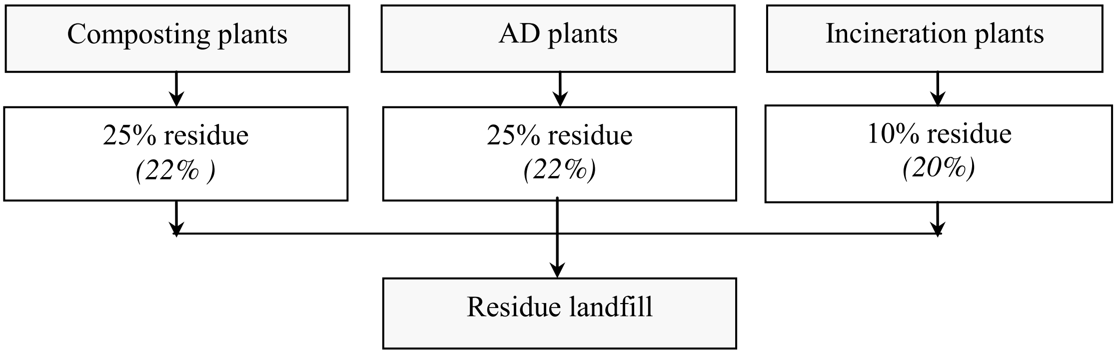

Figure 5.15 Flow chart of residue landfill.
Note: the percentages between brackets indicate the moisture content.

The estimated costs of residue landfills in HCMC are based on the costs of sanitary landfills, taking into account that: (1) the investment costs are lower due to more simple equipment as mentioned above; (2) the density of waste that goes to Residue landfill is lower than that of commingled MSW; (3) the operation costs are lower due to less activities related to biogas collection and treatment and leachate treatment and also post-closure care is less. Therefore, we take for the investment and operation costs of residual landfills per m^3 the ratio of 0.7 times the investment costs and operation costs of a sanitary landfill in HCMC. There are no financial benefits from residue landfills.

Table 5.24 Estimated costs of residue landfills for different capacities in Ho Chi Minh City.

Descriptions	**Capacity (1000 tons residue from MSW/year)**				
	100	300	500	800	1,100
Fixed costs (million USD/year)	1.40	3.89	6.00	8.68	10.78
Operation costs (USD/ton)	5.6	5.3	4.9	4.6	4.2
Treatment costs (USD/ton)	19.6	18.2	16.8	15.4	14.0

5.6 Conclusions

A discussion about the costs of MSW treatment technologies is hampered due to: (1) Lack of comprehensive and accurate costs information, (2) Price fluctuations across time and geography, (3) Uncertainties regarding composition of the waste, e.g the water content of the wastes, and the amount of recovered products.

The real costs of recent MSW treatment plants are often not public or change during the construction and operation period. Past practice has shown that novel technologies are gradually introduced, so that many solid waste treatment plants were built in stages and were re-designed along the way. Published figures may rather be estimations from feasibility studies and not reflect the cost of tried and tested systems (Joshua et al. 2008). For instance, in the case of PhuocHiep 2 sanitary landfill, the initially estimated costs to treat 1 ton of MSW was about 10 USD (CENTEMA 2006). However, due to many problems related to construction and operation in the weak soil the real treatment costs rose to 20 USD/ton MSW (DONRE, 2009). Anaerobic digestion and incineration are not applied in Viet Nam at the moment. The costs data from developed countries is quite different for labor, land, transportation, taxes, etc. compared to the costs characteristics for Viet Nam. The costs depend much on time and location, since these influences the price of material and labor. This can cause a wide costs variation at different locations.

In order to translate the costs from developed countries to HCMC, many factors were included:

- Exchange rates and history of inflation rate to convert all data from different currencies and years to a uniform currency (USD) and a fixed year (2009),
- Comparing the composition of MSW in HCMC and in references,
- Fractions in costs of each technology, for instance: the percentage of construction, equipment, labor, energy, fuel or material of the total costs,

- For each costs fraction, there are differences between developed countries and Viet Nam, for instance: ratio of labor costs of Europe and VN is 5/1. This means the salary for 1 hour labor in Europe is equal to 5 hours of the same labor in Viet Nam.

Table 5.25 presents an overview of the estimated costs of the various treatment technologies for MSW in HCMC.

Table 5.25 Estimated costs of the various treatment technologies for municipal solid waste at different capacities in Ho Chi Minh City, Viet Nam.

Technology	Capacity (ton/year)	Fixed costs (USD/year)	Operation costs (USD/ton)	Dumping costs (USD/ton)	Income (USD/ton)	Gross treatment costs (USD/ton)	Net treatment costs (USD/ton)
Aerated static pile composting	100,000	1,210,000	16.8	3.5- 4.9 (4.2)	12.7- 13.7 (13.2)	33.1	19.9
	200,000	1,760,000	14.0			27.0	13.8
	300,000	2,200,000	12.1			23.6	10.4
	400,000	2,750,000	11.2			22.3	9.1
	500,000	3,300,000	10.4			21.2	8.0
In-vessel composting	100,000	1,936,000	18.5			42.1	28.9
	200,000	2,816,000	15.4			33.7	20.5
	300,000	3,520,000	13.3			29.2	16.0
	400,000	4,400,000	12.3			27.5	14.3
	500,000	5,280,000	11.4			26.2	13.0
Batch anaerobic digestion	100,000	1,815,000	18.1	3.5- 4.9 (4.2)	17.6 - 20.7 (19.2)	40.5	21.3
	200,000	2,640,000	15.1			32.5	13.3
	300,000	3,300,000	13.1			28.3	9.1
	400,000	4,125,000	12.1			26.6	7.4
	500,000	4,950,000	11.2			25.3	6.1
Continuous anaerobic digestion	100,000	3,025,000	20.2		19.3 - 29.9 (24.6)	54.7	30.1
	200,000	4,400,000	16.8			43.0	18.4
	300,000	5,500,000	14.5			37.0	12.4
	400,000	6,875,000	13.4			34.8	10.2
	500,000	8,250,000	12.5			33.2	8.6
Incineration with energy recovery	200,000	6,900,000	22.4	1.4- 2 (1.7)	15.7 – 52.9 (34.3)	58.6	24.3
	300,000	9,600,000	19.9			53.6	19.3
	400,000	12,000,000	18.3			50.0	15.7
	500,000	14,400,000	17.3			47.8	13.5
	600,000	16,600,000	16.3			45.7	11.4
Incineration without energy recovery	200,000	5,700,000	19.1		0	49.3	49.3
	300,000	8,000,000	17.0			45.4	45.4
	400,000	10,000,000	15.7			42.4	42.4
	500,000	12,000,000	14.8			40.5	40.5
	600,000	13,800,000	13.9			38.6	38.6
Sanitary landfill	100,000	2,000,000	8.0	0	11.8- 16.0 (13.9)	28.0	14.1
	300,000	5,550,000	7.5			26.0	12.1
	500,000	8,500,000	7.0			24.0	10.1
	800,000	12,400,000	6.5			22.0	8.1
	1,100,000	15,400,000	6.0			20.0	6.1
Bioreactor landfill	100,000	2,600,000	7.4		15.5 – 20.2 (17.9)	33.4	15.5
	300,000	7,215,000	6.8			30.9	13.0
	500,000	11,050,000	6.3			28.4	10.5
	800,000	16,120,000	5.9			26.1	8.2
	1,100,000	20,020,000	5.4			23.6	5.7
Residue landfill	100,000	1,400,000	5.6		0	19.6	19.6
	300,000	3,885,000	5.3			18.3	18.3
	500,000	5,950,000	4.9			16.8	16.8
	800,000	8,680,000	4.6			15.5	15.5
	1,100,000	10,780,000	4.2			14.0	14.0

Note: The average numbers are shown between brackets.

For easier interpretation the data are presented graphically as well in figure 5.17 and 5.18. The gross treatment costs are equal to sum of fixed, operation and dumping (residue) costs. The net costs are equal to the gross treatment costs minus income.

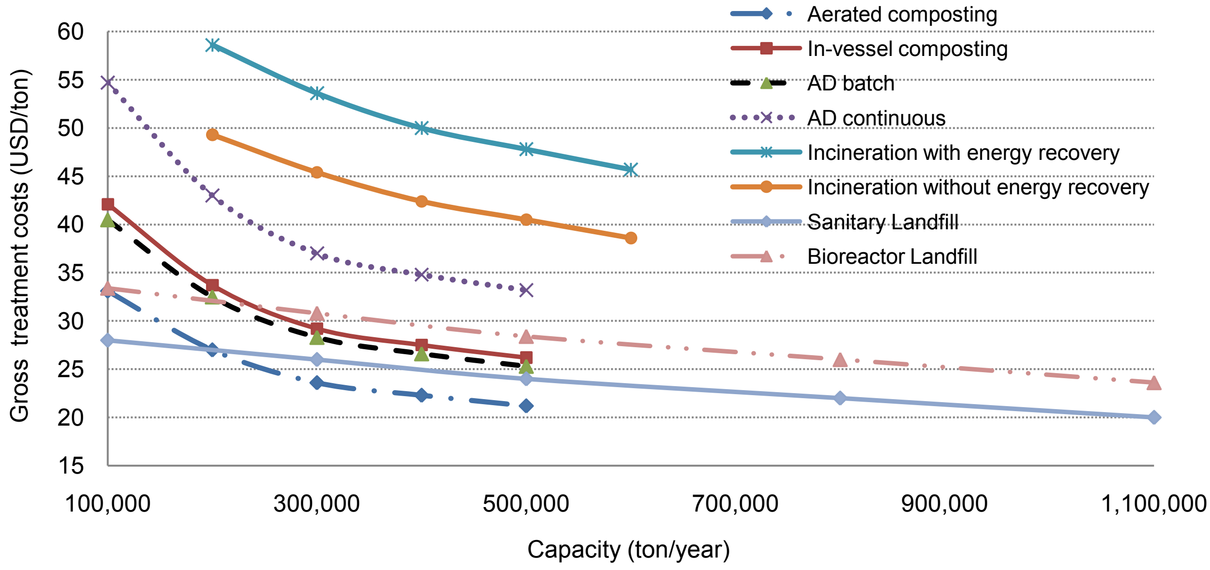

Figure 5.17 Gross treatment costs of 8 municipal solid waste treatment technologies as function of capacity for Ho Chi Minh City, Viet Nam.

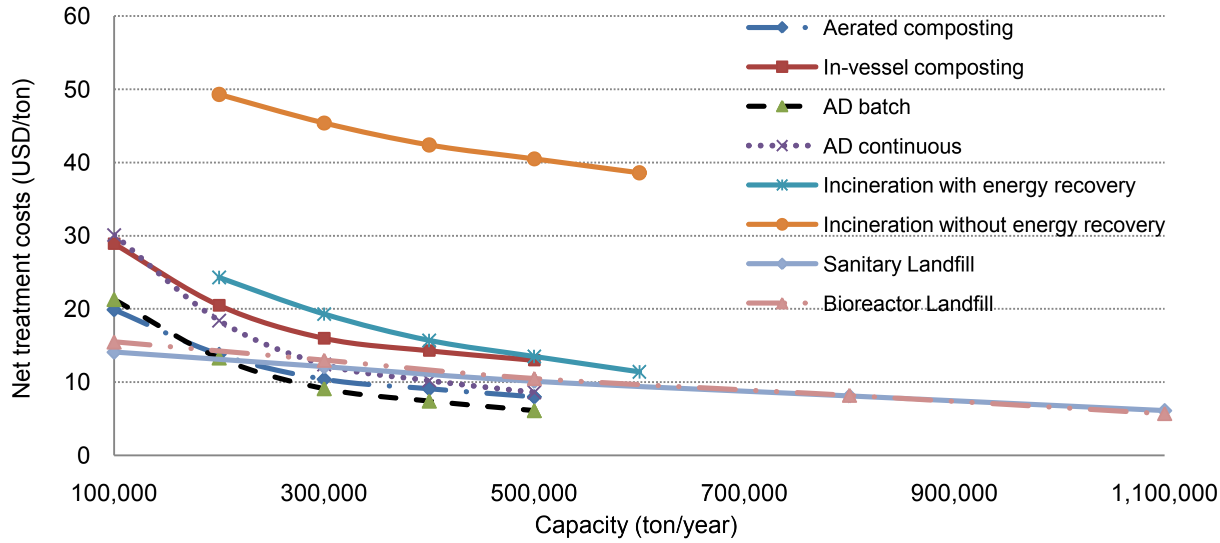

Figure 5.18 Net treatment costs of 8 municipal solid waste treatment technologies as function of capacity for Ho Chi Minh City, Viet Nam.

The costs analysis presented in table 5.25 and figure 5.17 & 5.18 shows that:

- In all treatment technologies there are considerable economy of scale effects: the treatment costs per ton of MSW decrease at higher capacities;
- Treatment costs of aerated static pile composting, in-vessel composting, batch anaerobic digestion and continuous anaerobic digestion decrease strongly at higher capacities, especially from a capacity of 100,000 to 300,000 ton/year (figure 5.17). While it reduced slowly at Incineration with and without energy recovery and Sanitary and Bioreactor landfill;
- Benefits (incomes) from MSW treatment are very sensitive to local circumstances. The values of products from waste are liable to much variation and uncertainty;

- Among the 8 technologies, aerated static pile composting is the least expensive option in term of gross treatment cost. However, if benefits are included, batch anaerobic digestion technology shows the lowest net treatment costs;
- Incineration, both with and without energy recovery, has highest gross treatment costs compared to other options. However, if the benefits of salable energy are included, the treatment costs of incineration with energy recovery decrease significantly.

Chapter 6
Development and application of SURMAT in Ho Chi Minh City

6.1 Introduction

Among the environmental issues in HCMC, MSW management has a first priority for the government. However, quite some uncertainties cling to the government's plans on MSW management, such as: (1) will there be a more intensive focus on separate collection at the source (plastic, waste paper, glass, heavy metals, chemical household waste)? (2) will there be production of sustainable energy from biowastes? (3) will there be a focus on the realization of CDM profits (selling CERs- Certified Emission Reductions)? (4) will disposal of organic waste in landfills be banned in the near future (as is currently the case in Europe)? (5) if electricity is going to be produced from MSW, can it be expected that the government will pay the same price as the production costs of electricity from coal fired power plants? (6) will incineration be regarded as socially acceptable? (7) will the government stimulate the industry moving into the direction of waste treatment? Although HCMC has been organising many activities in relation to these questions, up to now the way information has been organized was inadequate to build a coherent strategy for municipal solid waste management.

The previous chapters have made clear that the selection of treatment technologies is a complex matter due to the many MSW treatment options and factors that may impact the choices. It becomes even more complicated if transportation and appropriate treatment options are considered in combination. Moreover, not only the reduction of pollution is at stake but also the production of valuable products from waste. It is obvious that multiple criteria influence the optimal design of the MSW management system. The requirements of MSW treatment and the impact factors affecting the selection of treatment technology have been surveyed in chapter 2. Technology options for treatment have been studied and selected in chapters 3 and 4 and an economic assessment was made in chapter 5 for the case of HCMC.

In this chapter, a decision support tool in the field of solid waste management, named SURMAT (Sustainable Urban Waste Management Tool), is elaborated. The purpose of this chapter is (1) to select and design a model that could be used to handle material flows and assess the choices on MSW collection and transport, processing technologies and locations, (2) to configurate the model so that it can produce adequate strategies for HCMC, and (3) to detail adequate strategies using information about feasible technologies, local conditions and selected constraints.

The strategies developed in this chapter integrate: (1) financial aspects such as transportation costs of MSW from the City to the treatment zones, investment and operation costs of the different MSW treatment technologies and financial benefits (via produced end products) from the different MSW treatment technologies, (2) societal and infrastructural aspects such as small and poor quality transport routes, land use, marketable products, available labor, and (3) policy aspects such as the technologies deemed acceptable and preferable, existing MSW management plans, Vietnamese requirements for environmental control and product quality, and the integration of MSW treatment with other projects/programs, such as: solid waste separation at source program, urbanization program, public health and sanitation program.

This chapter deals with the design of an "optimal" system for the MSW treatment in HCMC. Section 6.2 provides a literature review on quantitative models for location-allocation in solid waste management. Section 6.3 describes the optimization framework of the selected SURMAT and elaborates the proposed strategies in terms of that model. Section 6.4 presents the modelling results under the requirement of costs minimization, while section 6.5 does the same under the condition of maximization of electricity production from MSW treatment. Section 6.6 discusses the applicability of the model applied in practice and section 6.7 finally presents the conclusions of the chapter. Several appendices containing input data and results are attached to this chapter.

6.2 Literature review

Many decision support models for waste management can be found in literature (Chang and Wang 1996; Valeo et al. 1998; Ghose et al. 2006). Costs and environmental analysis decision support models are the most commonly used. According to Abeliotis et al. (2009) there are two types of decision support models applied to solid waste management. The first type is based on applied mathematics and emphasizes the application of statistics and optimization modelling; the second type provides specific problem-solving expertise stored as facts, rules and procedures. Dewi (2010) divided the waste management decision support models into costs-based models, environmental impact-based models and multi-criteria-based models.

Decision support models for local and regional problems have been developed since the first interest in environmental issues (Talcott 1992; Bloemhof et al. 2003; Bloemhof et al. 2005). Within the field of Operations Research, location-allocation models are most commonly used to tackle waste management problems. A few examples are presented in paper of Chang and Wang (1996), Valeo et al. (1998), Ghose et al. (2006), Quariguasi et al. (2008), Ramuhin et al. (2008), Chaabane et al. (2011), Harris et al. (2011), and Barlishen and Baetz (1996).

Below, we review decision support models applied for solid waste management taking into account the following categories: (i) location-allocation models (applied for solid waste collection, transportation and location of depots) or models focusing on treatment systems (such as solid waste reduction, recycling, recovery and disposal), (ii) cost based models or models also including environmental (i.e. energy, emissions) impacts, and (iii) optimization models or generic decision support models. In this way, the review gives an insight in the main characteristics described in the waste management decision support models in literature.

- Chang and Wang (1996) dealt with selection of appropriate allocation between recycling and incineration plants in Taiwan. A decision support model was used with SAS (Statistical Analysis System) software as a graphical, interactive, problem-structuring tool for managing the solid waste management system;
- Valeo et al. (1998) developed a location-allocation model using geographic information systems (GIS) software to design a recycling depot scheme for a community of 22,000 people. The aim of the model was to maximize the coverage of depot sites subject to projected “recycler behaviour”. This GIS-based model showed a good result in terms of determining the number and location of recycling depots;
- A GIS optimal routing model was proposed by Ghose et al. (2006) to optimize the routing system for collection and transport of solid waste in the Asansol Municipality Corporation (AMC) of West Bengal State (India). The results of the model showed the minimum costs of collecting and transporting the solid waste to the landfill. The input data included population density, waste generation, transport routes, storage equipment and collection vehicles;
- Quariguasi et al. (2008) developed a framework for the design and evaluation of sustainable logistic networks based on multi-objective programming (MOP), in terms of the environmental performance and costs. The research also discussed the expected computational challenges of such approach for the design of sustainable logistic networks. The European pulp and paper sector was used as a background for presenting the methodologies;
- Ramuhine et al. (2008) introduced a mixed integer mathematical model formulation for the integration of carbon market and green supply chain network. The methodology allowed

evaluating the different strategic decision alternatives (supplier, subcontractor, product allocation, capacity, transport) and their impacts on carbon emission. The model provided the decision maker in understanding the trade- off between total logistic costs and the impact of greenhouse gas reduction;

- Harris et al. (2011) assessed the impact of the traditional costs optimization approach to strategic modelling on overall logistic costs and CO_2 emissions. The logistic network was modelled by a commercially available supply chain design application named CAST-dpm by Radical Company. The analysis showed that the optimum design based on costs did not necessary equate to an optimum solution for CO_2 emissions; therefore, the research emphasized the need to address economic and environmental objectives explicitly;
- Chaabane et al. (2011) presented the methodology to address sustainable supply chain design problems via a multi-objective mixed integer linear programming (MILP) model to determine the trade-off between economic and environmental considerations under various regulations on carbon emissions. The research was illustrated with a case of a Canadian steel and aluminium firm that was facing new legislation that capped carbon emissions.
- Barlishen and Baezt (1996) combined knowledge-based systems with individual MSW management and planning models to assist with waste forecasting, technology evaluation, recycling and composting program design, facility sizing, location and investment timing and waste allocation;
- Wang et al. (1996) developed an interactive computer package model, named SWIM, to provide a structure for systems analysis of solid waste management problems at the municipal level. The model could assist decision makers to evaluate the economic and environmental impacts of various waste management options;
- Fiorucci et al. (2003) developed a non-linear optimization model to plan the number of landfills and treatment plants and to determine the quantities and the characteristics of the refuse that has to be sent to treatment plants, landfills and recycling. The model results in minimum costs of recycling, transportation and maintenance in a case study of the municipality of Genova, Italy;
- Jain et al. (2005), created a model to determine the least costs treatment and disposal system and the energy production for a given solid waste management problem in India. It calculated the costs incurred and the amount of recovered energy using waste treatment with four technologies (composting, anaerobic digestion, incineration and landfill).
- Kirkeby et al. (2007) developed a computer model using life cycle assessment (EASEWASTE) to evaluate resource and environmental consequences of landfill technology. This model could be used to evaluate different technologies with different liners, gas and leachate collection efficiencies and to compare the environmental consequences of landfilling with alternative waste treatment technologies such as incineration and AD;
- Abeliotis et al. (2009) applied ReFlows, a computer-aided decision support system for solid waste management. ReFlows was developed in MATLAB. It evaluated the performance of existing or planned waste management systems and configurations under different strategies with respect to quantitative targets defined by solid waste management policies;
- Su et al. (2010) applied the technique Order Preference by Similarity to Ideal Solution (TOPSIS) as a multi-criteria decision-making (MCDM) system to analyze the quantitative and qualitative performance with respect to social, economic, and management criteria. The model evaluated the waste reduction policy in Taoyuan County and provided best practices for MSW sorting among proposed alternatives;

- Banias et al. (2011) developed a web-based decision support system, named DenconRCM, in Greece within the framework of the DEWAM project. The aim of the model was to identify the optimal construction and demolition waste management strategy that minimized total costs and maximized material recovery. The model provided an accurate estimation of the generated construction and demolition waste quantities from different sources and also provided the user with the optimal end-of-life management alternative taking into account both economic and environmental criteria.

Table 6.1 shows the aspects that were described in the above literature references. The table shows that the recently developed decision support models for solid waste management mainly focused on one or some of the main aspects such as: location and allocation, treatment technology, cost and environmental impacts, societal and political aspects. None of the models described above integrates all these aspects. Therefore, in this research, we combined all these aspects in an optimaztion model. Many decision support models were based on a complex mathematical approach with many assumptions, constraints and variables (Bani et al. 2009). It should be noted that the more complex the model, the less marketable and applicable (Powell 2000). Therefore, in order to speed up the application of a decision support model, the model should be flexible in term of input conditions, simple enough to be used in practice and it should integrate the main impact factors. In this thesis, beside the problem of location – allocation of MSW from discharge sources to treatment zones, many other aspects are taken into account, such as: selecting MSW treatment technologies with a certain capacity, restricted land use, product markets, etc.

This is the reason we chose in this thesis to model the system using a location-allocation (Mixed Integer Linear Programming - MILP) model. As Chaabane et al. (2011) mentioned in a comparable study incorporating regulatory environmental constraints, traditional economic decisions, technology acquisition and transportation modes configurations: "*This approach uses a mixed integer Linear Programming model that facilitaties strategic decision-making and provides a better understanding of how the supply chain would react to various forms and combinations of environmental regulations and technological advances*.".

Table 6.1 The aspects were described in the literature references.

Authors	**Location-allocation**	**Treatment systems**	**Costs**	**Environ-mental impacts**	**Optimisa-tion**	**Generic decision support**
Chang and Wang (1996)	x					x
Valeo et al. (1998)	x					x
Ghose et al. (2006)	x		x			x
Quariguasi et al. (2008)	x		x	x	x	
Ramuhine et al. (2008)	x		x	x		x
Harris et al. (2011)	x		x	x	x	
Chaabane et al.(2011)	x		x	x		x
Barlishen and Baezt (1996)	x	x				x
Wang et al.(1996)			x	x		x
Fiorucci et al. (2003)		x	x		x	
Jain et al. (2005)		x	x	x	x	
Kirkeby et al. (2007)		x		x		x
Abeliotis et al. (2009)		x		x		x
Su et al. (2010)		x	x	x		x
Banias et al. (2011)		x	x	x	x	

6.3 Optimization framework

6.3.1. Introduction

The aim of our study is not to support decision making in a single choice dealing with one type or a few types of MSW treatment systems, but to help policy makers to determine regulatory measures for the development of complex public activities dealing with the management of waste streams and sustainable technologies. With this aim in mind, a number of numerical calculations based on empirical data had to be conducted for which mixed-integer linear programming (MILP) modelling was used as a general mathematical optimization framework. The optimization framework is flexible to incorporate multiple indicators, alternative optimization strategies as well as a variety of internal and external specific factors. At the core of the optimization framework is an integrated mixed-integer linear programming (MILP) model which can be solved by standard optimization software. MILP easily allows adding constraints representing composting, anaerobic digestion, incineration and landfill or a mix of these technologies, social and political impacts, benefits from CDM, etc.

To model industry-wide supply chains using MILP, relevant tasks, products and services have to be aggregated which, naturally, results in a certain degree of imperfection. Here such imperfection can be accepted as the purpose of this study was not to develop a model which was very precise in every detail. The decisions determined for the development of the supply chain are bounded by constraints, which limit the scope for action, e.g. constraints on the limited availability of land use or regulations about maximum allowable compost product, etc.

In this research, the SURMAT tool based on an optimization model was set up for the design of MSW management systems. The model proposes a structure on MSW management for a developing country taking into account societal and political constraints. Typical objective functions are oriented at minimized total net costs of MSW transport and treatment or maximized electricity production from MSW treatment. The software used in this research is MPL[46]. MPL (Mathematical Programming Language) is an algebraic modelling language that allows the user to formulate linear and integer (mixed integer) mathematical optimization problems. MPL is easy to learn, quickly to formulate and requires not much programming (Maximal Software 2012). The mixed integer linear program is solved by CPLEX (C Program Language), claimed to be the world's fastest and most advanced solver optimization engine. In the next paragraph we formulate the MSW management system problem as a Mixed Integer Linear Programming (MILP) model, dealing with both continuous and integer values.

In this research the SURMAT optimization focuses on two objectives. One is minimum total costs of transportation and treatment of MSW and the other is a maximum electricity production from MSW treatment. The objective of minimum costs is especially relevant in developing countries or in countries in economic transition due to a lack of financial means to solve environmental problems. The criterion of maximum electricity production is very relevant because in developing countries the sufficient production and supply of electrical energy often fails. Often the costs of production of electrical energy are relatively high and in that case it might be very profitable to investigate the financial benefits related with selling CERs. For developing countries these benefits can be very high. Both objectives are elaborated for the conditions of HCMC as an example for similar situations in developing countries.

Figure 6.1 shows the optimization framework applied in this chapter. The sought strategies were set up based on the external drivers: resources, demography, regulations, markets for end products of MSW treatment, and infrastructure. The technologies were selected based on the sustainability performance criteria (technically efficient, adapted the environmental standard of the local

[46] For more detail at website: http://www.maximal-usa.com/mpl/

authority, manageable under the institutional conditions of Asian cities, affordable to the cities). The input data were the conditions of HCMC as an example of developing countries.

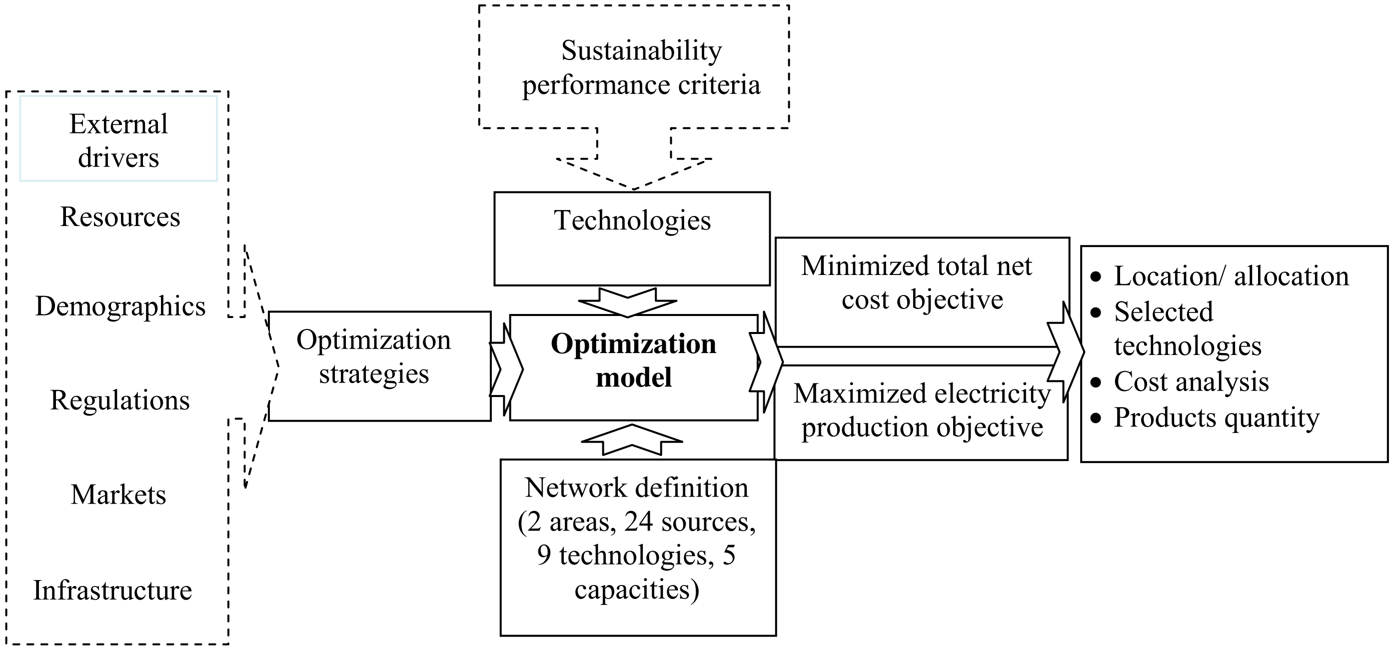

Figure 6.1 Optimization framework

Figure 6.2 shows the overall structure of the model. It presents the relevant model parameters and input data, type of model, performance indicators (the output of model) and decisions taken. In the MILP model, there are X_{ijt} and Y_{jt} as decision variables. X_{ijt} is the amount of MSW transported from District *i* to the plants with treatment technology *j* with capacity level *t*. Y_{jt} is the integer variable (0, 1, 2, 3 …) that represents the number of plants of technology *j* at capacity *t*. More detail of the model is presented in section 6.4.

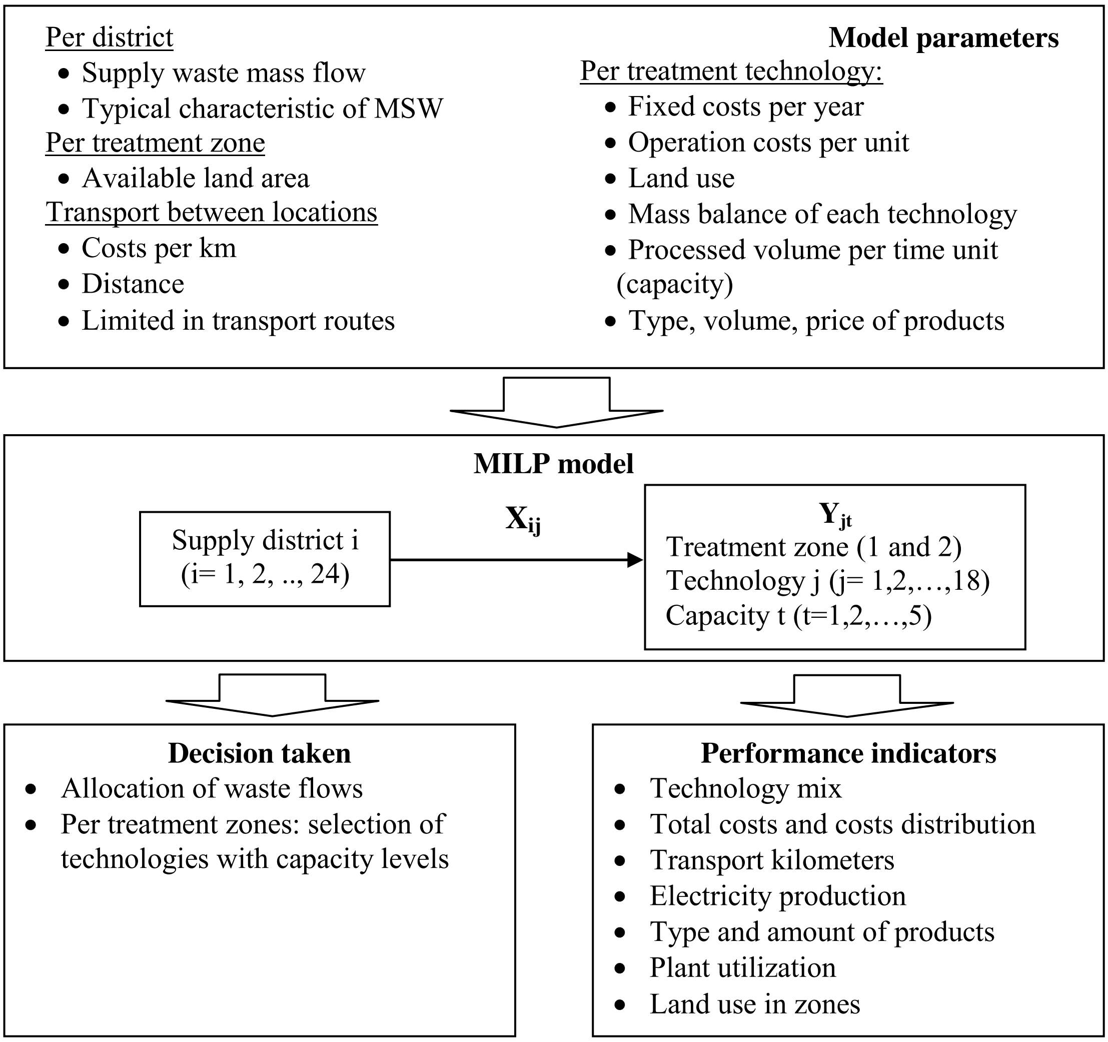

Figure 6.2 Structure of the model.

In the paragraph below we start to introduce the data for the application of SURMAT to the modeling of MSW management in HCMC.

6.3.2 List of assumptions

For the application of the SURMAT optimization methodology to the design of MSW management system, the following basic assumptions about the main model parameters were made. A summary of these main parameters for the case of minimization of costs is given in table 6.2 below.

Amount of MSW

- The amount of MSW put into the model was the average amount of MSW in 20 years for the considered 20 years period (2012-2032) not treated yet by current treatment facilities (see table A3.1 in appendix 3). This average amount was 3,569,759 ton/year which is rounded off to 3.6 million ton/year. The meaning of MSW is wet commingled MSW or raw MSW.
- In order to estimate the total amount of MSW in the future, and the average annual amount of waste during the 20 years planning period, we use the following statistics:
  - o The population growth of the last 10 years was 3.54%/year (Statistical Office of HCMC 2011). We took this number for estimating the population in the future. The estimated population per year for 20 years planning is presented in table A3.1 in appendix 3;
  - o The total growth rate of the amount of MSW in HCMC in the last 10 years was about 6-8%/year (DONRE HCMCb 2009). This high growth rate was not only due to increasing

amounts of discharged MSW but also to increased collection efficiency. Nowadays, the collected fraction of MSW is about 85-90% of total discharged amount. This fraction will probably not increase as the uncollected waste occurs in the rural areas where people manage the waste by themselves and do not make use of the urban collection system;

- The growth rate and the amount of MSW discharged per person in HCMC in the next 20 years is expected to be comparable to the data from cities such as Beijing and Bangkok. For Beijing the discharged amount of MSW in 1987 and 2006 was 1.040 and 4.134 million ton/year. In Beijing in 2006, the amount of discharged MSW was 0.85 kg/person/day (Zhen-shan et al. 2009). The discharged amount of MSW in Bangkok was 1.1 and 3.3 million ton/year in 1985 and 2001 and is estimated to be 6.6 million ton/year in 2015 (Chaya and Gheewala 2006); The growth rate of the amount of MSW is in agreement with the growth rates mentioned in governmental programs related to limiting MSW discharge in HCMC. An example is the program about modernization of the urban area (HCMC People's Committee 2009).

Based on the data sources above, we concluded to a declining growth rate for the amount of MSW in HCMC as follows: 7% for the period 2013 - 2017, 6.5% for the years 2018-2022, 6% for 2023-2027 and 5% 2028-2032. The first five years we took the same rate as the last 10 years (average of 7% annual growth). It should take into account that the amount of MSW input to the model is not included the amount of MSW which is treated via the existing composting plants and sanitary landfill until the end of their lifetime. The more detail explanation of amount of MSW to get into the model is presented in appendix 3 (table A.3.1).

Transport distances

Each district of HCMC has many routes to transport MSW to the MSW treatment zones. We assumed that the current transport route is the shortest and acceptable regarding the capacity of roads (table A3.2 in appendix 3).

Treatment technologies

We assumed that the government will accept to invest in new waste treatment technologies like batch and continuous anaerobic digestion, incineration with energy recovery, bioreactor landfill and residue landfill. Aerated static pile and in-vessel composting and sanitary landfills do already exist in Viet Nam.

Land use

Land for treatment facilities in HCMC is free of charge based on an existing regulation of the People's Committee.

Regarding the use of land we distinguished two groups of technologies. The first group we called process-oriented and comprises the technologies composting, anaerobic digestion and incineration. These technologies produce end products that leave the site of the facilities (flow-through principle) and residues that have to be disposed of at a residue landfill and gradually fill the site (accumulation system). The second group includes the technologies bioreactor landfill and sanitary landfill. Here, wastes accumulate over the entire period of their use.

The land use of these two types of technologies in time is different. The land use of the process-oriented group is calculated using the maximum mass flow to be treated at the end of the design lifetime (tons/year) divided by the treatment capacity per unit of land (tons/ha/year). Therefore, the land needed for a facility equals the area needed for the waste flow at the end of the design lifetime. In the second group of landfill technologies the land use increases gradually as more wastes or residues are stored. The required land area of these facilities is based on the total accumulated mass of wastes or residues expected over the entire lifetime (tons) divided by the storage capacity (tons/ha).

SURMAT was designed to calculate a mix of treatment technologies from both the first and the second group that would fit a certain available land area for an average year. In the case study of HCMC elaborated in this thesis, the waste flow increases gradually from the present up to the year 2032 (as the project horizon is 20 years). For the modelling of technology mixes, SURMAT needed as input the land area required for all technologies at the set conditions in the year 2032, the year with the highest amount of waste. For the process-oriented technologies this implied a design based on the maximum mass flow of 8.2 million tons MSW/years, which is 2.3 times the average flow, and for the landfill technologies the total accumulated waste mass over 20 years. The detailed calculations are explained in the appendix 3, table A.3.6a and b.

Valuable products

The PE plastics or other recyclable wastes are processed to end products only when the technology includes a separation system. Among the eight technologies assessed, the technologies with a separation system are aerated static pile and in-vessel composting, and batch anaerobic digestion and continuous technologies. The separation system applied for these four technologies is the same; therefore the benefits from PE plastic and other recyclable wastes were assumed to be the same for these four technologies. Ash is a by-product of incineration technology while aluminium and iron are recovered from ash. Therefore, aluminium and iron were assumed to be collected only when incineration is applied.

The type and amount of each product per ton of MSW input to the treatment plants was calculated based on the literature reviews in chapters 4 and 5. The detailed data of products and other data input to the model were listed in table A.3.5, appendix 3. The financial benefits of biogas production from sanitary landfill and Bioreactor landfill are not uniformly distributed over the period after the moment of disposal. For the model calculation the average benefits from biogas for each distinct year were assumed.

6.3.3 System boundaries

In the mathematical formulation of the MSW management problem in HCMC the following main aspects are discussed. There are in total 24 districts in HCMC where MSW is collected and transported to two treatment zones in Phuoc Hiep and Da Phuoc. The estimated amount of MSW of each District in the planning period is based on the actual amount of MSW in HCMC in 2008 (chapter 2) and the MSW growth rates mentioned in 6.3.1.

- As HCMC has two composting plants and one landfill at the moment with a combined capacity of 1,900,000 ton/year, the amount of MSW to be treated in new treatment plants is assumed to be equal to the amount of MSW calculated (per each year during the 20 years of planning) minus the amount already treated (see appendix 3, table A.3.1);

- The distances from the 24 Districts to the two treatment zones are presented in appendix 3 (Table A.3.3). The planned sizes for MSW treatment and dumping facilities are 276 and 233 ha for the treatment zone 1 and 2, respectively. This does not include surrounding protection zone areas;

- In total eight treatment technologies can be selected, named: (1) aerated static pile composting, (2) in-vessel composting, (3) batch anaerobic digestion, (4) continuous anaerobic digestion, (5) incineration with energy recovery, (6) incineration without energy recovery, (7) sanitary landfill and (8) bioreactor landfill. Besides, in order to landfill the residue which is rejected from composting, anaerobic digestion and incineration, also Residue landfills are needed (see figure 6.3). We call this the ninth technology. The detailed technology description, advantages and disadvantages of each technology are presented in chapter 4. Chapter 5 presents the cost analysis of each technology including fixed costs (USD per year or per ton of MSW), operation costs and negative costs (or benefits) (USD/ton). Besides, chapter 4 also mentions the societal and environmental aspects of each technology. We take into account the current situation of HCMC of chapter 2 and the results of our studies on anaerobic digestion of MSW presented in chapter 3.

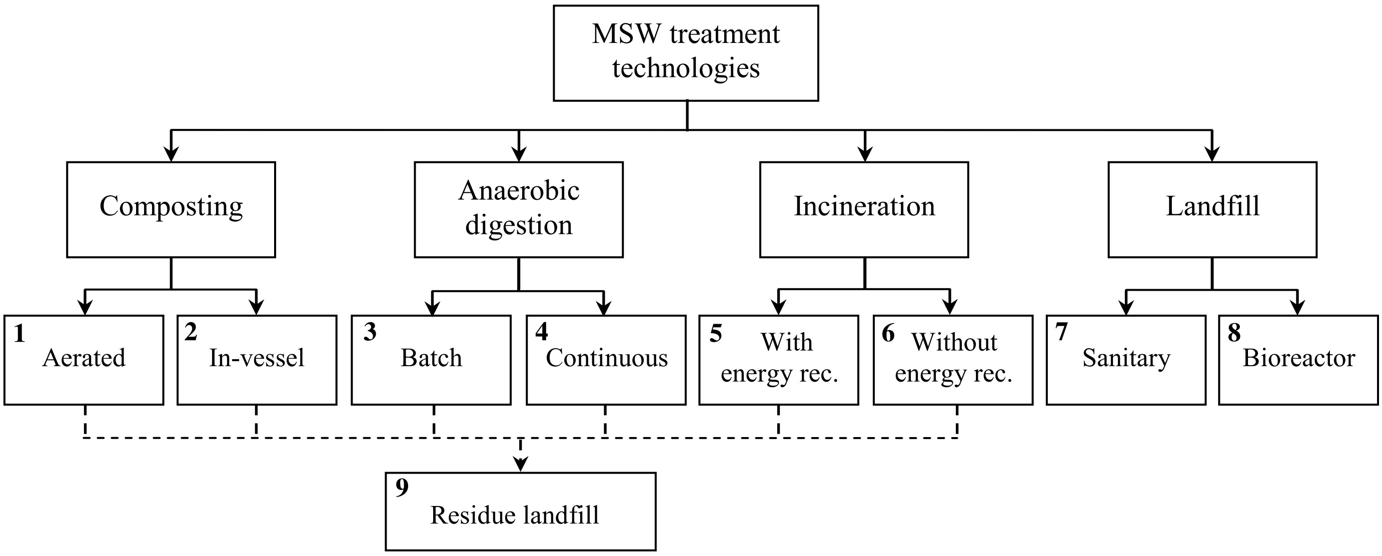

Figure 6.3 The possibility of municipal solid waste treatment technologies to apply in Ho Chi Minh City, Viet Nam.
Note: ⟶ *MSW flow,*
- - - -> *Residue flow*.

- The nine technologies can be located in both treatment zones. The costs of technologies (fixed, operation and negative costs) were calculated based on the costs of 2009 (see chapter 5).

6.4 Minimization the total net costs of transportation and treatment of municipal solid waste

If the aim of the government is to minimize the total net costs of transport and treatment of MSW in HCMC, the following model can be formulated.

6.4.1 Model formulation

The model uses the following notation:

Index sets:

$i \in I = \{1,2,.., 24\}$ = Set of 24 districts;

$j \in J_1 = \{1,2,\ldots, 9\}$ = Set of 9 treatment technologies to be applied in a plant in treatment zone 1;

$j \in J_2 = \{10,\ldots,18\}$ = Set of 9 treatment technologies to be applied in a plant in treatment zone 2 (see more detail in chapter 5);

$t \in T = \{1, 2, 3, 4, 5\}$ = Capacity levels of the treatment plants (see more detail in chapter 5).

Parameters:

t_{ij} : the unit transport costs from district i to plants with treatment technology j($j \in J_1 \cup J_2$) (USD/ton);

r_i : the amount of MSW[47] at district i (ton/year);

f_{jt} : the fixed costs of plants with treatment technology j ($j \in J_1 \cup J_2$) with capacity level t (USD/year);

[47] MSW not treated at current facilities yet

b_{jt} : the operation costs per unit in plants with treatment technology j ($j \in J_1 \cup J_2$) with capacity level t (USD/ton);

n_{jt} : the negative costs (benefits from products) of plants with treatment technology j ($j \in J_1 \cup J2$ with capacity level t (USD/ton);

l_{jt} : the land use[48] of treatment plant j ($j \in J_1 \cup J_2$) at capacity level t (ha);

$v_{j,t}$: capacity of plants with treatment technology j and capacity level t (ton)

z_1, z_2 : the total area of treatment zone 1 and 2 (ha);

k_1 : fraction from composting and anaerobic digestion plants to residue landfill (0.25 of MSW input to the plants);

k_2 : fraction from incinerators to residue landfill (0.1 of MSW input to the plants).

Decision variables:

X_{ijt} : amount MSW from district i to treatment plant j at capacity level t (ton/year).

Y_{jt} : integer variable (0, 1, 2, 3 …): the number of treatment plants with treatment technology j at capacity level t. Y_{jt} represents the possibility to use a certain technology at a certain capacity. Y_{jt} can be 0 (it means that plant cannot be used with capacity t) or = 1,2,3,4… (the number of plants with treatment technology j at capacity level t)

Model formulation

The objective (1) expresses that we are looking for a solution with total minimum transportation costs, fixed yearly costs, operation costs, negative costs (benefit from products) and extra operational costs of residues from composting, anaerobic digestion and incineration technologies. It can be expressed by the following equation:

Minimize

$$\{\sum_{i\in I}\sum_{j\in J1}\sum_{t\in T} t_{ij}X_{ijt} + \sum_{i\in I}\sum_{j\in J2}\sum_{t\in T} t_{ij}X_{ijt} + \sum_{j\in J1}\sum_{t\in T} f_{jt}Y_{jt} + \sum_{i\in I}\sum_{j\in J1}\sum_{t\in T} b_{jt}\, X_{ijt} + \sum_{j\in J2}\sum_{t\in T} f_{jt}Y_{jt} + \sum_{i\in I}\sum_{j\in J2}\sum_{t\in T} b_{jt}\, X_{ijt} - \sum_{i\in I}\sum_{j\in J1}\sum_{t\in T} X_{ijt}\, n_{jt} - \sum_{i\in I}\sum_{j\in J2}\sum_{t\in T} X_{ijt}\, n_{jt} + \left(k_1\sum_{i\in I}\sum_{j=1}^{4}\sum_{t\in T} X_{ijt} + k_2\sum_{i\in I}\sum_{j=5}^{6}\sum_{t\in T} X_{ijt}\right) b_{9t} + \left(k_1\sum_{i\in I}\sum_{j=9}^{12}\sum_{t\in T} X_{ijt} + k_2\sum_{i\in I}\sum_{j=13}^{14}\sum_{t\in T} X_{ijt}\right) b_{18t}\} \quad (1)$$

Subject to:

$$\sum_{j\in J1}\sum_{t\in T} X_{ijt} + \sum_{j\in J2}\sum_{t\in T} X_{ijt} = r_i \;\; \forall i \in I \quad (2)$$

The constraint (2) shows that all amount of MSW of each district has to be transported to one of the treatment plants.

$$\sum_{i\in I} X_{ijt} \le v_{jt}Y_{jt}\,, \forall j \in J_1 \cup J_2, \forall t \in T \quad (3)$$

Constraint (3) states that the amount of MSW that is transported to each MSW treatment plant must be equal or smaller than the total capacity of the number of open plants with capacity t.

$$\sum_{j=j1}\sum_{t\in T} l_{jt}\;\; Y_{jt} \le z_1 \quad (4)$$

$$\sum_{j=j2}\sum_{t\in T} l_{jt}\;\; Y_{jt} \le z_2 \quad (5)$$

[48] Adapted for the year with largest amount of MSW

Constraint (4) and (5) show the total land use in the planning years (20 years) (including land use for the treatment plants and landfill of MSW, land use for the landfill of the residue) in each treatment zone must be smaller than the available area of treatment zone.

$$k_1 \sum_{i \in I} \sum_{j=1}^{4} \sum_{t \in T} X_{ijt} \quad + k_2 \sum_{i \in I} \sum_{j=5}^{6} \sum_{t \in T} X_{ijt} \leq \sum_{t \in T} v_{9t} \quad Y_{9t} \tag{6}$$

$$k_1 \sum_{i \in I} \sum_{j=9}^{12} \sum_{t \in T} X_{ijt} \quad + k_2 \sum_{i \in I} \sum_{j=13}^{14} \sum_{t \in T} X_{ijt} \leq \sum_{t \in T} v_{18t} \quad Y_{18t} \tag{7}$$

Constraint (6) explains that the amount of residue (pretreatment and post treatment) from composting, anaerobic digestion and incineration technologies to residue landfill in treatment zone 1 should be smaller than the capacity of the residue landfill in treatment zone 1. In which, the amount of residue (pretreatment and post treatment) from composting and anaerobic digestion plants is equal to 25% (k_1= 0.25) of input MSW to these plants and the amount of residue from incinerator is equal to 10% (k_2= 0.1) of input MSW to the incinerators.

We have two separately treatment zones (treatment zone 1 and treatment zone 2). Therefore, we formulate constraint (6) for treatment zone 1 and constraint (7) for treatment zone 2. Constraints (6) and (7) show that it is not allowed transporting residue from one treatment zone to another. So, if in the treatment zone there are one or more technologies different from Sanitary landfill like composting, anaerobic digestion or incineration, then there must exist also a residue landfill to dump residue.

Y_{jt} is the number of treatment plants with treatment technology *j* at capacity level *t*. Therefore, Y_{jt} is non- negative and integer.

$$Y_{jt} = 0, 1, 2, .. \text{ for all } j, t \tag{8}$$

The residue landfill is designed to dump the residue only, not commingled MSW. Therefore, the constraints (9) and (10) show that commingled MSW must not be dumped in residue landfill.

$$\sum_{i \in I} \sum_{t \in T} X_{i9t} = 0 \tag{9}$$

$$\sum_{i \in I} \sum_{t \in T} X_{i18t} = 0 \tag{10}$$

The constraint (11) states that the amount of MSW transported to the treatment plants is of course non-negative.

$$X_{ijt} \geq 0 \;\; for\ all\ i, j, t \tag{11}$$

6.4.2 Strategies

Based upon the data and insights gathered in the previous chapters, we discussed potential waste management strategies with key stakeholders in the workshop at the Department of Natural Resource and Environment in HCMC (DONRE HCMC) on 3rd April 2010. As a result a number of interesting strategies came to the front that are worth examining. The reason to apply these strategies are included in the explanation of each strategy below. As mentioned in chapter 2, land is a limited factor in HCMC. Therefore, for each strategy we discussed 3 options based on land availability. The options differed with respect to the availability of land for waste treatment facilities. The first option assumed no limitation of the availability of land. The second option took the present conditions of land availability for future MSW treatment in HCMC as point of departure. As mentioned in chapter 2, HCMC has planned areas for MSW treatment at Phuoc Hiep and Da Phuoc communes with 267 and 233 ha, respectively (We named treatment zone 1 and 2). We take this data into account for option 2. The third option modelled the waste management for the condition that the government is not successful in clearance and therefore, it may only half of the land of option 2 would be available. Therefore, in option 3, the land availability of Phuoc Hiep and Da Phuoc are 140 and 120 ha, respectively. In the end we distinguished among 5 strategies and 3 options for each strategy. In total we obtain 15 modelling results.

The first strategy is modeled using the standard conditions. The second strategy onward, we model using standard conditions with additional constraints. The strategies are as follows:

Strategy 1: using standard condition, planning for 20 years. The standard condition is the current situation of HCMC with no specific constraints.

Strategy 2: takes into account the standard condition (as strategy1) and including a constraint about the strategy of MSW treatment of HCMC. This strategy proposes that there are at least 50% of total collected MSW to be treated by composting or anaerobic digestion technology to product compost, and at least 30% of total collected MSW should be treated by incineration with energy recovery. Therefore, in strategy 2, besides all constraints of strategy 1, we add 2 more constraints (12) and (13). The meaning of this strategy is that the government wants to put this proposed strategy into practice. Therefore, by modeling, we can show how much the costs will be higher than the case without this strategy (strategy 1).

- Additional parameters:
  l_1: fraction of MSW treated by composting and anaerobic digestion technology (l_1= 0.5).
  l_2: fraction of MSW treated by incineration with energy recovery technology (l_2= 0.3).
- Additional constraints:
  $$\sum_{i\in I}\sum_{j=1}^{4}\sum_{t\in T}X_{ijt} + \sum_{i\in I}\sum_{j=9}^{12}\sum_{t\in T}X_{ijt} \geq l_1\sum_{i\in I}r_i \quad (12)$$
  $$\sum_{i\in I}\sum_{j=5}\sum_{t\in T}X_{ijt} + \sum_{i\in I}\sum_{j=13}\sum_{t\in T}X_{ijt} \geq l_2\sum_{i\in I}r_i \quad (13)$$

Strategy 3: takes into account the standard condition (as strategy 1) and including a constraint about the problems of infrastructure in HCMC as discussed in chapter 2. The two constraint of strategy 2 (constraint 12 and 13) are not included in strategy 3.

In HCMC, the transport route from the city to treatment zone 2 is narrow. To be sure that there is no problem with traffic jams and to adapt the infrastructure of HCMC, constraint (14) shows the maximum amount of MSW transported to treatment zone 2 is not higher than 50% of total amount of MSW. Assume that in the coming years, when the amount of MSW increasing, then the infrastructure is also increasing to transport 50% of all collected MSW. Therefore, in strategy 3, beside all constraints of strategy 1, we add one more constraint (14).

- Additional parameters
  m: fraction of MSW transported to Treatment zone 2 ($m = 0.5$).
- Additional constraints
  $$\sum_{i\in I}\sum_{j\in J2}\sum_{t\in T}X_{ijt} \leq m\sum_{i\in I}r_i \quad (14)$$

Strategy 4: takes into account the standard condition of strategy 1 and includes a constraint about the possibility to market the products. Constraints 12, 13 and 14 are not included in strategy 4.

The constraints (15 and 16) show that due to the market demand; the amount of compost product must be higher than a certain amount (p) and lower or equal to the market demand (q). (p - q is the estimated range in amount of compost needed at the year that discharges 3.6 million ton MSW).

- Additional parameters
  n: the faction in amount of compost production in total amount of MSW input (n=0.2).
  p: minimum compost production per year (200,000 ton/year).
  q: maximum compost production per year (300,000 ton/year).

- Additional constraints

$$n\sum_{i\in I}\sum_{j=1}^{2}\sum_{t\in T}X_{ijt} + n\sum_{i\in I}\sum_{j=9}^{10}\sum_{t\in T}X_{ijt} \geq p \qquad (15)$$

$$n\sum_{i\in I}\sum_{j=1}^{2}\sum_{t\in T}X_{ijt} + n\sum_{i\in I}\sum_{j=9}^{10}\sum_{t\in T}X_{ijt} \leq q \qquad (16)$$

Strategy 5: takes into account the standard condition of strategy 1 and adds the benefit from heat energy and the benefit from selling carbon credits (CERs) under the CDM program. In this strategy, we will recalculate the benefit from all technologies, now taking into account also the benefit from heat energy and CERs. Therefore, in this strategy, there is no more additional constraint compared to strategy 1, but the input data of benefits is changed.

- The benefit from heat energy is calculated based on the amount of biogas production (kWh) which is estimated in Chapter 5. Assume that the cost of heat energy is 1cent/kWh (compare to cost of electric energy which is 8 cent/kWh).
- The benefit from CERs is calculated according to the methods elaborated in literature. In that respect the following references can be mentioned:
  - Waste Concern Organization and the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) apply the United Nations Framework Conversion on Climate Change (UNFCCC), a CDM program for Composting project in 2008 (UNFCCC 2008; UNESCAP 2011). Based on this, by converting organic waste from land filling towards Composting, landfill gas methane emissions are for 100% prevented. The prevented methane emission from the landfill that otherwise would occur is claimed as emission reductions. They calculated about 0.35- 0.42 ton CO_2 reduction/ton of wet commingled MSW in their Composting project in Bangladesh.
  - In the project application form applied to UNFCCC for an anaerobic digestion project of MSW in Jiaonan City, China, about 0.41 ton CO_2 reduction/ton of wet commingled MSW is reported in the anaerobic digestion project (Qingdao Jiaonan Green Investment Environmental Protection Co. Ltd 2010).
  - In the Zhejiang Pinghu MSW project in China about 161,874 ton CO_2/year reduction is estimated by incinerating and 219,000 ton wet commingled MSW/year by incineration with energy recovery. This is about 0.74 ton CO_2 reduction/ton of wet commingled MSW (The institute for thermal power engineering 2005).
  - A landfill gas to energy CDM project in the Philippine calculated that 1 MW of base load power (8,000 hours/year) can earn 25,000- 40,000 CERs/year (Beltran 2005). It is about 0.5 ton CO_2 reduction/ton of wet commingled MSW in the landfill project.
  - Based on the information of UNESCAP (2011) and DONRE (2011), the costs for selling 1 ton CO_2 reduction (1 CERs) in HCMC is assumed to be about 15USD/ton CO_2 reduction.

Table 6.2 is a summary of the constraints of each strategy.

Table 6.2 The number of relevant constraints included in each strategy. (Number of constraints refers to the numbering of equations in section 6.4.1 and 6.4.2).

Strategies	The relevant constraints including
1 (standard condition)	o Constraint 2: all amount of MSW of each district has to be transported to one of the treatment plants. o Constraint 3: the amount of MSW that is transported to each MSW treatment plant must be equal or smaller than the capacity of the plant if that plant is open. o Constraint 4 and 5: the total land use in the planning years (20 years) (including land use for the treatment plants and landfill of MSW, land use for landfilling of the residue coming from the pretreatment and the post treatment) of all treatment plants in each treatment zone must be smaller than the available area of treatment zone. o Constraint 6 and 7: the amount of residue (pretreatment and post treatment) from composting, anaerobic digestion and incineration technologies to residue landfill in treatment zone 1 and 2 should be smaller than the capacity of the residue landfill in treatment zone 1 and 2. o Constraint 8: the number of treatment plants with technology j at capacity level t must be non- negative and integer. o Constraint 9 and 10: commingled MSW must not be dumped in residue landfill. o Constraint 11: the amount of MSW transported to the treatment plants is of course non-negative.
2	o Including all constraints of strategy 1 and o Constraint 12 and13: Constraints (12) and (13) are based on the strategy of HCMC on MSW treatment, which is to treat 50% of the total amount of MSW in HCMC by composting and anaerobic digestion technology (constraint 12) and 30% of total amount of MSW by incineration with energy recovery (constraint 13).
3	o Including all constraints of strategy 1 and o Constraint 14: the maximum amount of MSW transported to treatment zone 2 is not higher than 50% of total amount of MSW.
4	o Including all constraints of strategy 1 and o Constraint 15 and 16: due to the market demand; the amount of compost product must be higher than a certain amount (p) (constraint 15) and lower or equal to the market demand (q) (constraint 16).
5	o Including all constraints of strategy 1 and o Additional benefit from heat energy and CERs.

Figure 6.4 shows the three levels of the aim, strategies and options applied in the study of minimization of costs.

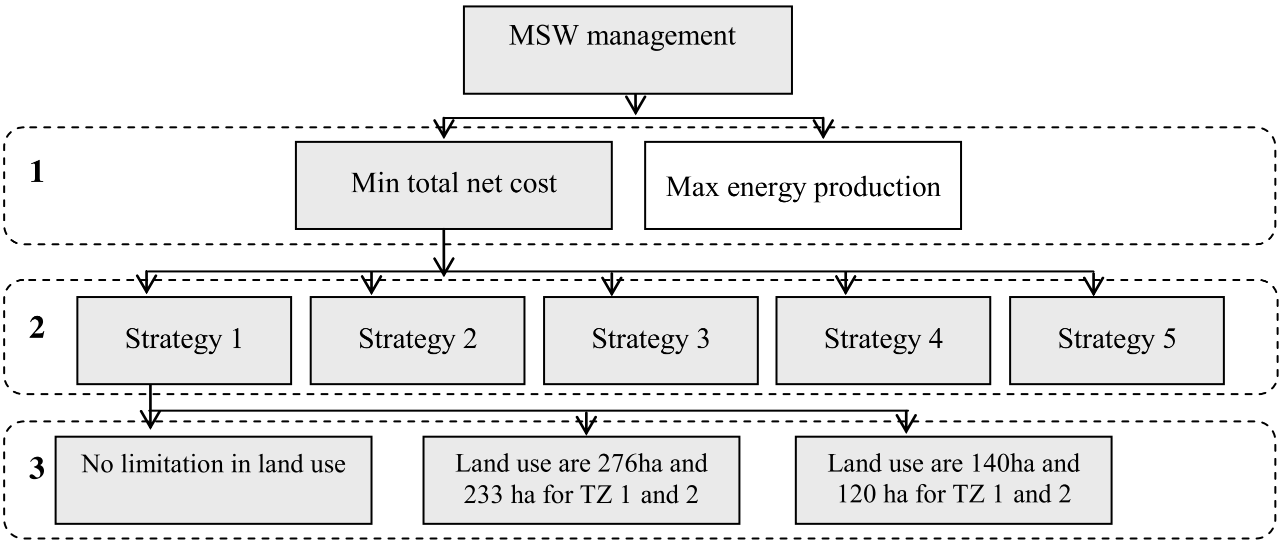

Figure 6.4 The aims, strategies and options will be discussed in section 6.3.

The values of the key parameters used in the model are presented in table 6.3. The supporting evidence for this data is given in Chapter 2, 3, 4 and 5.

Table 6.3 Summary of the values of the key parameters used in the models.

No.	Parameters	Value
Current condition		
1	Average amount of MSW within 20 years planning	3,569,759 ton/year
2	Amount of MSW in each of 24 districts of HCMC	Presented in appendix 3
3	Transport costs to treatment zone 1	0.21 USD/km
4	Transport costs to treatment zone 2	0.27 USD/km
5	Distances from districts to treatment zones	Presented in appendix 3
6	Planned land for treatment zone 1 for 20 year used	276 ha
7	Planned land for treatment zone 2 for 20 year used	233 ha
MSW treatment technology		
8	Fixed, operation, treatment costs of each treatment technology	Presented in chapter 5
9	Mass balance of each treatment technology	Presented in chapter 5
Products		
10	Amount of compost	20% of amount of MSW input to composting or anaerobic digestion plants
11	Amount of PE plastic recyclable waste	3.2% of amount of MSW input to composting or anaerobic digestion plants
12	Amount of other recyclable material	1.8% of amount of MSW input to composting or anaerobic digestion plants
13	Amount of biogas production	- 72m^3/ton MSW input to continuous anaerobic digestion plant - 39m^3/ton MSW input to batch anaerobic digestion plant - 91 m^3/ton MSW input to sanitary landfill - 105 m^3/ton MSW input to bioreactor landfill
14	Amount of electricity production	323 kWh/ ton MSW input to incineration
15	Amount of electricity converted from biogas	2 kWh/1m^3 biogas
16	Amount of heat production	2 times the amount of electricity
17	Aluminum recovery from ash	0.88 kg/ton MSW input to incineration
18	Iron recovery from ash	15.4 kg/ton MSW input to incineration
Price of products		
19	PE plastic recovery price	180 USD/ton (450USD * 40%)
20	Other recyclable material price	180 USD/ton
21	Compost price	32.5 USD/ton
22	Electricity price	8 cent USD/kWh
23	Heat price	0 cent USD/kWh
24	Aluminum price	0.9 USD/kg
25	Iron price	0.5 USD/kg

6.4.3 Model results and discussions

A. Strategy 1

Strategy 1 is based on the standard conditions (see table 6.1). In order to get the minimum total costs of transportation and treatment of MSW in HCMC, SURMAT proposes the distribution of MSW from the 24 districts to the two treatment zones as indicated in table A.4.1 in appendix 4. Depending on the options, the distribution is changed.

A.1 Selected treatment technology and distribution ratio of each treatment technology

The modelling results in table 6.4 show the treatment technologies and the number of used capacity types for the three options of strategy 1, in the case of the average amount of MSW input to the model is 3.6 million ton/year.

Table 6.4 Selected MSW treatment plants and capacities in treatment zones for 3 options of strategy 1.

Options	Treatment zone 1	Treatment zone 2	Overview treatments chosen
1 (unlimited land availability)	o Bioreactor landfill (31%): 1,100,000 ton/year x 1plant	o Batch anaerobic digestion (8%): 300,000 ton/year x 1 plant o Bioreactor landfill (61%): 1,100,000 ton/year x 2 plants o Residue landfill: 100,000 ton/year x 1 plant	o Batch anaerobic digestion (8%): 300,000 ton/year o Bioreactor landfill (92%): 3,300,000 ton/year o Residue landfill: 100,000 ton/year x 1 plant
2 (current land availability)	o Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant o Bioreactor landfill (30%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 2 plant	o Batch anaerobic digestion (56%): 500,000 ton/year x 4 plant o Residue landfill: 500,000 ton/year x 1 plant	o Batch anaerobic digestion (70%): 2,500,000 ton/year o Bioreactor landfill (30%): 1,100,000 ton/year o Residue landfill: 700,000 ton/year
3 (half of current land availability)	o Batch anaerobic digestion (33%): 500,000 ton/year x 2 plant 200,000 ton/year x 1 plant o Sanitary landfill (3%): 100,000 ton/year x 1 plant o Residue landfill: 300,000 ton/year x 1 plant	o Continuous anaerobic digestion (14%): 500,000 ton/year x 1 plant o Incineration with energy recovery (50%): 600,000 ton/year x 3 plant o Residue landfill: 300,000 ton/year x 1 plant	o Batch anaerobic digestion (33%): 1,200,000 ton/year o Continuous anaerobic digestion (14%): 500,000 ton/year o Incineration with energy recovery (50%): 1,800,000 ton/year o Sanitary landfill (3%): 100,000 ton/year o Residue landfill: 600,000 ton/year

Note: in the bracket next to each technology is the percentage in amount of MSW that is treated by the technology.

Option 1 is the case having no land limitation. Therefore, option 1 is the most flexible and the least expensive compared to other options. Comparing the net treatment costs (including the financial benefit of products and the costs of dumping residues) among the eight technologies, bioreactor landfill is the cheapest. Therefore the results of option 1 are mostly Bioreactor landfill. In option 1, one batch anaerobic digestion plant of 300,000 ton/year is proposed due to the economies of scale. It means, the costs of a batch anaerobic digestion plant with a capacity of 300,000 ton/year is the cheapest compared to other technologies with the same capacity.

Option 2 is the case of limited land. According to the planning of the government, the land available at treatment zones 1 and 2 is 276 and 233ha, respectively. The modelling results in partial replacement of Bioreactor landfills (of option 1) by Batch anaerobic digestion which requires less land. However, the land use for batch anaerobic digestion is higher than for In-vessel composting, Continuous anaerobic digestion and incineration technologies. It means, that in the option 2 land is limited but not so much that even more land efficient technologies are required.[49]

In option 1 the distribution of the MSW over the two treatment zones depends on the distance from sources to treatment zones and on the capacity of the treatment plants. Therefore, most MSW is transported to treatment zone 2 as most districts in HCMC are positioned closer to zone 2 than to zone 1. However in option 2, the transportation also depends on the land available in each treatment zone. Accordingly, a certain amount of MSW collected in the vicinity of treatment zone 2 must be transported to treatment zone 1.

Option 3 has half of the land available compared to option 2. It is 140 and 120 ha for treatment zone 1 and 2, respectively. Therefore, the selected technologies now partially change to continuous anaerobic digestion and incineration with energy recovery, options with relatively low land use per ton of treatment. The treatment zone 2 is closer to the waste collection points than treatment zone 1. Therefore, most waste is transported to treatment zone 2. This means land is faster lacking in treatment zone 2. Therefore, technologies with low use of land are preferable in treatment zone 2. Therefore, in option 3, Continuous anaerobic digestion and incineration with energy recovery are selected for the treatment zone 2. At first glance, it does not seem logical that the model selects a sanitary landfill with a very small capacity of 100,000 ton/year in option 3, zone 1. However, among eight technologies with a capacity of 100,000 ton/year, Sanitary landfill is the cheapest and there is still enough land available for a Sanitary landfill.

Comparison of the 3 options shows that: (1) with decreasing availability of land the preferred technology changed from bioreactor landfill (option 1) to batch and continuous anaerobic digestion (option 2) and then to incineration with energy recovery (option 3), (2) option 1 has a small percentage of batch anaerobic digestion (8%) and option 3 a small Sanitary landfill (3%). The model leads to this result due to the fact that we use discrete numbers for the capacity of plants.

A.2 Costs analysis

Table 6.5 presents the costs analysis of the three options of waste management in HCMC under the conditions of strategy 1. The analysis comprises the total net costs per year, the net treatment costs per ton MSW, transport costs, fixed costs, operation costs and negative costs[50]. In table 6.4 we converted “Total net costs per year” into the “Net costs per ton of treated MSW” by dividing the “Total net costs per year” by the “Amount of treated MSW per year”. For calculation of the “Net costs per person per year”, we divided the “total net costs per year” by the population for the year (2017) that the average MSW tonnage of 3.57 million tons/year will be reached. The population of HCMC in that year is estimated at 9,450,000 (table A.3.1 in appendix 3).

[49] These results depend on the assumption that land use should cover the largest amount of waste in 2032. Sensitivity analysis on this assumption can be found in section 6.4.4.

[50] Note that negative costs is synonymous to financial benefits from selling waste treatment end products.

Table 6.5 Costs analysis of the 3 options of strategy 1.

	Option 1	Option 2	Option 3
Amount of treated MSW (million ton/year)	3.6	3.6	3.6
Total net costs per year (million USD/year)	47.4	49.5	61.5
Net costs per ton treated MSW (USD/ton)	13.3	13.9	17.2
Net costs per person per year (USD/person/year)	5.0	5.2	6.5
Transport costs per ton (USD/ton)	7.2	7.6	7.3
Fixed costs per ton (USD/ton)	18.1	15	22.5
Operation costs per ton (USD/ton)	6.2	10.2	14.8
Negative costs per ton (USD/ton)	18.3	19	27.4

The total net costs in table 6.4 are the average total costs per year within 20 years planning with the average amount of 3.57 million ton MSW/year. Table 6.4 shows that if the land is not limited (option 1), the government has to pay an average of about 47.4 million USD/year for transport and treatment of MSW. If land is available as planned (267 and 233 ha) (option 2), the government has to pay about 49.5 million USD/year and if the government would not be successful in clearance and the land available would be only half of the area planned (140 and 120 ha) (option 3), the government has to pay about 61.5 million USD/year.

Option 1 results in lowest costs and option 3 in highest costs as was expected. The results show that the availability of land strongly affects the costs of waste management. The net treatment costs of option 2 are not much higher than the net treatment costs of option 1. It means that the land available at the two treatment zones in option 2 is only slightly lower than the maximum area required until the planning horizon (option 1 in year 2032). The slight lack of land increases the treatment costs of option 2 by 5% in comparison to the lowest costs (13.9 vs. 13.3USD/ton). The limited land in option 3 results in a significant 24% increase of the total costs in comparison to option 1.

The calculated transport costs 7.6 USD/ton are more or less in agreement with the actual costs (DONRE HCMCb 2010). Across the options the net costs of transportation and treatment of MSW range from 13.3 to 17.2 (USD/ton) depending on land availability. Counting with the presently planned areas of treatment zone 1 and 2 (276 and 233 ha, respectively), the net costs are 13.9 USD/ton treated MSW (option 2). These costs are much lower than the actual costs in HCMC in 2009 of about 7–8USD/ton for transport and 16.4–20USD/ton for landfilling (DONRE HCMCb 2010). This shows that proper integrated planning could probably lead to significant cost reductions.

In option 2 Batch anaerobic digestion technology replaces a part of the Bioreactor landfill of option 1. This reduces the fixed costs (15 vs. 18.1 USD/ton), but it increases the operation costs (10.2 vs. 6.2 USD/ton). Therefore, if budgets (for capital cost) are limited, this possibility of reducing the fixed costs and pay higher operation costs should be taken into account. Option 3 applies the technology with high fixed and operation costs but its financial benefits are high as well. The solution found with option 3 is interesting if the price of energy increases. When the price of electricity has increased, heat energy can be sold, and/or selling CERs become successful.

Table 6.4 shows that the expected net costs per person in HCMC are 5.0-6.5 USD/person/year. At an average number of persons per household in HCMC of 5 persons, the transport and treatment costs are about 25 - 32 USD/household/year (2.1-2.7 USD/household/month). If we include also the costs of collection of waste from households to collecting points, the total costs will be about 3 USD/household/month. Presently, the government collects from households only 0.5- 0.7 USD/month as fees for waste management and pays the rest from the general city budget (DONRE, 2009). If full cost recovery from households would become a policy target, households would have to pay for solid waste management four to six times the present fees.

A.3 Products quantity

From the results of the model, we can derive other outputs such as: compost, biogas and electricity production, heat energy production and volume of recycling wastes. The amounts of products per year and per ton MSW for strategy 1, options 1 until 3, are summarized in table 6.6. The amount for each product is the sum for all treatment plants in both treatment zones per year. The amount for each product per ton treated MSW was calculated by dividing the amount for that product per year by the average yearly amount of treated MSW (3.6 million ton/year). Based on these results, decision makers can make a planning to market these products. Although biogas can be used to produce electricity, in this thesis we present two products separately to make clear from which processes the products come (biogas from anaerobic digestion and electricity from incineration). Depending on the applied technologies, the products are different among the three options. Depending on the market, the products can be utilized and compensate for the costs of MSW management.

Table 6.6 Calculated total amounts of products per year and per ton of MSW input for strategy 1

Products	***Units***	**Option 1**		**Option 2**		**Option 3**	
		per year	*per ton*	*per year*	*per ton*	*per year*	*per ton*
Compost	*ton*	$60*10^3$	$17*10^{-3}$	$500*10^3$	$140*10^{-3}$	$340*10^3$	$95*10^{-3}$
Biogas	*m^3*	$348*10^6$	98	$210*10^6$	59	$75*10^6$	21
Electricity	*kWh*	0	0.0	0	0.0	$581*10^6$	163
Heat	*kWh*	0	0.0	0	0.0	$(1,163*10^6)$	(326)
PE	*ton*	$9.6*10^3$	$2.7*10^{-3}$	$80*10^3$	$22.4*10^{-3}$	$54*10^3$	$15*10^{-3}$
Recyclable material	*ton*	$5.4*10^3$	$1.5*10^{-3}$	$45*10^3$	$12.6*10^{-3}$	$31*10^3$	$9*10^{-3}$
Aluminum	*ton*	0	0.0	0	0.0	$1.6*10^3$	$4*10^{-2}$
Iron	*ton*	0	0.0	0	0.0	$28*10^3$	$8*10^{-3}$

Note:

- *Heat (between brackets) from incineration is used in the pre-treatment (drying) process of incineration technology (not for sale).*
- *Biogas can be converted to electricity and heat by the conversion factor of 1.9 and 3.8, respectively. (1m^3 biogas equals 1.9kWh electricity and 3.8 kWh heat)*

Option 1 produces mostly biogas from bioreactor landfills, while option 2 produces biogas, compost and also recyclable products (from anaerobic digestion technology). Option 3 produces all types of products, especially electricity and heat from incineration technology. It should be noted that the heat from incineration is used for the pre-drying process and not for selling. Therefore, there is no benefit from this heat. Biogas in option 1 and 2 can be converted to electricity and heat. Therefore, in option 1 and 2, there is no direct electricity production. If this biogas is converted to electricity, the electricity production will be 661,770,000 and 398,430,000 kWh/year or 185.4 and 111.5kWh/ton treated MSW for option 1 and 2, respectively. Heat energy in Viet Nam is needed for industry, not for residential consumption. Therefore, an integrated planning between solid waste management and industrial management is needed to support the heat market.

Option 2 produces the highest amount of PE recyclables, 80,000 ton/year or 22.4 kg/ton MSW input. Based on data from Vietstar Company (2011), the amount of plastic product from the PE recycling process is 40% of total PE recyclables input. Therefore, the plastic product is about 32,000 ton/year or 9 kg/ton MSW input.

Option 3 yields more products than options 1 and 2. Therefore, the expected financial benefits from products from option 3 are higher than from option 1 and 2. These benefits are, however, more sensitive to fluctuations in market prices of products.

A.4 Benefit of each type of product

Based on the type and amount of products, we can estimate the benefit of products. Table 6.7 shows the calculated benefit from each product per ton treated MSW in strategy 1. The unit price of each product is presented in chapter 5 and table 6.3. In this table, the benefit of biogas is calculated by converting it into electrical energy.

Table 6.7 Calculated benefits (from each product) per ton MSW input (treated) in strategy 1.

Unit: USD/ton MSW input

Products	Option 1	Option 2	Option 3
Compost	0.5	4.6	3.1
Biogas	14.8	8.9	3.2
Electricity	0.0	0.0	13.0
Heat	(0.0)	(0.0)	(0.0)
PE	0.5	4.0	2.7
Recyclable material	0.1	0.6	0.4
Aluminum	0.0	0.0	0.4
Iron	0.0	0.0	3.9

Note:

- *Heat (between brackets) from incineration is used in pre-treatment (drying) process of incineration technology (not for sale).*
- *Biogas can be converted to electricity and heat by the conversion factor of 1.9 and 3.8, respectively. (1m3 biogas equals 1.9kWh electricity and 3.8 kWh heat). In this calculation, biogas is sold via electricity.*

B. Strategy 2, 3, 4 and 5

The additional strategies 2 until 5 take into account the standard conditions of strategy 1 but include extra constraints: (a) constraints requiring a high degree of biological treatment in agreement with the MSW treatment policy of HCMC (strategy 2), (b) a constraint about the fraction of MSW transported to zone 2 (strategy 3), (c) constraints related to the market demand of compost (strategy 4), and (d) a full account of the financial benefits of heat energy and the CERs arrangement (strategy 5) (see table 6.1). Similar to strategy 1, strategies 2 until 5 comprise three options dealing with different land availability.

The distribution of MSW from 24 districts over the two treatment zones and to the treatment plants for the three options of the five strategies is presented in chapter 6 appendix 4, table A.4.1.

B.1 Selected treatment technologies and their distribution ratio

A complete overview of the treatment technologies for each strategy (1 until 5) and their distribution is presented in appendix 4, table A.4.3. Figure 6.5 summarizes the technology distribution.

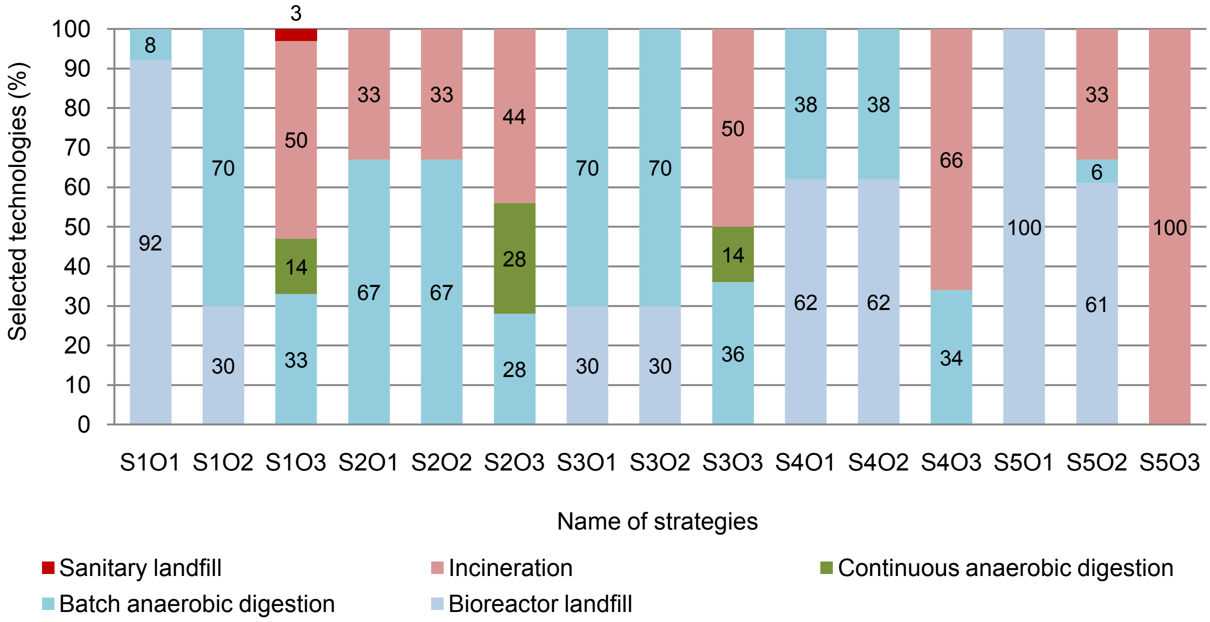

Figure 6. 5 Technology distribution (%) over strategies (1 until 5) and options (1 until 3).
Note: S1O1 refers to strategy 1 with option 1.

Similar to strategy 1, the selected technologies for the three options of the strategies 2, 3, 4 and 5 are strongly depending on the land available in the different options. The less land available (land option 3 < land option 2 < land option 1), the more the technologies with low land use, like batch anaerobic digestion and incineration, are selected, while the tool still sought to keep net costs as low as possible.

The selected technologies for options 1 and 2 of the three strategies 2, 3 and 4 are similar, namely batch anaerobic digestion and bioreactor landfill though in different proportions. It means that the land available in option 2 is not a limiting factor.

In strategy 2 (with the additional constraints of at least 50% of the MSW used for the production of compost and at least 30% for incineration), the technologies selected in the three options are much different as compared to strategy 1 as expected. Among the four technologies to produce compost (aerated static pile composting, in-vessel composting, batch anaerobic digestion and continuous anaerobic digestion technology), the tool selected batch anaerobic digestion technology for both treatment zones in option 1 and 2. Strategy 2 requires also that at least 30% of MSW must be incinerated; therefore, incineration with energy recovery was selected in all three options. Logically, the tool located the technology with the least land use in treatment zone 2 (shorter transport distance compared to treatment zone 1). Therefore, in all three options, incineration technology was selected for treatment zone 2. The outcome shows that to reach minimum total costs, the tool not only selected the technologies and their capacities but also the most appropriate location (i.e. treatment zone) of each type of technology.

In strategy 3 (with the additional constraint that no more than 50% of the waste goes to treatment zone 2), the tool selected the same technologies as for strategy 1 (option 2 and 3). The difference is that the location of the technologies (treatment plants) was changed due to limited transport of MSW to treatment zone 2. This additional constraint does not strongly influence the selection of technologies but affects primarily the location of technologies (batch anaerobic digestion and bioreactor landfill in options 1 and 2 and continuous anaerobic digestion and incineration in option 3).

In strategy 4, options 1 and 2 (with the additional constraints related to the production of compost) the technology distribution changed: less bioreactor landfill and more batch anaerobic digestion compared to strategy 1. In strategy 4, option 3 continuous anaerobic digestion is replaced by incineration as less compost is saleable. It shows how the limitation in the compost market affects the selection of MSW treatment technologies.

In strategy 5 with addition of the benefits from heat energy and CERs arrangements, the tool omitted in option 1 the anaerobic digestion by choosing 100% bioreactor landfill. In option 2 also a shift to bioreactor landfill takes place and in option 3 due to the limitation in land the tool choose 100% incineration. With increased benefits and the lack of land, incineration now becomes the most appropriate choice. The outcomes of strategy 5 show the strong impact of benefits from end products on the technology selection. The outcomes of strategy 5 are very sensitive to the market yields of electricity, heat and the possibilities to sell CERs under CDM program; therefore the sensitivity analysis of section 6.4.4 takes these parameters into account.

B.2 Costs analysis

A complete overview of the costs analysis for all strategies is presented in Appendix 4, table A.4.5.

Comparing the total net costs of the strategies 2, 3 and 4 with those of strategy 1 shows that with additional constraints the net costs increases (as expected). The net costs are highest under strategy 2 (with additional constraints of at least 50 % of the MSW processed for production of compost and at least 30% for incineration). In the special case of strategy 5, due to the assumed additional financial benefits from the sale of electricity, heat energy and carbon credits, the total net costs are very low compared to other strategies. It showed the potential strong impact of benefits from energy and CERs arrangements. It should be noted that in the case of incineration the produced heat is used for drying the waste prior to incineration and therefore cannot be sold on the market.

The total net costs of options 1 (unlimited land) and 2 (with currently planned areas) were more or less the same for strategy 2 and 3 and a little bit higher for strategy 4. It showed that the currently planned areas in treatment zones 1 and 2 would be sufficient for the strategies 1 until 4. The total net costs of the three options of strategy 5 were significantly different. The total net costs of option 2 (1.1 USD/ton) and 3 (1.4 USD/ton) of strategy 5 were 270% and 350% of option 1 (0.4 USD/ton). This strategy shows the strong impact of land use on total net costs.

Option 3 has reduced land availability. Therefore, compared to options 1 and 2, option 3 always selected the more compact technologies. The higher gross costs of these compact technologies were compensated by higher benefits to a considerable degree, but not fully. This made option 3 for reduced land availability always more expensive than the other options with more land available.

The overview of costs of all strategies clearly shows that transport costs, fixed costs, operation costs, benefits and extra costs depend on the type of technology and its capacity chosen and the location where this technology was applied.

B.3 Products quantity

An overview of the type and amount of products generated under the regimes of the different strategies is shown in Appendix 4, table A.4.7. The following insights were gained. Depending on the product markets and the overall plan of the government, it is possible to focus on the products that are most wanted. Using constraints as was done in strategy 4, the amount of a certain product can be regulated. The type and amount of products are dependent of the selected technologies and their capacities. Among the three options of land availability, option 1 (unlimited land) produces mostly biogas (from bioreactor landfill), option 2 produces biogas, compost and recyclable wastes (from anaerobic digestion and bioreactor landfill) and option 3 produces mostly electricity and metals (from incineration with energy recovery). Among the various strategies, option 1 of strategy 1 produces the highest amount of compost (500,000 ton/year); option 2 of strategy 1 produces the highest amount of biogas (346 million m^3/year) and PE (80,000 ton/year); and option 3 of strategy 5 that fully relies on incineration with energy recovery produces the highest amount of electricity (1.16 billion kWh/year).

6.4.4 Sensitivity analysis for the SURMAT modelling

Effect of changing the price of products or the amount of products

Besides for calculating the costs of the various strategies, we have also used SURMAT to calculate the effect of variation of the parameter values of compost amount, electricity price and PE plastic price on the selection of treatment technologies and treatment costs. In the table 6.8, the three cases are presented. Moreover, we do sensitivity analysis for the land use assumption described at the later part of this section.

In the sensitivity analysis, we use the default conditions of strategy 1 option 2 (S1O2) as reference and in all cases only one parameter has been varied at the time. In case 1, the amount of compost that can be produced from 1 ton of wet commingled MSW was proposed to be equal to 15% of the commingled MSW input, whereas it was assumed to be 20% in strategy 1, option 2. Case 2 shows the effects of a possible government measure to increase the electricity price to 12 cent USD/kWh, which is equal to the actual price in Thailand and Malaysia. The assumed electricity price used in the default strategy 1, option 2 was equal to the price of electricity in HCMC in 2009 (8 cent USD/kWh). In case 3 the price of PE plastic was supposed to rise from the actual 450 USD/ton to 600 USD/ton. The price of PE plastic is related to the price of diesel oil which is supposed to increase in the future.

Table 6.8 Proposed change in the value of a parameter of each case

Case	Parameter	Value in strategy 1, option 2	New value
1	Compost amount (% of MSW input to plants)	20	15
2	Electricity price (cent USD/kWh)	8	12
3	PE plastic (USD/ton product)	450	600

Tables 6.9, 6.10 and 6.11 show respectively the results for the three cases with changed parameter values.

Table 6.9 Effect of the variation in parameter values in selecting treatment technology

	Strategy 1, option 2	Case 1	Case 2	Case 3
Treatment zone 1	- Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant - Bioreactor landfill (31%): 1,100,000 ton/year x 1plant - Residue landfill: 100,000 ton/year x 2 plants	- Batch anaerobic digestion (11%): 400,000 ton/year x 1 plant - Bioreactor landfill (31%): 1,100,000 ton/year x 1plant - Residue landfill: 100,000 ton/year x 1 plant	- Incineration with energy recovery (25%): 600,000 ton/year x 1 plant - Residue landfill: 100,000 ton/year x 1plant	- Batch anaerobic digestion (41%): 500,000 ton/year x 3 plants - Residue landfill: 100,000 ton/year x 1 plant 300,000 ton/year x 1plant
Treatment zone 2	- Batch anaerobic digestion (56%): 500,000 ton/year x 4 plants - Residue landfill: 500,000 ton/year x 1 plant	- Batch anaerobic digestion (56%): 500,000 ton/year x 4 plants - Sanitary landfill (3%): 100,000 ton/year x 1plant - Residue landfill: 500,000 ton/year x 1 plant	- Incineration with energy recovery (75%): 600,000 ton/year x 5 plants - Residue landfill: 300,000 ton/year x 1plant	- Batch anaerobic digestion (56%): 500,000 ton/year x 4 plants - Sanitary landfill (3%): 100,000 ton/year x 1plant - Residue landfill: 500,000 ton/year x 1 plant
Total	- Batch anaerobic digestion (70%): 2,500,000 ton/year - Bioreactor landfill (31%): 1,100,000 ton/year - Residue landfill: 700,000 ton/year	- Batch anaerobic digestion (66%): 2,400,000 ton/year - Bioreactor landfill (31%): 1,100,000 ton/year - Sanitary landfill (3%): 100,000 ton/year x 1plant - Residue landfill: 600,000 ton/year	- Incineration with energy recovery (100%): 3,600,000 ton/year - Residue landfill: 400,000 ton/year	- Batch anaerobic digestion (97%): 3,500,000 ton/year - Sanitary landfill (3%): 100,000 ton/year x 1plant - Residue landfill: 900,000 ton/year

Note:

- *Case 1: amount of compost reduces from 20% to 15% of amount of MSW input.*
- *Case 2: price of electricity increased from 8 to 12 cent USD/kWh.*
- *Case 3: price of PE plastic increased from 450 to 600 USD/ton.*

Table 6.10 Effect of the variation of parameter values for the costs analysis

Costs analysis	Strategy 1, option 2	Case 1	Case 2	Case 3
Total net costs (million USD/year)	49.5	53.5	20.7	43.3
Total net costs (USD/ton)	13.9	15.0	5.8	12.1
Total net costs/person (USD/person/year)	5.2	5.6	2.2	4.5
Transport costs (USD/ton)	7.6	7.5	7.2	7.5
Fixed costs (USD/ton)	15	14.9	29.4	13.4
Operation costs (USD/ton)	10.2	10.3	16.8	12.2
Negative costs (USD/ton)	19	17.5	47.6	21.1

Note:
- *Case 1: amount of compost reduce from 20% to 15% of amount of MSW input.*
- *Case 2: price of electricity increased from 8 to 12 cent USD/kWh.*
- *Case 3: price of PE plastic increased from 450 to 600 USD/ton.*

Table 6.11 Effect of the variation in parameter value for products

Products (per ton MSW)	Strategy 1, option 2	Case 1	Case 2	Case 3
Compost (kg)	140	100	0	200
Biogas (m^3)	59	56.6	0	40.6
Electricity (kWh)	0	0	323	0
Heat (kWh)*	0	0	(646)	0
PE waste (kg)	22.4	21.5	0	31.4
Rec. waste (kg)	12.6	12.1	0	17.6
Aluminum (kg)	0	0	0.9	0
Iron (kg)	0	0	15.4	0

Note:
- *Case 1: amount of compost reduce from 20% to 15% of amount of MSW input.*
- *Case 2: price of electricity increased from 8 to 12 cent USD/kWh.*
- *Case 3: price of PE plastic increased from 450 to 600 USD/ton.*
- *Heat (between brackets) from incineration is used in pre-treatment (drying) process of incineration technology (not for sale).*
- *Biogas can be converted to electricity and heat by the conversion factor of 1.9 and 3.8, respectively. (1m3 biogas equals 1.9kWh electricity and 3.8 kWh heat)*

Case 1 shows that if the amount of compost produced from 1 ton of commingled MSW decreases by 29% from 140 to 100 kg/ton MSW due to a changed composition of commingled MSW, the required capacity of batch anaerobic digestion sinks from 70% to 66%. The benefits (negative costs) decrease by 8% (1.5 USD/ton MSW) and total net costs increase by 8% (1.1 USD/ton MSW). This case shows that the financial benefits of compost affects the total benefit only to a minor degree.

Case 2 with the increase of the electricity price to 12 USD cent/kWh showed a significant change in technology from 70% batch anaerobic digestion/30% bioreactor landfill in the default strategy to 100% incineration in case 2 and a reduction of the total net costs from 13.9 to 5.8 USD/ton MSW. Apparently incineration with energy recovery would be the best option if electricity is not subsidized from government's budget (the current condition) and the price of electricity would be 12 USD cent/kWh.

In case 3 with a price increase of PE plastic product from 450 to 600 USD/ton, the tool moved its choice from batch anaerobic digestion/bioreactor landfill (70/30%) to nearly full batch anaerobic digestion (97%). Bioreactor landfill is not attractive at such high PE prices as no collection of recyclable PE plastics takes place. The preference for batch anaerobic digestion demonstrated the important advantage of the separation of recyclables such as PE waste. This sensitivity analysis showed that the value of the input variables can have a strong influence on the results of the tool.

Effect of the introduction of factor 2.3 on the minimum costs and the selection of treatment technologies.

As already mentioned, in the year 2032 we have to treat 8.2 million ton MSW. This is 2.3 times (8.2/3.6) the average amount which is put in the model. If we assume that also in practice when we have to deal with a strong increasing amount of MSW from about 1 million to about 8.2 million ton/year, during the whole planning period the ratio of the selected technologies will be the same for each year, then we need at the year 2032 a capacity for the process-oriented treatment technologies that is 2.3 times of the average capacity as calculated in the model with the constant annually amount of MSW of 3.6 million/year. This assumption includes that the net treatment costs per ton of MSW (USD/ton) during the entire planning period is more or less the same. Of course, at the end of this period we have a small positive effect of economic of scale.

For the condition of strategy 1, option 1, 2 and 3, we have calculated the effect of the land use factor 1 (F1), 1.7 (between 1 and 2.3) and 2.3 on the net costs and selected technologies. It means the land use of the process-oriented technologies in case of factor 1.7 (F1.7) and 2.3 (F2.3) will be 1.7 and 2.3 times higher than in case of factor 1, respectively. The land use of sanitary landfill, bioreactor landfill and residue landfill are independent on the factor 1, 1.7 and 2.3. The results are shown in figure 6.6 and 6.7.

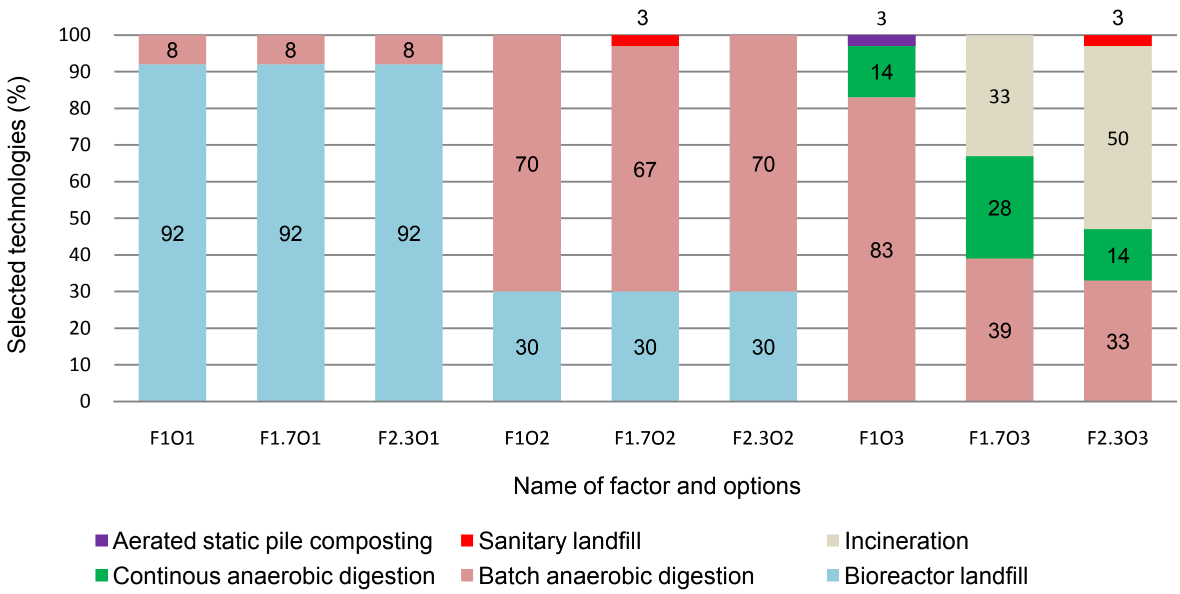

Figure 6. 6 Selected technologies of 3 options of 3 case factors.
Note: F1O1 refers to factor 1, option 1.

In option 1, land is un-limited. The results show that the selected treatment technologies and the ratios of these treatment technologies and the net costs for the 3 factors are the same (figure 6.6). In option 2, when land availability of the two treatment zones is 509 ha, the model has made small changes in the selection of technologies and in location of technologies. In option 3, when the land availability in the two treatment zones are much limited with only 255 ha, the changes in the selection of technologies are increased.

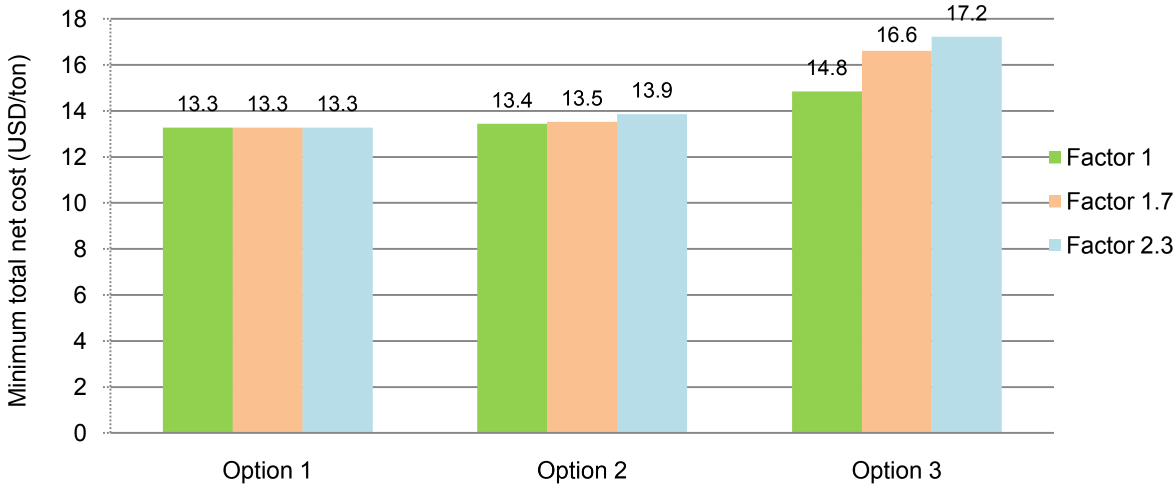

Figure 6. 7 Minimum total net cost of 3 options of 3 case factors

Figure 6.7 shows that the minimum total net cost of option 1 of the three factors are the same, while in option 2; it shows not clearly the changes. In option 3, in the case of factor 2.3 we have the highest cost. However, also in this case the costs are only slightly higher than in case of factor 1.

6.4.5 Discussion

In this chapter we assumed that the annual amount of waste to be treated is the same during the entire planning period. This annual amount of MSW is the average over the assumed 20 years planning period, which was about 3.6 million tons MSW/year. The initial amount of MSW to be treated in new facilities is about 1 million tons/year (in 2013) and is expected to increase to about 8.2 million tons/year at the end of the 20 years period (2032). Given the average waste amount of 3.6 million ton/year, not enough land is available in the current situation (total land available is 509 ha) to treat the waste in the economically optimal way, given by strategy 1, option 1. However, with this currently land availability and an appropriate selection of treatment technology the waste can be treated according to the optimal solution in strategy 1, option 2, with slightly higher costs compared to strategy 1, option 1.

The application of incineration with energy recovery was not required for the treatment of MSW in a cost-efficient way on the currently available land (509 ha). However, if the government would not succeed in removing the still extant houses and farms from that land, technologies with less land use would be required and application of incineration could not be avoided.

As a summary of the cost data from appendix 4, table A.4.6 and figure 6.8 show graphically total net costs of the three options of the five strategies. Depending on the conditions, the total net costs of transportation and treatment of MSW in HCMC in the strategies 1 until 4 ranged from 13.3 to 17.9 USD/ton. Strategy 5 resulted in very low net costs (0.4 - 1.5 USD/ton MSW) due to the additional financial benefits of heat energy and CERs. If this strategy was not included, strategy 1 is the cheapest. Comparison of the three options shows that option 2 was only slightly more expensive than option 1, while the costs of option 3 were significantly higher. It shows that the areas planned for future solid waste treatment zones in HCMC are large enough.

The proposed treatment technologies in strategy 1, 2, 3 and 4 showed that the preference of technologies in the case of HCMC (in all options) ranks from bioreactor landfill (highest) > batch anaerobic digestion > continuous anaerobic digestion > incineration with energy recovery (lowest). In the case of strategy 5, the selected technologies were bioreactor landfill > incineration with energy recovery. Comparison of the products from strategy 1, 2, 3 and 4 showed that with decreasing land availability, the products moved from biogas (or electricity and heat) from bioreactor landfill to biogas (or electricity and heat) and compost from anaerobic digestion and subsequently to electricity from incineration with energy recovery.

The sensitivity analysis showed that the modelling results are sensitive to the input data. Therefore, a realistic assumption for the data input is necessary, such as: composition of MSW, price and amount of electricity, current land available, life time of the technology, etc.

In the model calculations we assumed that the annual amount of MSW was equal to the average amount over the period 2013 to 2032. However, in reality the amount of MSW to be treated strongly increases from about 1 million ton that has to be treated in year 2013 to about 8.2 million ton that has to be treated in year 2032. The effect of this strong increase on the treatment options could not be calculated completely by the used model, as time is not a parameter in the model. However, sensitivity analysis comparing land use requirements from average amount of waste to maximum amount of waste gives more understanding on this issue. We will discuss this issue in more detail in chapter 7, section 7.1.5.

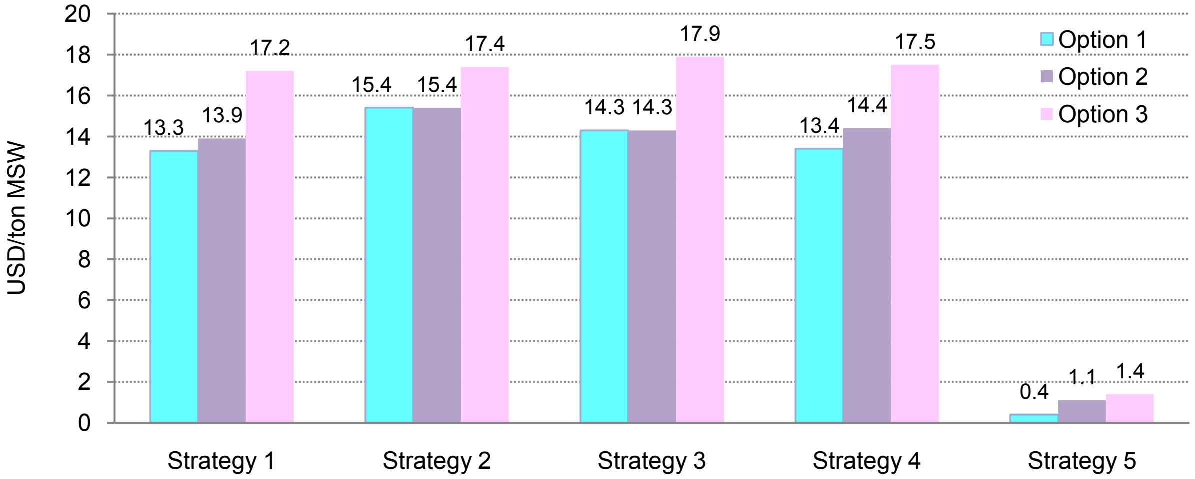

Figure 6.8 Total net costs of 3 options of each of the 5 strategies.

6.5 Maximization electricity production

Worldwide there is a growing interest in production of sustainable energy from biowaste. MSW is a biowaste with a high percentage of organic material that can be considered as a sustainable energy source. Therefore it is worthwhile to study the possibilities to maximize the energy production from MSW. With a high population growth rate and a strong industrial development, HCMC has an urgent need for energy, especially electricity, so waste-to-energy (electricity) projects could be an interesting investment goal.

6.5.1 Model formulation

It was assumed that maximization of the electricity production from MSW requires certain extra investments and accordingly an extra budget. The government (decision maker) could stimulate to increase the electricity production from MSW treatment by accepting higher net costs for the transport and treatment of MSW. We model this by allowing the total net costs to be equal to “M” times (M>1) the minimum net costs as calculated in strategy 1 option 2 (section 6.4). Index sets, parameters and decision variables were the same as for the modelling of minimized total net costs (section 6.4.1). There is an additional parameter:

- h_j: the amount of electricity production from the treatment technology j (kWh electricity/ton of MSW input).

Model formulation:

Maximum electricity production (kWh)= Maximum electricity production from batch and continuous anaerobic digestion + maximum electricity production from incineration with energy recovery + maximum electricity production from sanitary landfill + maximum electricity production from bioreactor landfill.

This statement was expressed mathematically as follows:

$$\text{Max } \{\sum_{i\in I}\sum_{j=3,4,5,7,8}\sum_{t\in T} X_{ijt}\, h_j + \sum_{i\in I}\sum_{j=12,13,14,16,17}\sum_{t\in T} X_{ijt}\, h_j\} \quad (16)$$

Further constraints (2) to (10) mentioned in the section 6.4 (table 6.2) were included in this formulation.

There is one more constraint (17) requiring total costs to be equal or smaller than "M" times the minimum net costs. This means: total costs of transportation + fixed costs + operation costs - negative costs + extra costs$\leq$ M $*$ minimum net costs.

Or mathematically:

$$\{\sum_{i\in I}\sum_{j\in J1}\sum_{t\in T} t_{ij}X_{ijt} + \sum_{i\in I}\sum_{j\in J2}\sum_{t\in T} t_{ij}\, X_{ijt} + \sum_{j\in J1}\sum_{t\in T} f_{jt}\, Y_{jt} +$$
$$\sum_{i\in I}\sum_{j\in J1}\sum_{t\in T} b_{jt}\quad X_{ijt} + \sum_{j\in J2}\sum_{t\in T} f_{jt}\, Y_{jt} + \sum_{i\in I}\sum_{j\in J2}\sum_{t\in T} b_{jt}\quad X_{ijt} -$$
$$\sum_{i\in I}\sum_{j\in J1}\sum_{t\in T} X_{ijt}\quad n_{jt} - \sum_{i\in I}\sum_{j\in J2}\sum_{t\in T} X_{ijt}\quad n_{jt} +$$
$$\left(k_1 \sum_{i\in I}\sum_{j=1}^{4}\sum_{t\in T} X_{ijt} \quad + k_2 \sum_{i\in I}\sum_{j=5}^{6}\sum_{t\in T} X_{ijt}\right) b_{9t} +$$
$$\left(k_1 \sum_{i\in I}\sum_{j=9}^{12}\sum_{t\in T} X_{ijt} \quad + k_2 \sum_{i\in I}\sum_{j=13}^{14}\sum_{t\in T} X_{ijt}\right) b_{18t}\} \leq$$
$$M * Min\ total\ cost\ of strategy\ 1\ option\ 2 \quad (17)$$

6.5.2 Increasing cost budget

In section 6.5 we limited the available land to 276 and 233 ha for treatment zone 1 and 2, respectively (option 2 of the five strategies discussed in section 6.4). In this study there is no additional constraint; only the parameter of the budget was changed. Therefore, we call section 6.5.2 parameter analysis. Using the standard conditions of HCMC (conditions of strategy 1 option 2 of section 6.4) parameter analysis was carried out starting with the minimum total net costs from strategy 1 option 2 (S_1O_2= 49.5 million USD/year). In the case of minimum net costs, the model had no possibility to select the technology that produced the highest amount of electricity. However, with increasing total net costs (budget), the model has more freedom to choose a technology that produces more electricity. Therefore, in the six options E_1 until E_6 below (table 6.11), we stepwise increased the budget until the electricity production did not rise anymore. As we can conclude from the M value, the maximum budget was 1.5 times the minimum budget (S_1O_2). Taking into account that the price of electricity will probably increase in the future this maximum budget can be considered as reasonable. Table 6.12 shows the M value and the total budgets of six options.

Table 6.12 Options and budgets

Options	**M value**	**Total budget** (million USD/year) (= M * net costs of S_1O_2)
Option E_1	1.01	50.0
Option E_2	1.1	54.4
Option E_3	1.2	59.4
Option E_4	1.3	64.3
Option E_5	1.4	69.3
Option E_6	1.5	74.2

Figure 6.9 shows the options to be discussed in the model of maximize electricity production.

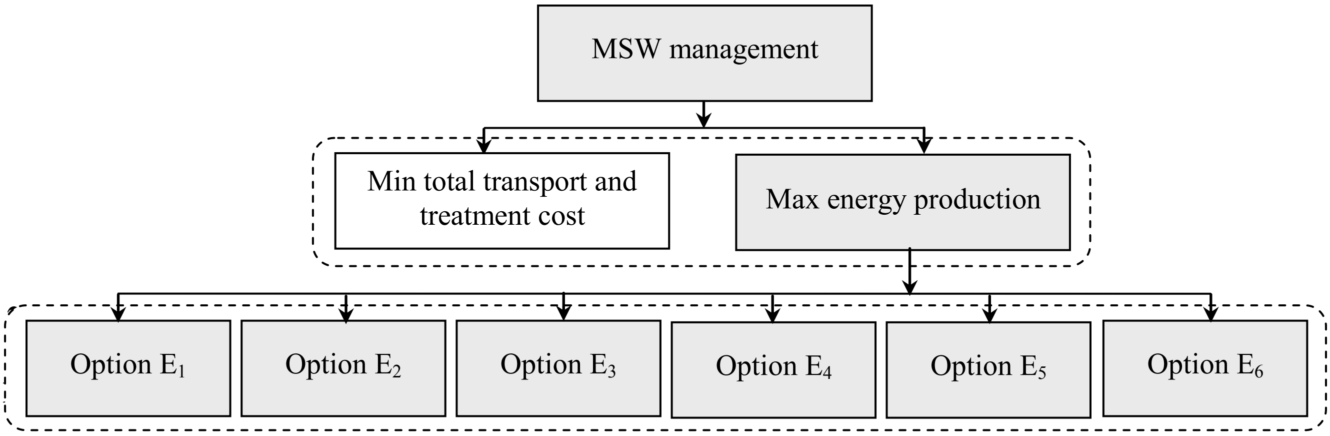

Figure 6.9 The options in the model ofmaximizing electricity production

6.5.3 Model results and discussion

The figures and table below show the proposed technologies (figure 6.10), costs analysis (figure 6.11) and products (table 6.13) of the six options as calculated by SURMAT. The overall result is shown in figure 6.12. More detail on proposed technologies are in appendix 4, table A.4.6 and A.4.8.

Selected treatment technologies and their distribution ratio

Figure 6.10 presents percentage of selected technologies in 6 options of the aim of maximum electricity production in a given budget. The modeling results show that with the lowest budget, the model selects bioreactor landfill and batch anaerobic digestion (option E_1). In option E_1, although bioreactor landfill produces more electricity than AD batch, but because of limited land availability (509ha), the model has to select also batch anaerobic digestion. With increased budget bioreactor landfill and incineration with energy recovery technologies are gradually increasing (option E_2, E_3, E_4). The required budget reached a maximum when the selected technology is incineration with energy recovery only (option E_5). A still higher budget (option E_6) does not lead to a higher electricity output, as there is not a more energy efficient technology than incineration with energy recovery.

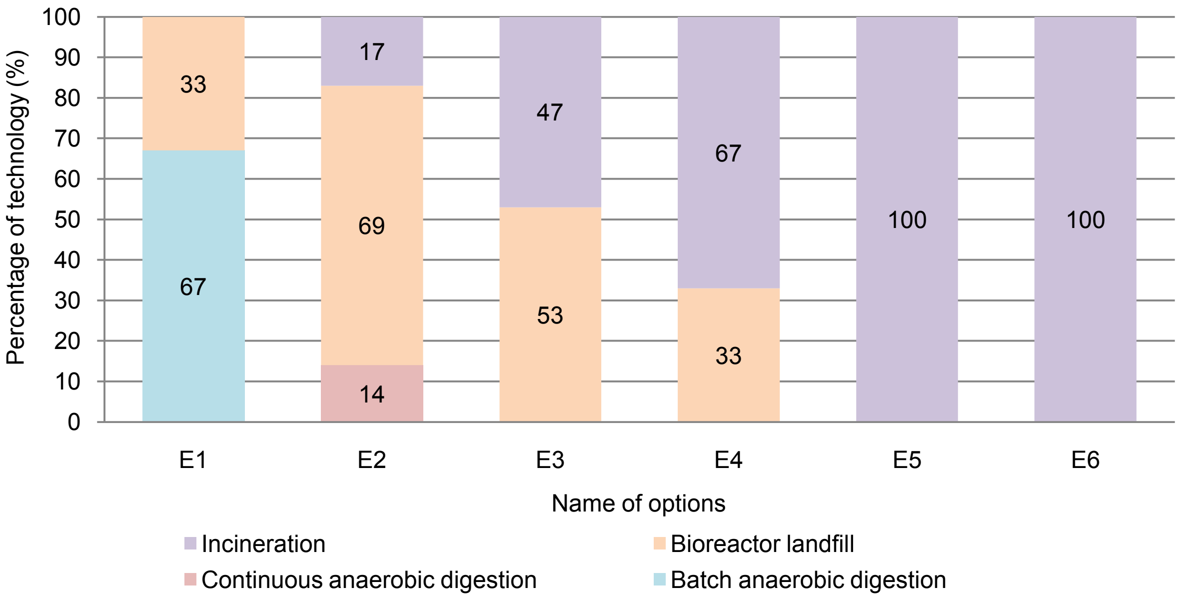

Figure 6.10 Optimal MSW treatment for 6 options.

Option E_1 had a budget of only 1% higher than the minimum total costs of S_1O_2. The aim of option E_1 was to see the effect of a very limited budget increment on the maximization of the electricity production, while the aim of S_1O_2 was minimization total net costs. The technologies proposed in option E_1 (67% batch anaerobic digestion and 33% bioreactor landfill) were hardly changed as compared to S_1O_2 (67% batch anaerobic digestion and 33% bioreactor landfill). The calculated electricity production in option E_1 was 411.7 million kWh/year or 115 kWh/ton MSW input. This was slightly higher than the electricity production in strategy 1, option 2.

The results of option E_2 showed that the tool selected several other technologies instead of batch anaerobic digestion technology at 10% budget increase as compared to the minimum budget of S_1O_2. Continuous anaerobic digestion and incineration became more appropriate. The electricity production in option E_2 was 746.5 million kWh/year or 209 kWh/ton MSW input. Comparison between option E_1 and E_2 showed an 81% increase of electricity production at a mere 9% increase of the MSW management budget.

In option E_3 with a 20% higher budget than S_1O_2 (budget of about 59.4 million USD/year) no anaerobic technologies were proposed. The proposed technology mix consisted of incineration with energy recovery (47%) and bioreactor landfill (53%). The electricity production in option E_3 was 913.7 million kWh/year or 256 kWh/ton MSW input. The electricity production of E_3 is 122% higher than E_1 and 22% higher than E_2.

In option E_4, the budget increases to 30% of the budget of S_1O_2 (new budget 64.3 million USD/year). The proposed technologies are the same as in option E_3 but then share of incineration increases further, while also the location changes with more waste treated in zone 1. The maximum electricity production in option E_4 was 1,003 million kWh/year or 281 kWh/ton MSW input.

When the budget increases to 40% of S_1O_2 (option E_5), the proposed technologies were solely incineration with energy recovery. With this budget, incineration is the best choice to achieve a maximum electricity production. Maximum electricity production in option E_5 was 1,153 million kWh/year or 323 kWh/ton MSW input.

The proposed technology of option E_6 was incineration, the same as in option E_5. Maximum electricity production in option E_6 was therefore the same as in option E_5. Apparently, the budget of option E_6 was higher than needed to get the maximum electricity production. The maximum budget needed to get maximum electricity production ranged from higher than the budget of E_4 (64.3 million USD/year) to the budget of E_5 (69.2 million USD/year).

Costs analysis

The costs analysis in figure 6.11 and the products analysis in table 6.13 show the increase of the electricity production from 115 to 323 kWh/ton MSW at an increase of costs for MSW transport and treatment.

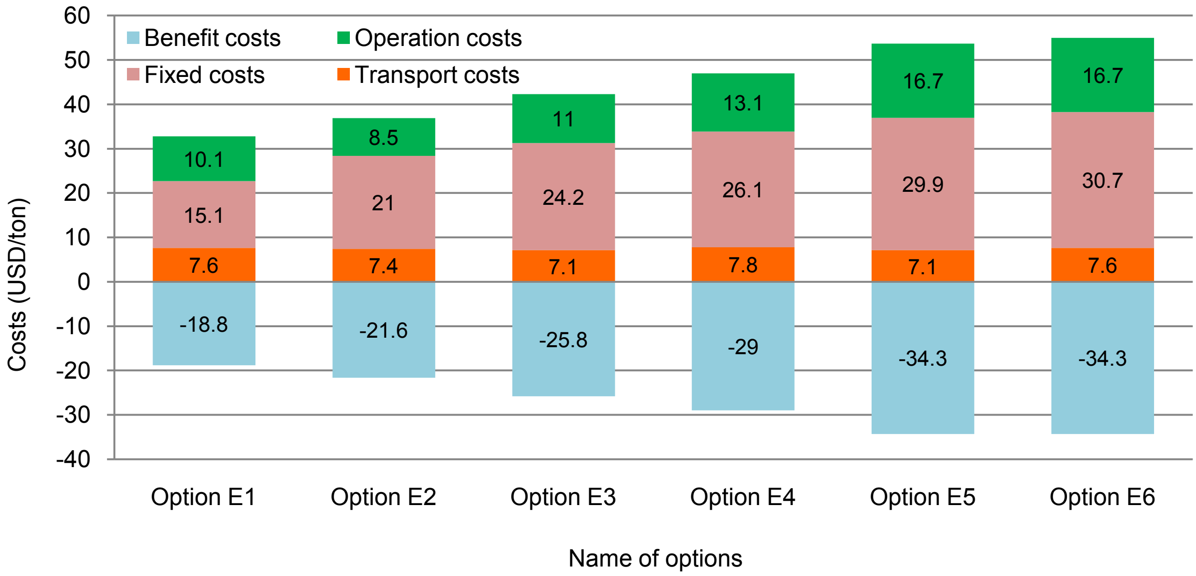

Figure 6. 11 Costs analysis of 6 options.

The maximum electricity production in all options was calculated by adding the electricity production from incineration and from biogas generation. One (1) m^3 biogas with about 55% of CH_4 can be converted into 1.9 kWh electricity. The benefits of the combined electricity products in option E_1 up to E_6 are 9.2, 16.7, 20.5, 22.5, 25.8 and 25.8 USD/ton, respectively. These amounts make up 49, 77, 79, 77, 75, and 75% of the total financial benefits (negative costs) of these options, respectively.

Product quantity

Table 6.13 Maximum electricity production for the 6 options.

	Option E_1	Option E_2	Option E_3	Option E_4	Option E_5	Option E_6
Max. electricity production (GWh/year)	412	747	914	1,003	1,153	1,153
Max.electricity production[51] (kWh/ton)	115	209	256	281	323	323
Compost product (ton/ year)	480,000	100,000	0	0	0	0
Biogas production (million m^3/ year)	216	261	194	122	0	0
Electricity production (GWh/ year)	0	194	549	775	1,153	1,153
Heat energy production[52] (GWh/year)	(0)	(388)	(1,098)	(1,550)	(2,306)	(2,306)
PE plastic recyclable waste collected (ton/ year)	76,800	16,000	0	0	0	0
Other recyclable waste (ton/ year)	43,200	9,000	0	0	0	0
Aluminum (ton/year)	0	528	1,496	2,112	3,168	3,168
Iron (ton/year)	0	9,240	26,180	36,960	55,440	55,440

[51] Maximum electricity production is calculated by the sum of electricity from incineration and electricity from converting biogas. One (1) m^3 biogas with about 55% of CH_4 can be converted to 1.9 kWh electricity.
[52] Heat energy is from incineration (between brackets). This product is reused for pre-treatment (drying MSW) in incineration process. In case if biogas is converted into electricity, it also produce heat energy, the amount of heat can be sold if there is a market.

The relation between maximum electricity production and net budget

Figure 6.12 shows the relation between maximum electricity production at given (net) budgets for transport and treatment of MSW in HCMC. With increasing budget the electricity production increases. In this calculation for HCMC, the maximum energy production increases from 115 kWh (option E_1) to 323 kWh/ton MSW input (option E_5 and E_6). The electricity production does not linearly increase with the increasing budget. For example, comparing between option E_2 and E_1 shows that the amount electricity production increases 82% while the amount of budget increases with only 9%. The decision maker should consider between the benefits of electricity production and the budget to take the best decision. Maximum electricity production is 323 kWh/ton, which corresponds to net costs for transport and treatment of 19.4 USD/ton MSW.

Though the emphasis in this part of the modelling was on electricity generation also the other utilizable products did contribute significantly to the financial benefits. For example in option E_5 the products were annually 1153 GWh electricity, 3,168 ton aluminium and 55,440 tons iron.

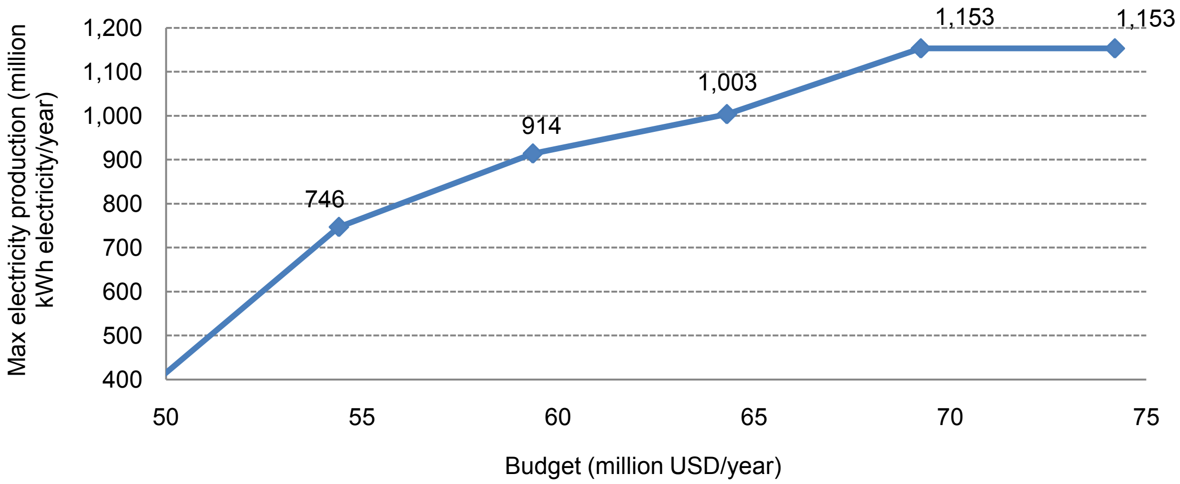

Figure 6.12 The relation between maximum electricity production and available budget for transport and treatment of MSW.

Effect of benefits from electricity on the net budget

Table 6.14 shows the effect of benefits from electricity on the budget by comparison between case 1 and 2 in which the electricity prices were 0.08 and 0.12 USD/kWh, respectively. In option $E_{1,2,3,4,5}$ the model proposed a mix of technologies and calculated the amount of produced electricity (kWh/ton MSW treated) (in column 3). Based on these amounts of electricity, the benefits of electricity was calculated for case 1 and 2 (column 4 and 5). The additional benefits due to the increase of the electricity price is presented in column 6. The new budget needed for case 2 was calculated using the budget of case 1 minus the additional benefits of case 2 (column 7). Data of column 8 shows that the budgets required in case 2 are much lower than in case 1, which are about 67, 45, 38, 38, 33 % of case 1, respectively. The gaps between total net costs of case 1 and 2 are larger when the given budget is higher or when the dominant selected technology is incineration with energy recovery. This is because the latter technology produces more electricity compared to other technologies. Figure 6.13 shows the comparison in total net costs between case 1 and 2.

Table 6.14 Costs analysis of the 5 strategies of maximized electricity production model for two electricity market prices (The strategy 6 is not mentioned due to the fact that the budget of strategy 6 is over the maximum budget need).

Options	Budgets in case 1 (million USD/year)	Amount of electricity (kWh/ton)	Benefits from electricity (USD/ton)		Additional benefits (case 2-case 1) (USD/ton)	New budgets need in case 2 (million USD/year)	Percentage of budget (% of case 2/case 1)
			Case 1	Case 2			
E_1	49.95	115	9.2	13.8	4.6	33.53	67
E_2	54.41	209	16.7	25.1	8.4	24.57	45
E_3	59.36	256	20.5	30.7	10.2	22.81	38
E_4	64.30	281	22.5	33.7	11.2	24.18	38
E_5	69.25	323	25.8	38.8	12.9	23.13	33

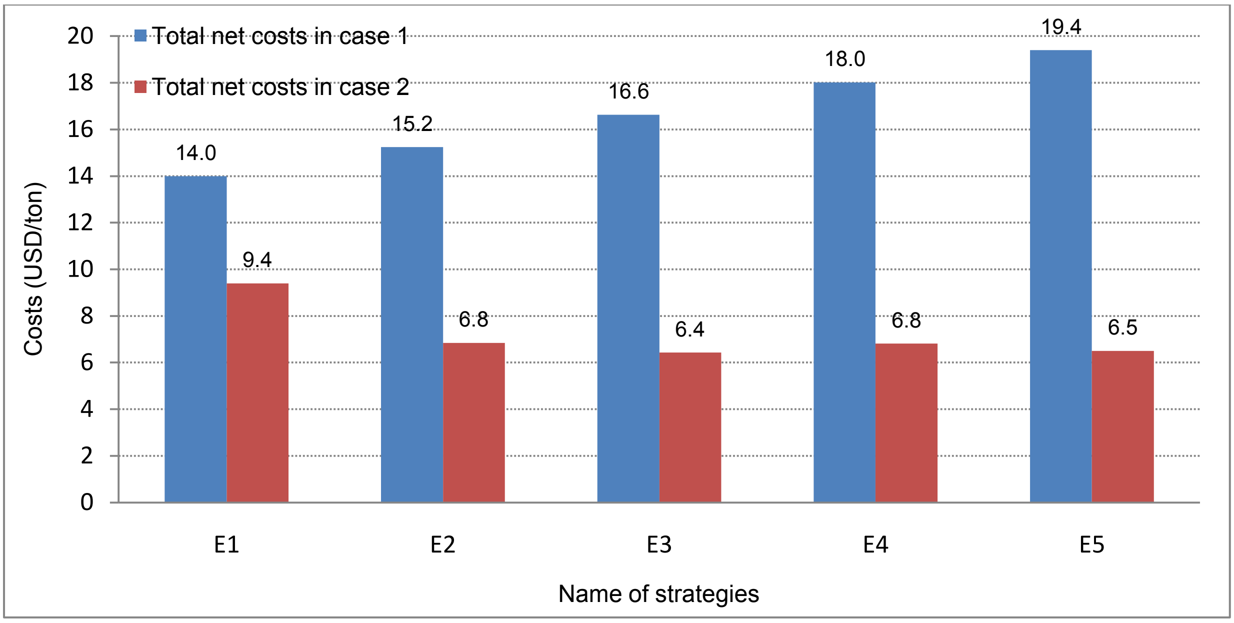

Figure 6.13 The comparison between total net costs when the price of electricity is 8 (case 1) and 12 (case 2) cent USD/kWh.

6.5.4 Discussion of the model to maximize electricity production

The results above show that the model could well process the aim of maximum electricity production. Comparison between S_1O_2 and $E_{1,2,3,4,5,6}$ shows that logically, the technology mix changed with the alteration of the aim from minimization of total net costs to maximization energy production. With the aim of maximum electricity production, the model selected the technologies bioreactor landfill and incineration with energy recovery. The budget increase led to a shift towards incineration with energy recovery as treatment technology (options E_5 and E_6).

The maximum electricity production on the basis of the average available flow of MSW was 1,153 GWh/year or 323 kWh/ton at a total budget for MSW management in HCMC of about 69 million USD/year. The figure showing the relation between maximum electricity production and fixed budget gives interesting information in the case of average amount of MSW is 3.6 million ton/year.

6.6 Applicability of SURMAT in practice

From the demonstrations of modelling above, it is evident that the outcomes depend to a high degree on the impact factors. The most important factors are summarized here.

- *Effect of local conditions*. There are many local conditions which affect the results of the model, such as the characteristics of MSW, policies on MSW management, the master plan on MSW management and treatment zones, the activity of land clearing, the acceptance of new technologies, changes in the market of electricity, compost and PE plastics. Depending on the conditions, the model may need some structural improvements or constraints to be added. Fortunately, the model has a simple structure, so that modifications are not difficult to apply and more constraints can be added.

- *Effect of life time of the MSW treatment technologies*. In this study the life time of technologies (composting, anaerobic digestion and incineration) was assumed to be 20 years and the model was run for that period (up to 2032). As much as possible effective use was made of installed capacity of treatment plants and this capacity was supposed to be used until its designed life time. However, shortening of the technical life of installations would lead to higher prices. For example: poor maintenance or new regulation with respect to the use of technologies. But also other factors could shorten the effective life time, such as changing characteristics of the wastes or new policies.

- *Effect of strongly increasing annual amount of MSW*. The outcomes of the SURMAT modelling (the technology mixes) were obtained using a constant average annual amount of MSW to be treated. However, in practice, the amount of MSW is increasing requiring a gradual augmentation of the installed capacity. Therefore, based on the results of modelling with the average amount of MSW and on the estimated amount MSW for each year during 20 years, the decision maker could make a plan for step-wise investment. In the preparation of such plans several considerations count. The first is the chosen investment interval. A short interval of say five years has the strength of being able to adjust plans to more accurate estimations of the increases of the MSW mass flow to be treated. During the preparation of a new investment phase SURMAT could be run again to determine the most appropriate technology mix for the new planning period. For HCMC such results could deviate from those given in this thesis. Another positive point of a short investment interval is the relatively limited degree of under-utilization of new plants. Rather soon after the start-up of a new plant a good part of its capacity will be utilized: under-utilization is small and the costs per ton treated relatively low, different from the larger under-utilization of a larger plant built for a capacity only reached after for instance ten years. A disadvantage of a short investment interval could be higher costs, e.g. costs related to the application of smaller-scale plants and transaction costs related to the preparation and execution of construction projects: it is usually cheaper to build once than twice. The impact of the investment interval on overall costs would have to be assessed for the situation under study. A second important consideration in solid waste management would be the possibility of opening new treatment sites. The SURMAT modelling calculates technology mixes for a certain flow of waste and a given area of land. Obviously the availability of more land could profoundly change the selection of most appropriate technologies as a comparison between the options 2 and 3 in this thesis show. The possibilities of using SURMAT in situations with an increasing MSW mass flow are elaborated in more detail in chapter 7, section 7.1.5.

6.7 Conclusions

In this Chapter 6 two cases regarding the selection of treatment technologies for MSW in HCMC have been elaborated using the decision support tool SURMAT, which works with a mixed integer linear programming model. One case focused on minimization of the total net costs of transportation and treatment of MSW and the other on maximizing the electricity production from MSW applying fixed budgets. The results obtained with the model show that the model is able to assess different strategies for a constant annual amount of MSW. The model gives information about: (1) the distribution of MSW from the discharge sources to the two treatment zones and to each treatment plant within each zone; (2) selection of technologies and their capacities for both treatment zones; (3) costs analysis regarding transport costs, fixed costs, operation costs, benefits from products and costs of residues disposal. Besides, strength of the model is that it can be easily changed by e.g. adding more constraints; therefore, it can be used efficiently for sensitivity analysis which may give relevant and important information for decision makers.

Five strategies (strategies 1 to 5) have been modelled focused on the aim of minimization the total transportation and treatment costs of MSW in HCMC. Each strategy comprised three options. In option 1 land use was not a limiting factor; in option 2 lands was limited to 276 ha in treatment zone 1 and 233 ha in zone 2; and in option 3 the land area was further reduced to 140 ha in zone 1 and 120 ha in zone 2. In all options the land was available for a period of 20 years. For each strategy, the model calculated the optimum technology or mix of technologies and other relevant aspects. The main conclusions are summarized below:

- Strategy 1 characterizes the current situation in HCMC and has the lowest total costs compared to other strategies. The minimum total costs were 47.4, 49.5 and 61.5 million USD/year for option 1, option 2 and option 3, respectively. The total costs increased when land availability was limited. For the situation of the currently available land (option 2), the costs of the most appropriate treatment system, consisting of 31% bioreactor landfill and 69% batch anaerobic digestion, were only slightly higher than the cheapest option (option 1).
- The total costs of transportation and treatment of MSW of the three options in strategy 1were 13.3, 13.9 and 17.2 USD/ton which was much lower than the costs in HCMC nowadays (16.4-20 USD/ton for disposal at sanitary landfills, 12 USD/ton for composting and about 7-8 USD/ton for transportation.
- Strategies 2, 3, 4 and 5 referred to situations with more requirements (constraints) from the government. In strategy 2, two extra constraints defined the amounts of MSW to be treated by composting or anaerobic digestion of at least 50% and by incineration of at least 30% of the total amount of MSW. Strategy 3 required that not more than 50% of the total MSW be transported to treatment zone 2. Strategy 4 put a constraint to the effective demand for compost, which would be limited to between 200,000 and 500,000 ton/year. The additional constraints resulted in increases of the total net costs. For example, in the options 2 of the four strategies the total net costs of strategy 2 (15.4 USD/ton), 3 (14.3 USD/ton), 4 (14.4 USD/ton) were higher than the costs of strategy 1 (13.9 USD/ton) by about 11, 3 and 4%, respectively.
- Strategy 5 assumed that heat energy and carbon credits under a CDM program would be sold to gain more financial benefits (in other strategies heat energy and carbon credits were not included in the benefit of products). Therefore, strategy 5 was similar to strategy 1 but the benefits were much higher, so that the total net costs were much lower as compared to other strategies. The total costs of option 1, 2 and 3 of strategy 5 are equal to only 3, 8, and 8 % of strategy 1, respectively. The results show that because of the high benefits from electrical energy and heat energy from bioreactor landfill, anaerobic digestion, and especially the high benefit from electrical energy from incineration with energy recovery, these technologies are all very interesting. These results also show the important role of the CDM program in a MSW management system.
- Comparison of the total net costs of the three options shows that the total net costs of the "less land use" option were logically higher than the "higher land use" option. For example, in strategy 1, the total net costs of option 2 and 3 were higher than option 1 with about 5 and 30%, respectively. It has to be kept in mind that in the model no costs of land use are included. Land is provided free of costs. However, it is rather simple to include in the model also a costs factor for the use of land. The results of all five strategies showed that the net costs of option 2 and option 1 did not differ strongly from each other. It showed that the planned land area of option 2 (276 ha and 233 ha) was only a little lower than the maximum need using the cheapest technology namely bioreactor landfill. In other words, land availability in HCMC is not a grave limiting factor with respect to the total net costs. Based on this data, the decision maker could trade-off between enlarging the available land for MSW treatment or increasing the budget for MSW treatment.

- The proposed treatment technologies in strategy 1, 2, 3 and 4 showed that in HCMC the preference order goes from bioreactor landfill (high preference) > batch anaerobic digestion technology > continuous anaerobic digestion technology > incineration technology (low preference). In the case of strategy 5 (option 2), the selected technologies were bioreactor landfill (62%) and incineration technology (33%).
- The results of a sensitivity analysis showed that the input parameters (process parameters) very much affected the results of the modelling. Depending on the type and value of a parameter the effect on the model differed. At modelling the minimization of total net costs, the effect of electricity price on the results was higher as compared to the effect of changing content of organic matter in MSW or the effect of changing price of PE recyclable waste obtained from MSW.

The effect of an increase in the budget on the maximum production of electricity has been investigated for six options: $E_1$to E_6 which represented strategies with a budget of respectively 1.01, 1.1, 1.2, 1.3, 1.4 and 1.5 times the minimum budget of strategy 1 (option 2). Two main conclusions are summarized.

- The tool showed that with an increasing budget the electricity production increased to a maximum value of 323 kWh per ton MSW input. This higher electricity production was achieved through a higher share of incineration with energy recovery in the technology mix. The maximum production was reached when the budget amounted to about 1.3 to 1.4 times the minimum budget.
- With increasing budget the proposed technology mix in each option moved from batch anaerobic digestion technology (strategy 1 option 2, option E_1) to bioreactor landfill (option E_1, E_2, E_3, E_4) and then to incineration (E_3, E_4, E_5 and E_6). The tool also showed that from a budget of 54.4 million USD/year upwards (15.2 USD/ton MSW) the incineration technology was applied.

As already remarked the findings depend to a large extend upon the assumptions made and input data used. For example, the MILP model calculates the optimal treatment plan for a given constant annual amount of MSW over a specific period. However, the tool can also be used to give an indication about the policy that has to be followed if the decision maker has to deal with a strong increase in the annual amount of waste during the period under consideration. This will be elaborated in more detail in chapter 7 (in section 7.1.6B).

Chapter 7
Discussion and conclusions

The present chapter gives in section 7.1 an advanced interpretation and discussion of the findings of previous chapters, in particular of the decision support tool SURMAT elaborated in chapter 6. Subsequently, section 7.2 gives conclusions and recommendations of the thesis.

7.1. Discussion

7.1.1 Introduction

The management of MSW in developing countries and countries in economic transition is a growing problem. The amount of MSW is increasing enormously, while only a few technologies are seen as appropriate to the prevailing conditions. Among these technologies, landfill is dominant, composting is being applied with varying success and anaerobic digestion and incineration are in a demonstration phase. The aim of this thesis is to improve and support decision making about the technologies for the treatment of MSW, especially in developing countries. The identification of optimal single- or multi-technology solutions for specific situations is difficult, since a host of technological, environmental, economic, social and policy factors may influence the technology selection. To find appropriate solutions a decision support tool is needed that must be able to optimize decision making in a complex situation including issues on transportation, treatment, land availability and other impact factors. This thesis focuses on MSW management for HCMC as a case study representative for cities in developing countries. It elaborates a decision support tool that generates appropriate MSW management strategies taking minimum costs and maximum energy (electricity) production as main objectives. In order to achieve the aim of the thesis, the following activities have been executed: (1) describing the current situation of MSW management system in HCMC, Viet Nam (chapter 2); (2) investigating the applicability of dry anaerobic batch digestion of the organic fraction of the MSW in HCMC (chapter 3); (3) reviewing potentially feasible treatment options, encompassing landfill, composting, anaerobic digestion and incineration technologies (chapter 4); (4) a quantitative technical and economic assessment of these treatment options with respect to the applicability in Viet Nam (chapter 5); (5) development and application of an optimizing decision support model (chapter 6); (6) a discussion about the results of the model, including sensitivity analyses, followed by conclusions and recommendations for the case of HCMC (chapter 7). This section proceeds with a discussion of these activities.

7.1.2 Current municipal solid waste management system in Ho Chi Minh City

As the MSW management system affects the choice of MSW treatment technologies, its characteristics were analyzed in chapter 2. In particular relevant to this thesis were:

(1) The high and increasing quantity of MSW caused by continued growth of the population and the economy;
(2) The need to treat commingled waste with a high percentage of organic matter and moisture, a low percentage of recyclable materials and a low heat value;
(3) An inadequate collection and transport infrastructure and lack of land for new MSW treatment zones;
(4) The lack of public awareness on MSW management and hygiene and an urgent need for capacity building on MSW management and treatment;
(5) An over-complex and often inefficient institutional framework. The roles and responsibilities of organizations are in some cases overlapping and in others they are ill-defined;
(6) The lack of relevant and adequate legislation/regulations and poor implementation of rules;
(7) The insufficient government budget and cost recovery especially in view to the need for new sophisticated treatment installations and more strict requirements for environmental safety;

(8) The large but poorly equipped informal system of waste recycling. Inadequate process technologies results in low quality products and high pollution emissions;
(9) The in appropriate MSW treatment technology. MSW is commonly dumped without pollution control activities. Sanitary landfills and composting are applied in some big cities. Anaerobic digestion and incineration are not applied for MSW yet.

The conditions found in HCMC seem typical for developing countries which render this case study and the solutions proposed in this thesis relevant for a wider area than Viet Nam. Though the mentioned characteristics point at serious challenges, the analysis of chapter 2 also shows clear positive trends in the domains of reorganization of the collection services, increase of the cost recovery and an increasing role of private investment in MSW treatment.

7.1.3 Assessment of municipal solid waste treatment options for developing countries

Landfill, composting, anaerobic digestion and incineration were identified in chapter 4 as the main potentially suitable ways of treatment of MSW. Based on the conditions prevailing in urban areas of developing countries, eight technological treatment methods were defined out of a long list of solid waste treatment technologies, namely aerated static pile composting, in-vessel composting, continuous anaerobic digestion, batch anaerobic digestion, incineration with energy recovery, incineration without energy recovery, sanitary landfills and bioreactor landfills. The criteria used for this selection of appropriate technologies for MSW treatment were subdivided into the following main categories: technical efficiency, environmental performance, social manageability and economic affordability.

Sanitary landfill was included in the options list because it still is the first choice in developing countries, despite its high land requirement and emissions of leachate and gases. The bioreactor landfill is an improved sanitary landfill that is still new to developing countries but apparently advantageous to places with high temperatures and wet wastes with a high organic carbon content. Important strengths of the technology are the lower footprint (land use) and the reduced costs of ex-situ leachate treatment.

Different from the situation in many industrialized countries the composting technology can be attractive in developing countries where the MSW often has a high percentage of organic matter and a high agricultural demand exists for organic fertilizer for which compost can be the basis. In addition, composting is a more simple and flexible technology than incineration and anaerobic digestion and therefore interesting to reduce the waste flow to sanitary landfills. However, composting in developing countries comes with some typical problems: (1) requirement of a complicated pre-separation system (dealing with commingled MSW and high moisture content); (2) composting of commingled MSW (as the most cases of developing countries) may result in products of inadequate quality; (3) the high moisture content in MSW easily creates anaerobic conditions and therefore the production of odors; (4) in the tropical areas, rain can be heavy which requires an indoor composting process leading to increased investment costs. Aerated static pile composting is the most commonly used in developing countries due to its relatively simple technical lay-out and lower costs compared to in-vessel composting, and better performance and control compared to windrow composting. The financial benefits of collected recyclable waste from the pre-separation process of composting and anaerobic digestion can lower the total net treatment costs. In-vessel composting is a favorable technology if costs are affordable, land is a limiting factor and the area is sensitive to odor emissions.

Anaerobic digestion of the organic fraction of MSW (OFMSW) is a proven technique and is applied worldwide. However, it is a new approach in developing countries and therefore needs research on a lab and pilot scale to prove the application. Research presented in this thesis in chapter 3 on dry anaerobic batch digestion of MSW or mixtures of MSW and pig manure in the conditions of HCMC showed that this form of treatment with leachate recycling under mesophilic conditions had a good performance with a biogas production of 59 m^3/ton wet OFMSW (65% moisture content). Although this technology is more complex compared to composting, it can be attractive in developing countries due to: (1) benefits from the end products, i.e. green energy, compost and collected recyclables; (2) the utilization of a potentially large energy source; (3) overcoming the problem of a high moisture content in MSW; and (4) additional benefits if the process is applied under a CDM regime. Out of the many technical options for anaerobic digestion of MSW mesophilic single-stage continuous and a batch dry digestion were selected as feasible technologies for Viet Nam. As mentioned in chapter 4, the main arguments for the choice of these technologies were: (1) the easier control of the mesophilic as compared to the thermophilic process; (2) the lower complexity and price of the single-stage system as compared to the two-stage system. About 90% of the full-scale anaerobic digestion plants for OFMSW in Europe at this moment are single-stage systems; (3) the high solids content of the MSW (about 30% total solids) makes the high-solids treatment process the most simple treatment process for OFMSW (Hartmann, 2006).

Incineration is more expensive and complicated in terms of design, construction, operation and maintenance as compared to composting, anaerobic digestion and landfill. Although in Europe nowadays only the incineration with energy recovery is allowed, in Asian developing countries like Viet Nam, incineration without energy recovery could still be acceptable. At the moment, interest in incineration in Asian developing countries is rising due to: (1) increasing budgets available for MSW treatment; (2) scarcity of land for MSW treatment and increasing transport costs; (3) the growing force of skilled labor; (4) high demand of electricity and heat; (5) impossibility to apply other technologies for environmental, social and political reasons; (6) high benefit from selling CERs (under CDM projects); (7) beneficial utilization of ash residues. Apart from the two main constraints of complex technique and high costs, the application of incineration in Asian developing countries is impeded also by the high moisture content in MSW. This reduces the heat value of the waste.

7.1.4 Costs analysis of municipal solid waste treatment options

In taking decisions about investments in MSW treatment systems costs are certainly considered as one of the most important and sensitive factors. A good insight in costs is difficult to attain amongst others due to uncertainties regarding the flow and composition of MSW, continuous development of technologies and lack of time- and place-specific information about equipment costs and markets of inputs and end products.

In order to translate the costs of MSW treatment technology (investment, operation, benefits) cited in literature to other places and times, many factors need to be considered, such as: (1) type of technology; (2) the characteristics of MSW (source separated MSW or commingled waste, wet or dry MSW, composition, heat value); (3) local conditions with regard to costs of inputs and outputs, for example costs of construction materials, equipment, labor, energy, fuel and benefits; (4) special local conditions or regulations with regard to land costs and the dumping costs of rejects or ash; (5) inflation rate and currency exchange rates. It is evident that even the meticulous consideration of these factors that was practiced in this thesis did not lead to more than indicative estimations of treatment costs. These estimations primarily served the costs comparison of technologies.

Concerning the costs analysis for MSW treatment in HCMC the following conditions were presupposed: (1) costs were calculated in USD based on the estimated price in Viet Nam in 2009; (2) the costs were calculated based on commingled MSW which has the typical composition of an Asian developing and tropical country; (3) ash from incinerators would not be disposed on landfills but reused as construction material of which the price is nil; (4) land is given for free based on a regulation of the government; (5) recycling and thus removal of valuable fractions from MSW is very well developed in Asian developing countries. This affects the characteristics of MSW (e.g. low heat value) and accordingly the selection of treatment technologies and the benefits from selling collected recyclable waste.Due to the economies of scale, the treatment costs (USD per ton MSW) increase at decreasing capacity of treatment plants. Financial benefits of MSW treatment can have a significant effect on the estimated overall costs of a certain technology. The total gross, net costs and financial benefit of all treatment technologies in the case of their maximum capacity are presented in figure 7.1.

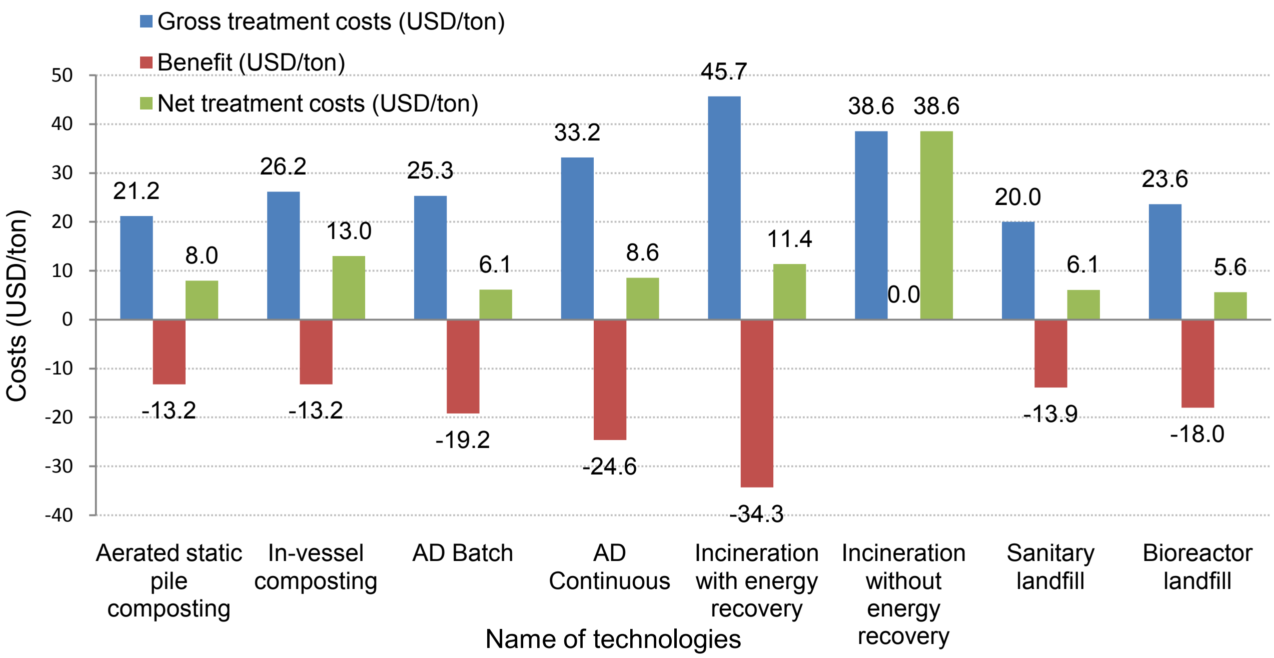

Figure 7.1 Total gross costs, net costs and benefit (USD/ton commingled MSW) of all treatment technologies in the case of maximum capacity.

Note: Gross treatment costs including fixed, operation and residue disposal costs;
Net treatment costs equal gross treatment costs minus estimated financial benefit;

We may conclude that under the conditions of HCMC among the eight analyzed treatment technologies, sanitary landfill is the cheapest option in terms of gross treatment costs (20 USD/ton). However, if the benefit from products is included, bioreactor landfill technology came out as the cheapest treatment technology (5.6 USD/ton). Anaerobic batch digestion also turns out to be a relatively inexpensive option (6.1 USD/ton). Incineration with energy recovery has highest gross treatment costs compared to other options (45.7 USD/ton). If however the benefits of energy generation were included, the net treatment costs of incineration decreased significantly to 11.4 USD/ton. Moreover, if the benefits of application of CDM (selling CERs) would be included, incineration with energy recovery would in terms of net treatment costs become an option comparable to the other ones. Looking solely at low net costs bioreactor landfill, sanitary landfill, anaerobic batch digestion and aerated static pile composting came out as the most attractive MSW treatment technologies.

7.1.5 The decision support tool

The task of the tool is to generate solid waste management strategies for a certain situation over a certain time span taking into account all relevant input data and impact factors and making a trade-off between different transport routes, locations of treatment facilities and types and capacities of technologies. To integrate all these factors a mathematically formulated optimizing decision support model was formulated. The tool models situations making use of all system data gathered in chapter 2 to 5 and a Mixed Integer Linear Programm (MILP) model and has been named SURMAT (Sustainable Urban waste Management Tool). Two cases have been set up. The first was the case aiming at minimum total net costs of transport and treatment and the second had as goal maximum electricity production assuming a certain total budget. The modeling and the impact factors which affect the results of the model are similar between two cases. Therefore, in this section, we take the case of minimum total net cost as an example for discussion.

The first strategy that minimizes the total net costs was set up for the current conditions of MSW management in HCMC (strategy 1). Under these conditions MSW is collected from 24 districts and transported to two treatment zones named Phuoc Hiep and Da Phuoc. The tool can choose among eight treatment technologies and for each technology among five different capacities. Most technologies produce rejects or residues that are discharged at residue landfills. Therefore the ninth technology of residue landfill was added, for which the tool could also choose among five capacities. The modeling was carried out for a planning horizon of 20 years up to the year 2032 applying the average amount of MSW over this period of 3.6 million tons MSW/year.

In addition to the default-strategy, four other strategies were modeled applying additional constraints. In strategy 2 the extra requirement was that compost production and incineration would handle more than 50% and 30% of the total amount of MSW respectively. The technologies to produce compost are aerobic composting and anaerobic digestion followed by post-composting. In strategy 3 not more than 50% of total MSW can be transported to the treatment zone 2 that is located most closely to the gravity point of the HCMC. In strategy 4 the amount of produced compost remained fixed within the current range of 200,000-300,000 ton compost/year with respect to the average 3.6 million ton MSW/year over the 20 years planning period. The assumption in strategy 5 was an increased financial benefit from heat energy and selling CERs (carbon credits). Every strategy was run with three options of the land available over the planning period (un-limited land as option 1, 509 ha as option 2, and 255 ha as option 3). In total, there are 15 modeling outcomes (five strategies and three land availability options per strategy).

For each option the model calculated the amounts of MSW to be transported from each district to the treatment zones, the selected MSW treatment technologies and their capacities in the two treatment zones, a cost analysis, and the amounts of utilizable products from wastes and their financial worth. The most important outcomes of the strategy modeling are discussed below.

A. The logistics of waste transport

In order to minimize transport costs, the model logically selected the shortest way to transport MSW from the 24 districts of HCMC to the two treatment zones (in strategy 1, option 1). However, requirements and constraints as to land availability, the application of certain technologies, the product market, etcetera had consequences for the transport routes so that distances became longer. Most discharge sources of MSW are closer to treatment zone 2 than to zone 1, so that transport costs will be lower at MSW transport to zone 2. Therefore, all results of the five strategies showed that treatment zone 2 was proposed to locate the treatment technologies that need less land (which mean the technology can processes high amount of MSW per unit of land use), such as incineration. For treatment zone 1 the model calculations propose the location of technologies with low treatment costs and a potentially high land requirement, such as bioreactor landfill.

B. Selected technologies

Figure 7.2 presents the percentage of selected technologies in all strategies in the condition of option 2 (S_1O_2 – S_5O_2). Dependent on the conditions of each strategy, the tool proposed different sets of technologies. Comparison of strategies with the same land availability (options 2) shows for strategy 1, option 2 (S_1O_2- standard condition) the proposed technologies are batch anaerobic digestion and bioreactor landfill, which treat 70% respectively 30% of the MSW flow; in strategy 2, option 2 (S_2O_2) with the additional constraints of compost production and incineration the model proposed 67% treatment by batch anaerobic digestion and 33% by incineration with energy recovery. In the case of strategy 5 (S_5O_2), the opportunity of additional financial benefit from heat energy and a CDM project is posited. The proposed emphasis on energy production leads to bioreactor landfill (62%) and incineration (33%).

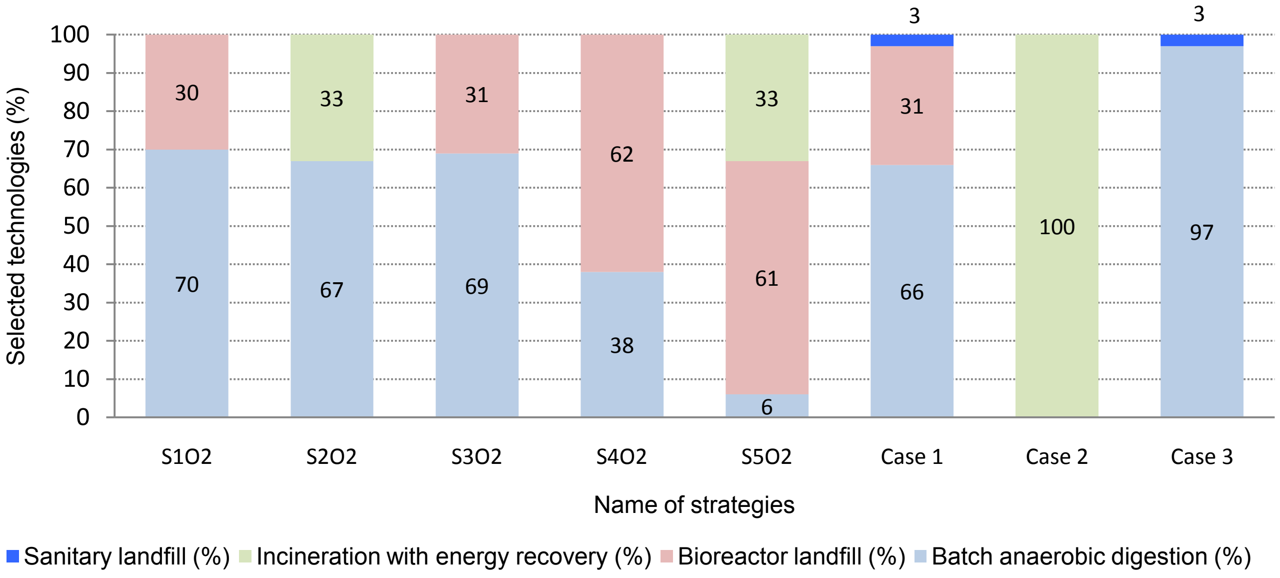

Figure 7.2 Percentage (%) of selected technologies in all strategies in the condition of option 2 (available land for treatment is 276 ha in zone 1 and 233ha in zone 2).

From the perspective of low treatment costs (figure 7.1) bioreactor landfill ranks first, batch anaerobic digestion second and incineration without energy recovery last, while other technologies rank in between. Based on low land use, incineration is the first priority, continuous anaerobic digestion is second, and the last one is sanitary landfill. As a consequence, to minimize the costs at a fixed availability of land (for example in the options 2) the model proposed in all strategies a mix of technologies commonly consisting of bioreactor landfill, batch anaerobic digestion and incineration with energy recovery (figure 7.2).

C. Effect of financial benefit on the selected technologies

SURMAT can also be used to perform a sensitivity analysis. This was illustrated by three cases in which the input data to the calculation of default strategy 1 option 2 were modified. In case 1 a reduction of the amount of compost product from 20% to 15% of total amount of MSW input was presupposed; in case 2 the electricity price was heightened from 0.08 USD to 0.12 USD/kWh and in case 3 the price of recyclable waste increased from 450 USD/ton to 600 USD/ton of processed PE plastic. With respect to other conditions the input data of these cases were equal to the ones of the default strategy (S_1O_2). In case 1 the changes as to selected technologies were slight; in case 2, however, the electricity price hike led to a profound change in which incineration with energy recovery became the single selected technology (100%); in case 3 batch anaerobic digestion came close to being the single selected technology (97%) while it covered 70% in the default strategy. It can be concluded that the results can be very sensitive to the input data. Therefore, always a very clear assumption of data input is necessary, such as the composition of MSW (which effects to the amount of compost, for example), the price and amount of electricity produced, availability of land, design life time of the technologies, etc.

D. Costs analysis

Figure 7.3 presents the gross costs, net costs and benefits (USD/ton MSW) of all strategies in the condition of option 2 including the abovementioned cases 1 until 3. The gross costs of S_2O_2 and $S_5O_2$are high (39 – 40 USD/ton) and of case 2 is very high (53.4 USD/ton) as compared to others due to the selection of incineration. However, by virtue of the equally high benefits from products, the strategies S_5O_2 and case 2 result in very low to low net costs of 1.1 (S_5O_2) and 5.8 (case 2) USD/ton respectively. It shows the sensitivity of the selection of technologies to the product market.

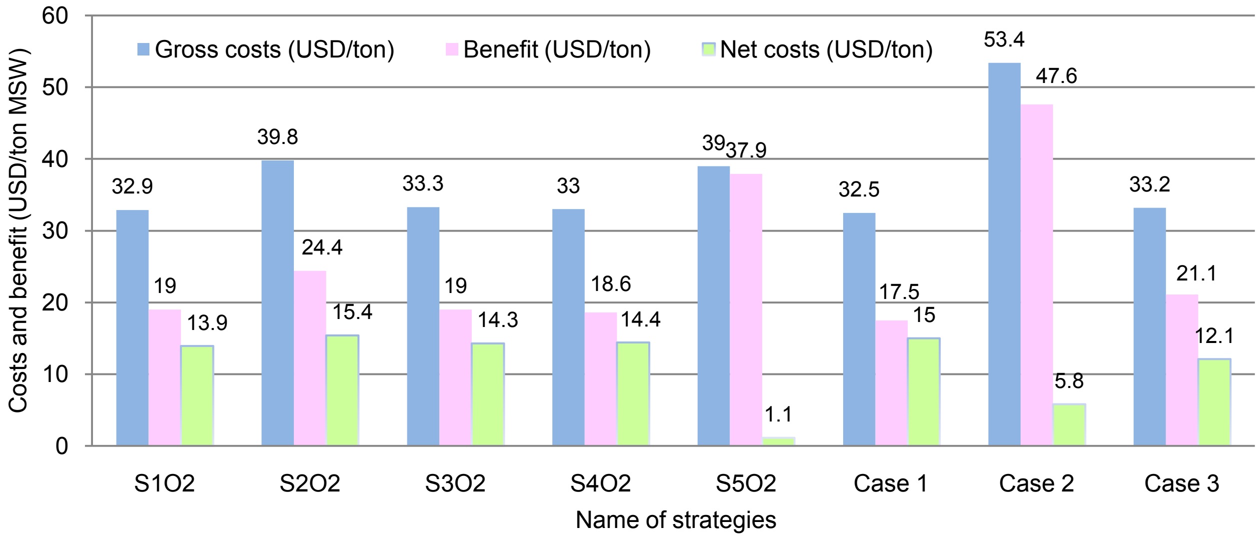

Figure 7.3 Gross costs, net costs and benefit (USD/ton commingled MSW) of MSW management in HCMC for all strategies in the condition of option 2 (available land for treatment is 273 ha in zone 1 and 233 ha in zone 2).

The formulation of the model can easily be modified to fit changes of conditions or new requirements (constraints). Adding more constraints in the strategies 2 until 4 gave more costly strategies as compared to the standard condition S_1O_2 (figure 7.3). More complete recovery of products from waste, higher product prices and addition of benefit from selling carbon credits led to lower net MSW management costs. For example, in the case of addition the constraint "requirement of compost production technologies and incineration technologies" (S_2O_2), the results are much different from the current condition (S_1O_2) and the costs are much higher. In strategy S_4O_2 having the constraint on "compost market", the results are not so different as compared to strategy S_1O_2. A comparison with data of DONRE (2010) showed that the solutions proposed by the tool in all strategies are less expensive than the costs which the government have to pay in 2009 (The costs in HCMC in 2009 were about 7 - 8 USD/ton for transport and 16.4 – 20 USD/ton for sanitary landfill). In the case of modifying the model by including the benefits of heat energy and CERs (strategy 5), the total net treatment costs (include benefits and residue disposal costs) are much less compared to current condition (strategy 1, option 2). Due to high benefits from heat energy and CERs, the most favorable technologies are bioreactor landfill and incineration.

E. The effect of land availability on the net costs and on selecting technologies

Figure 7.4 compares the net costs of the 3 options (of strategies 1 and 5 as an example) in order to check the effect of land availability to net costs. The net cost of option 2 is just slightly higher than option 1. It shows that the planned areas of treatment zone 1 and 2 of HCMC are big enough; therefore, it not much effected net cost. Option 3 with limited land availability results in much higher net cost compared to option 1 (increase 17.2- 13.3= 3.9 USD/ton). Figure 7.5 shows that the factor of land availability has a lot of effect on the selection of technologies.

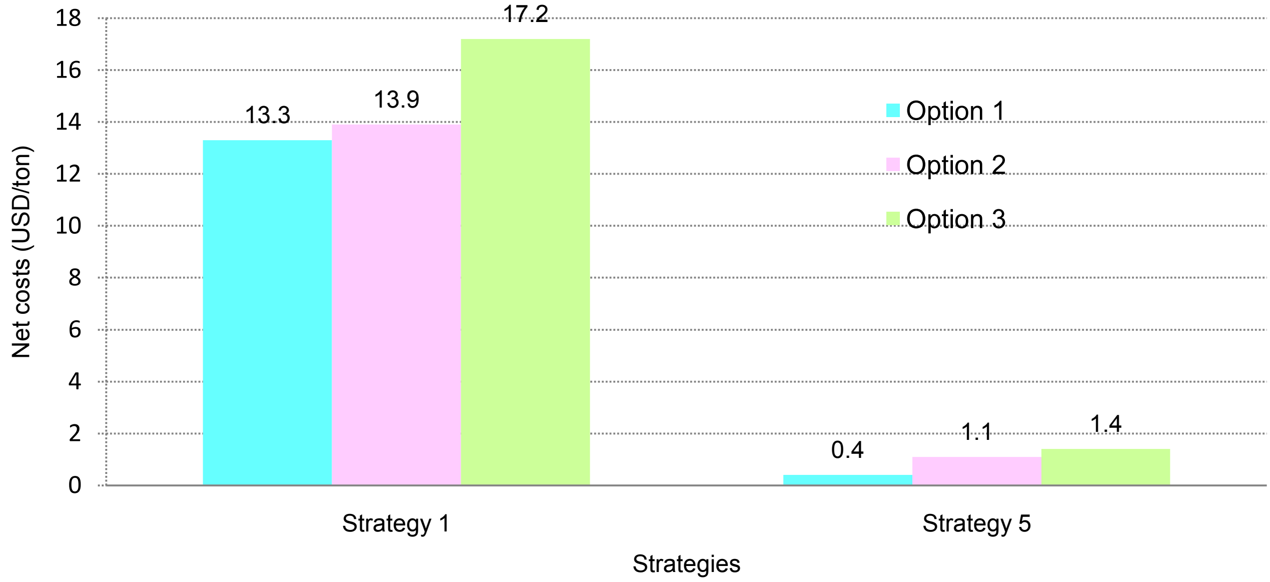

Figure 7.4 The effect of the land availability to the net costs of strategies1 and 5, an example.

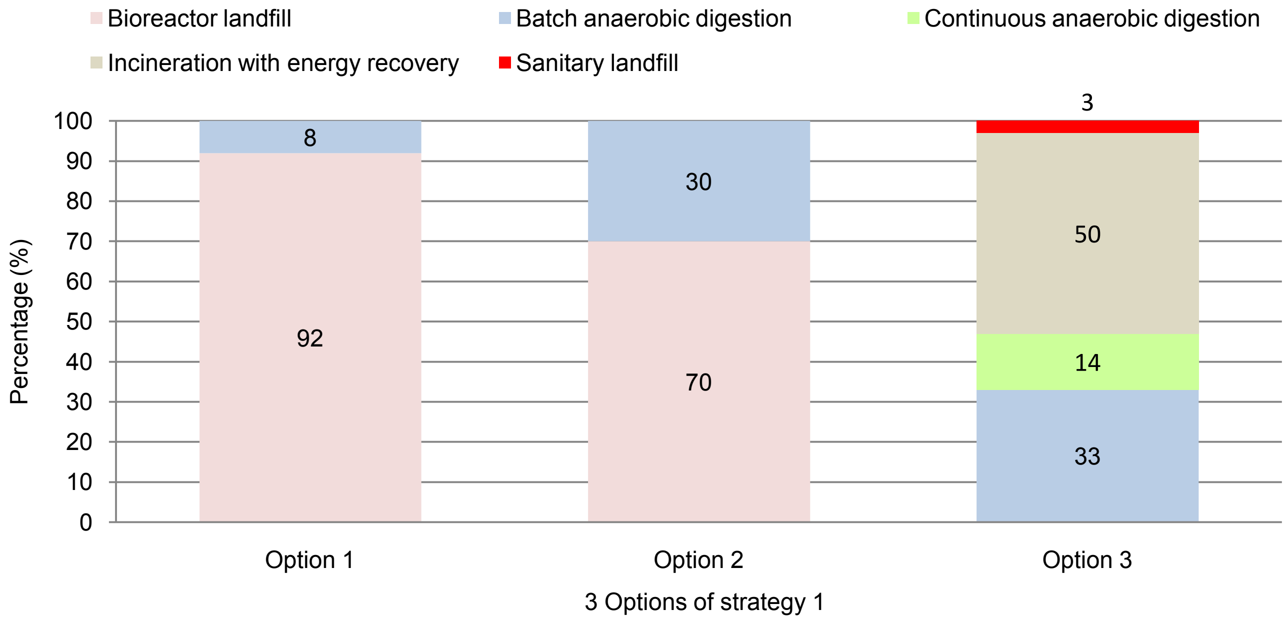

Figure 7.5 Percentage of selected technologies in 3 options of strategy 1.

To minimize total net costs, if land availability is not limiting, the bioreactor landfill will be the best choice (option 1). If land availability is reduced, batch anaerobic digestion or continuous anaerobic digestion will be selected (option 2). If land is very much limited, incineration with energy recovery will be dominant (option 3). The results of strategy 1, option 2 show that in the case of HCMC to treat the MSW flow until the year 2032 (20 years planning) in a cost efficient way on the currently available land of HCMC (509 ha), the application of incineration with energy recovery is not required. Incineration with energy recovery technology has only be selected if the government will not be successful in making land available (so usable the land is less than 509 ha).

In general, there are two main factors that are very influential to the results of the SURMAT. One is the land availability and the other is the benefit from products. The availability of land is affected by social and policy aspects. Important are for example the City's land budget, people's acceptance of MSW treatment zones (or MSW treatment plants) near their community, the rulings of the City's master plan on solid waste management with respect to the location of MSW treatment zones and

MSW treatment technologies, etc. The dominating benefit of MSW treatment is energy (biogas and electricity). Compost and recyclable wastes are of less financial importance, while, other benefits (such as: iron and aluminum recovery from ash) are much less. All benefits are affected by the local market. Besides, the composition of commingled MSW also affects the quantity and quality of products and therefore also the revenues. Furthermore, there are still other economic, social and policy aspects that influence the results such as the applicability of the CERs market, the possible role of heat energy in industry, the application of MSW separation at sources program.

7.1.6 The application of SURMAT in practice

In this section a few considerations are elaborated concerning factors that could affect the results of SURMAT modeling. These factors are categorized under the headings of changes in local conditions, the economic lifetime of the applied technologies and the changes of the waste flow to be treated.

A. Changes of local conditions

The configuration and use of SURMAT modelling depend on a great deal on local conditions. Important aspects are:

- The environmental policy with respect to the long term treatment of MSW, especially for the period after 20 years when the disposal sites are expected to be full. Relevant questions in this regard are: which sites should be closed or opened? Is increase in lifetime of an existing site possible? Is there a need in the short term, for example within 10 years, to consider other treatment possibilities of MSW? This aspect is dealt with in the next subsections.
- Spatial planning policy. In particular changes concerning the future expansion of a town and related to this expansion: traffic circulation, possible opening of new treatment sites for MSW and the closure of existing ones;
- Changes in annual amount and the composition of the waste, especially regarding the moisture content, the amount of plastics and the amount of organic material in the waste. Of course, the environmental policy of the government could strongly influence these changes. The introduction of a "waste separation at the source" program or changes in life-style for example could drastically affect the amounts and composition of the waste;
- Changes in the national and international prices of raw materials and energy which could enforce a shift in the desirable products produced from waste and therefore also in the treatment processes;
- Changes regarding the public acceptance of certain practices and technologies. For reasons of lack of acceptance not always the most cost-effective treatment options can be applied;
- Development of innovative technologies. Appearance of new effective and efficient technologies on the market could require a reconsideration of choices made in the past.
- Changes of the life times of installations. Under normal conditions with proper operation and maintenance a technological installation would serve its design life time or even could continue after that. However, there can be societal circumstances in which an installation has to be closed sooner. If plants have to be replaced before the end of their intended life time, the fixed costs increase and with them the costs per ton MSW treated. Such circumstances could be the availability of innovative more effective technologies, changes in the composition of the waste, changed policies, etc. Several of these changes were noted above.

B. Application of SURMAT in case of strongly increasing annual amount of municipal solid waste

In the previous calculations with SURMAT, it was assumed that the amount of MSW input is the same for every year during the 20 years planning period. However, in practice, the amount of MSW to be treated will increase year by year. The required treatment capacity and the corresponding investment must fitthis increase. The result is that the costs in practice are higher than the costs calculated with SURMAT for a constant annual amount of waste. The general question now is how to keep the costs as low as possible in case the annual amount of MSW to be treated is strongly increasing during the 20 years' period we consider. However, if the decision maker has a good master plan for investment, the gap in costs between practice and theory will be much reduced.

To make a concrete master plan for investment in MSW treatment for the increasing amount of waste the total treatment period (2013-2032) may be divided into four equal investment periods with a length of five years. For each of these periods SURMAT can help to make an estimate for an investment plan. This estimate is based on: (1) the results (technology selection, fraction of each selected technology, costs analysis, products) of the SURMAT dealing with the average amount of MSW within the 20 years planning period; (2) the amount of MSW discharge for each year within the 20 years planning period; (3) land availability at the investment time; (4) costs and economy of scale of each selected treatment technology. The investment in the process-oriented treatment systems (composting, anaerobic digestion, and incineration) has to be implemented at the start of each five-year period with a treatment capacity that is equal to the maximum treatment capacity that is required at the end of that period. An example how this approach might be elaborated is given in appendix 4.

C. Strategy with regard to the change in the availability of treatment sites for municipal solid waste

SURMAT is very effective in the optimal selection of treatment technologies for MSW if land availability is limited. SURMAT can easily be used assuming a constant annual amount of MSW to be treated and the land availability and the total operational period of the treatment site are known. Also in case the annual amount of MSW to be treated is changing, i.e. in general strongly increasing, SURMAT can be a helpful tool in supporting decision making regarding treatment strategies and treatment options. For each set of boundary conditions SURMAT clearly shows when land availability for treating MSW might be a problem. Therefore, SURMAT can also be useful in determining a strategy if the availability of sites for treating MSW changes. These changes in availability of sites can be a consequence of a decrease or increase of the operation time of existing sites, opening new sites or combinations of these site management strategies. Also the future reuse or use of existing sites for sanitary landfill, bioreactor landfill and residue landfill after a certain period can be considered in this framework.

From the previous elaboration it might be clear that the currently available land for the planned period of 20 years is operationally sufficient to treat all produced MSW in the planned period. However, due to the strongly increasing amount of waste and the high treatment capacity required at the end of the 20 years period it is impossible to treat the waste in a cost effective way. It would mean after 20 years existing batch anaerobic digestion plants would have to be closed and can no longer serve until the end of their design life time. To treat the waste in a cost-effective way a new site has to be opened and taken into operation. Knowing this several questions arise regarding the new site.

- When will this new site come into operation? For example, at the end of the existing period or ten years before? If it comes into operation at the end of the 20 years planning period the installations, especially the process-oriented installations should be kept in operation during the rest of their lifetime. The obtained residue has to be transported to the new site. If the new site is in operation

10 years before the end of the 20 years planning period of the current sites, it is possible to adapt the treatment strategy in such a way that the existing sites can be kept longer in operation including also the disposal of residue in the residue landfill of the existing sites. Investment in process-oriented treatment technologies can better be planned taking into account the lifetime of 20 years of these processes. Also installation of completely new more effective treatment processes can be considered. It can be concluded that the earlier a new site is opened the more flexible MSW management become.

- What should be the location of the new site? This is important for the transport distances from the discharge sources to the site and also the amount of residues to be transported from the old sites to the new site. Besides, the possible traffic jams have to be considered. The location of the new site also depends on the type of treatment technologies applied. For example aerated static pile composting with the possibility of bad smells should be located far from residential areas.

- What should be the size of the site? From the previous discussion it is clear that the size of the site is an important factor regarding the net treatment costs. The size and the set lifetime of the site very much influence the selection of technologies and the net treatment costs.

D. *Application of SURMAT in developing cities*

This thesis elaborates SURMAT and illustrates its possibilities for the case of HCMC, Viet Nam. Application in other Vietnamese cities or in other developing countries would require carrying out the same five activities that were described in this thesis namely: data collection about the solid waste management situation, selection of feasible treatment technologies for the situation under study, analysis of costs and benefits of each technology, setting up and running of the model and discussion of the results.

In data collection about solid waste management situations the ISWM concept of analysis can be followed as was done in chapter 2. For SURMAT especially technical, economic, management and legal aspects are important. Accurate data is needed about the quantities and characteristics of the MSW to be treated, the system of MSW transportation and transport costs, the location and size of one or more treatment zones, the roles and capacities of stakeholders in the system and legal requirements. The choice of feasible technologies is highly dependent on the situation under study. Here, technical and legal compatibility, financial affordability, manageability and public acceptance are important factors. E.g. in The Philippines incineration plants for MSW combustion are legally banned, so that this technology could not be selected. In cities of Sub-Saharan Africa incineration of MSW would possibly not be deemed feasible due to high capital costs, technical complexity and the availability of sufficient land for other less land-saving technologies. An accurate prediction of the gross and net costs of MSW management systems can be a time-consuming part of the analysis. Here, the data presented in this thesis could be used as a first approximation and perhaps the known costs of existing facilities in the situation under study like sanitary landfills and composting plants can be used for adjustment of the international and Vietnamese prices presented in this thesis to the local circumstances. The best approach for analysis of costs and benefits would be to prepare estimates based on detailed designs for the situation under study.

If the previously mentioned data are available, the adjustment of SURMAT to the situation under study is not difficult and can be done quickly. For new situations, new constraints can be added. Depending on the local demand and issues SURMAT can work out strategies and carry out sensitivity analyses. The final analysis of the results and the discussion of this analysis could be done in a way similar to what this thesis has shown in chapter 6 and 7.

7.1.7. Contribution of the thesis to the scientific and technological knowledge regarding management and treatment of MSW in developing countries.

The research executed within the framework of this thesis has resulted in an innovative contribution to the scientific and technological knowledge regarding management and treatment of MSW in developing countries.

- The research has given a thorough and integrated analysis of the technical and economic performance of relevant technologies to treat MSW in developing countries. This analysis makes it possible to compare the various treatment technologies in an integrated systematic, complete and understandable way. Besides, the technical and economic performance also other characteristic advantages and disadvantages of the various MSW technologies for application in developing countries have been elaborated and structured.
- The research has resulted in a decision support tool, SURMAT, that makes it possible to select the most optimal technologies for MSW treatment within a framework of constraints and conditions such as costs, available land for treatment, type of products that are produced from the treatment process and benefitsfrom theseproducts, environmental and political aspects. Besides, SURMAT includes also the costs of transport of waste and the consequences of this transport for the public traffic system to the waste disposal site. None of the existing models integrates all these aspects together.
- At an academic level SURMAT brings together technological and managerial information in the determination of sustainable solid waste management strategies in an integrated decision support tool. The tool aims at an optimal approach to solve the problem of solid wastes management

7.2 Conclusions and recommendations

7.2.1 Conclusions

The thesis draws in chapter 2 a picture of a typical urban solid waste management system in a developing country (Viet Nam) explaining all the components of the management chain, stakeholders and sustainability aspects. These data were gathered primarily to deliver the input material for the SURMAT modelling. In particular relevant were the strongly increasing amount of MSW and its high moisture and organic matter content, the limited availability of land, and the good opportunities of end products markets. But chapter 2 can also be seen as an in-depth analysis of the MSW management system of HCMC around the year 2010 in its own right.

The feasibility of separate MSW treatment technologies that might be applied in developing countries and costs analysis are discussed in detail. Eight technologies feasible for developing countries were chosen as input to the decision support tool SURMAT, namely aerated static pile composting, in-vessel composting, batch anaerobic digestion, continuous anaerobic digestion, incineration without energy recovery, incineration with energy recovery, sanitary landfill and bioreactor landfill. The selection was made based on criteria of technical compatibility with the specific conditions of application in developing countries, environmental sustainability, and degree of required expertise and costs. The parameterizing of the various technologies makes it possible to compare these technologies.

The final result of this thesis is a useful and applicable decision support tool (SURMAT). This tool supports in a systematic way the selection of logistics and the optimal treatment technologies in dependence of specific situation-bound constraints. The results of SURMAT give detailed insight in the logistics of MSW transport from discharge sources to treatment zones and treatment plants. In addition, SURMAT selects treatment technologies, their capacities, production of recovered products and costs. Therefore, SURMAT can be used to generate guidelines or master plans for solid waste management. Besides the most appropriate logistics, treatment technologies and their capacities, the tool may give additional information for the situation under study. For example, it may show the costs of alternative, less optimal, strategies. Therefore, it can be used to make a clear comparison among strategic options using data for a representative year. It is also very simple to conduct a sensitivity analysis if the input data are changed.

The model on which SURMAT is based is simple to set up and operate and easy to adapt to a change of situation. It is understandable and can be applied as a management tool in a national or a local MSW management system. The methodology applied to develop this decision support tool can be used to set up other tools for MSW management or for other domains.

The research showed that the characteristics of MSW do much affect the results of SURMAT modelling (proposed treatment technologies and costs). In particular the effects of organic matter and moisture content were significant. It can be concluded that to reduce the treatment costs (1) a policy should be applied that stimulates people to reduce the moisture content of MSW. Such a policy would lead directly to lower costs of transport, separation, drying and incineration and higher energy production per ton of waste; (2) the focus should be on the recovery of valuable products; (3) an efficient policy should be developed regarding the short and long term availability of land for treatment of MSW.

The quality of the quantitative results obtained by the decision support tool depend strongly on the quality of the input data. These input data, especially regarding costs, derived from local and international literature showed strong variations. As a consequence the cost information in this thesis may contain considerable uncertainties about the real costs and therefore also the optimal waste management strategies in the situation under study.

In the costs calculations of the case study of HCMC, the costs of land use have not been included. In certain cases, the costs of land could have an effect on the outcomes of the modelling. However, the model can be easily adapted to the new situation by adding new parameters.

7.2.2 Recommendations

The uncertainties of the outcomes of the tool could be reduced through an actualization of input data. Especially relevant in this respect are type and mass balance of treatment technologies, costs analysis and products market.

The tool has primarily been developed and run under the assumption of a constant average annual amount of MSW. In practice, especially in developing countries, the amount of MSW is increasing and usually at the final planning date the amount of MSW is much higher as compared to the average amount. Therefore, additional research is recommended to adapt the tool for calculation with variable amounts of MSW.

As feasibility technologies and costs vary with local conditions, SURMAT for other developing countries than Viet Nam should be fed with adapted data sets on technologies and their costs applicable to these countries.

Summary

Introduction

The main objective of the research presented in this thesis is to support decision making on more sustainable and cost-effective municipal solid wastemanagement strategies of developing countries, in particular in Viet Nam. For this purpose a tool named SURMAT (Sustainable urban waste management tool) was developed and applied on a case study in Ho Chi Minh City (HCMC), Viet Nam. This large city struggles with a rapidly increasing flow of municipal solid wastes and a forseeable scarcity of land to continue landfilling, the main treatment method applied up to now. The decision support tool elaborated in this thesis is therefore very welcome in this city.

The thesis comprises seven chapters. Chapter 1 introduces the research objective, research questions and methods. Chapter 2 describes the current situation of the MSW management system in HCMC as an examplary case study of the situation in developing cities and delivers input data to the modeling work carried out in chapter 6. Chapter 3 primarily studies the possibilities to apply batch anaerobic digestion technology to MSW only and to mixtures of MSW and pig manure. Chapter 4 makes a selection of feasible solid waste treatment technologies for cities in developing countries. Chapter 5 is a costs analysis of each of the proposed technologies selected in Chapter 4. Chapter 6 formulates the mathematical model that forms the core of the SURMAT tool. This model was built up and run with information from the chapters 2 until 5. The outcomes indicate the effectiveness of potential strategies for the future MSW management system of HCMC. Based on the results of the model, sensitivity analysis was carried out to show the impacts of input data variations on the outcomes of the model. Chapter 7 deals with discussions, conclusions and recommendations. The next sections will present the main findings of each of these chapters.

Municipal solid waste management in developing countries (Chapter 2)

Through extensive study of ‘grey’ Vietnamese literature and attending workshops and conferences on solid waste management we identified a number of critical issues of urban MSW management systems in developing countries. These are:

(1) The high and increasing quantity of MSW caused by growth of the population and the economy;
(2) The need to treat commingled waste with a high percentage of organic matter and moisture, a low percentage of recyclable materials and a low heat value;
(3) An inadequate collection and transport infrastructure and lack of land for new MSW treatment zones;
(4) The lack of public awareness on MSW management and hygiene and an urgent need for capacity building on MSW management and treatment;
(5) An over-complex and often inefficient institutional framework. The roles and responsibilities of organizations are in some cases overlapping and in others they are ill-defined;
(6) The lack of relevant and adequate legislation and poor implementation of rules;
(7) The insufficient government budget and cost-recovery especially in view to the need for new sophisticated treatment installations and more strict requirements for environmental safety;
(8) The large but poorly equipped informal system of waste recycling;
(9) The inappropriate MSW treatment technology.

During the last decade the HCMC government has taken many initiatives in the field of MSW management. Successful were improvements of the waste collection, human resource development and theinvolvement of the foreign and private sector. The latter has to a certain extent strengthened the collection and treatment system. Less successful up to now have been the attempts towards introduction of waste separation at source and the restructuring of collection fees.

The specific strategies elaborated for HCMC in this thesis especially address improvement of the logistics and treatment of rapidly increasing amounts of wet organic MSW under circumstances of inadequate government budgets and treatment technologies (items 1, 2, 3, 7 and 9).

Anaerobic digestion of municipal solid waste (Chapter 3)

By virtue of its relatively modest costs and production of biogas from MSW, anaerobic digestion is a promising technology. As anaerobic digestion of solid wastes is new in most developing countries, not excepting Viet Nam, chapter 3 presents experimental research in which batch anaerobic digestion was tested under local conditions.The research shows that addition of pig manure to OFMSW led to significant increase of the biogas production, while the pH remained more stable when OFMSW was mixed with digestate. The maximum accumulated biogas production found was 59 m^3/ton of a mixture of OFMSW, digestate and pig manure at a ratio of 10:1:1. For economic reasons the digestion time should be about 20 days. Aerated static pile composting of digestate during 7 days was used as a post-treatment technology. This resulted in good compost in terms of the Vietnamese standards for compost quality. Reduction of moisture content in the digestate and the compost processing needs to be taken into account due to the fact that a high moisture content leads to a bad smell. The compost production amounted to 0.2-0.25 ton/ton MSW.

This research showed the feasibility of the dry batch anaerobic digestion for the waste of HCMC in terms of applicability, reduction of environmental problems and production of biogas and compost.

Municipal solid waste treatment technologies for developing countries (Chapter 4)

On the basis of the characteristics of technologies, including process flow sheets and mass balances, and technical, environmental, social and economic criteria an assessment was made to find appropriate MSWtechnologies for developingcountries, especially for HCMC. This delivered a list of eight potentially feasible technologies, namely aerated static pile composting, in-vessel composting, batch anaerobic digestion, continuous anaerobic digestion, incineration with energy recovery, incineration without energy recovery, sanitary landfill and bioreactorlandfill. This chapter also provided data on the land requirements of the different technologies for the SURMAT tool.

Results show that relatively low costs and the possibility of disposal of all kinds of waste make sanitary landfill a widely applied treatment method in developing countries. It is usually considered as an unavoidable element of any waste management system. Land scarcity, increasing environmental requirements and high leachate treatment costslead to decreasing appreciation for this method. As a consequence the bioreactor landfill has become an attractive alternative. Compared to the sanitary landfill, the capital costs and complexity of the bioreactor landfill are higher but it requires less land, produces more biogas and comes with reduced leachate treatment cost.

Besides landfilling, composting is the second choice to treat MSW in developing countries.It is a simple, inexpensive and proven technique. Its success however depends to a considerable degree on the effective demand for compost.With the increasing emphasis on energy production, anaerobic digestion gains preferenceover composting due to the green energy it produces and the value of the digestate as raw material for the production of soil conditioner. However, this technology needs adjustments for applicability in developing countries.

The aim of incineration is to reduce the volume and polluting potential of MSW and the production of energy from waste. In developing countries incineration is hardly selected due to its high investment and operation costs, high requirements of staff skills and its sensitivity for high moisture content in the MSW. An important part of the costs of incineration can be balanced by the financial benefits from the energy generated from wastes. Since the electricity price in developing countries is usually still low, incineration is attractive only if land is a crucial factor or/and significant financial benefits from selling carbon credits (CERs) can be obtained.

Costs analysis of municipal solid waste treatment technologies in developing countries (Chapter 5)

The costs estimations in chapter 5 were based on data from existing treatment plants in HCMC, adapted data about European treatment plants and detailed designs.The estimated costs of the eight selected treatment technologies subdivided in gross treatment costs, financial benefits and net treatment costs (gross costs minus benefits) are presented in table 1 (see also figure 5.17). The financial benefits accrue from sales of energy (biogas, electricity), compost, plastics and metals.The estimates show considerable economy of scale effects for all treatment technologies in the studied range of 100,000 to 1,100,000 tons MSW/year. The effect of costs reduction at higher capacities was in particular strong foraerated static pile composting, in-vessel composting, batch anaerobic digestion and continuous anaerobic digestion. Economies of scale were more modest for incineration with and without energy recovery and sanitary and bioreactor landfills.

Table 1 Costs analysis of MSW treatment in Ho Chi Minh City (scale 100,000 – 1,100,000 tons MWS/year) (USD/ton MSW).

Technologies	Gross treatment costs	Benefits (negative costs)	Net treatment costs
Aerated static pile composting	22.3 - 33.1	12.7 - 13.7	8.0 - 19.9
In-vessel composting	26.2 - 42.1	12.7 - 13.7	13.0 - 28.9
Batch anaerobic digestion	25.3 - 40.5	17.6 - 20.7	6.1 - 21.3
Continuous anaerobic digestion	33.2 - 54.7	19.3 - 29.9	8.6 - 30.1
Incineration with energy recovery	45.7 - 58.6	15.7 - 52.9	11.4 - 24.3
Incineration without energy recovery	38.6 - 49.3	0	38.6 - 49.3
Sanitary landfill	20.0 - 28.0	11.8 - 16.0	6.1 - 14.1
Bioreactor landfill	23.6 - 33.4	15.5 - 20.2	5.7 - 15.5

Note: Gross treatment cost is sum of fixed, operation and residue costs.

The financial benefits from MSW treatment turn out very sensitive to local circumstances. The values of products from waste are liable to much variation and uncertainty and therefore have a significant influence on net treatment costs.

Among the eight technologies, sanitary landfill is the least expensive option in term of gross treatment cost. However, if benefits of enhanced biogas utilization are included, bioreactor landfill shows the lowest net treatment costs in the higher capacity range. Incineration, both with and without energy recovery, has the highest gross treatment costs compared to other options. However, if the benefits of salable energy are included, the treatment costs of incineration with energy recovery decrease significantly depending on electricity output and price.

Optimization model (chapter 6)

The decision support tool SURMAT incorporates an optimization framework which core is an integrated mixed integer linear programming (MILP) model. The tool was used to assess waste management strategies for HCMC applying the objectives of (1) minimized total net costs of MSW transport and treatment and (2) maximized electricity production from MSW. The data elaborated in the chapters 2 until 5 were used as input to the model. The model outcomes provide information about the distribution of MSW from discharge sources to treatment plants, the optimum mix of treatment technologies and their capacities given a certain area of land and an overview of costs and benefits.

Five strategies have been modeled aiming at minimization of the transportation and treatment cost of MSW in HCMC. For each strategy, there were three optionsthat differ as to the availability of land. In option 1 land was not a limiting factor,in option 2 276 respectively 233 ha were available in treatment zone 1 and 2 and in option 3 the land availability was assumed to be half of the land area of option 2.

To reach the aim of minimum costs, the model selects the least expensive technologies given the conditions of land availability. Among the five strategies, strategy 1 with standard conditions resulted in lowest costs. These standard conditions were the current conditions of HCMC without specific constraints.

Strategies with more constraints are of course more expensive than the standard strategy as they further limit strategy options. These extra constraints regarded the prescribed degree of biological treatment of MSW (strategy 2), the fraction to be transported to zone 2 (strategy 3), a reduced market demand of compost (strategy 4). Among the three options, option 1 always was the cheapest, while option 3 was most expensive, since increasing scarcity of land (area option 3< area option 2 <area option 1) resulted in selection of land-saving but more expensive technologies. A sensitivity analysis showed that changes of the input data, such as amount and price of electricity and salable compost much affected the modeling results.

Six management options were modeled to identify the effect of expenditures on waste management on the maximum production of electricity. Taking the standard strategy for HCMC as point of departure the expenditures ranged from about 14.0 USD/ton (option E_1) to 20.7 USD/ton (option E_6). With increasing expenditures the electricity production from MSW rose to a maximum value of 323 kWh per ton MSW. The electricity production increased through a higher share of incineration with energy recovery in the technology mix. The technology choice moved from batch anaerobic digestion (E_1) to bioreactor landfill ($E_{1,2,3,4}$) and subsequently to incineration ($E_{3,4,5,6}$).The calculation also showed that from an expenditure of 15.3 USD/ton upwards incineration with energy recovery could be applied.

Overall conclusions (chapter 7)

Chapter 7 takes a critical look at the results of the SURMAT tool and subsequently focuses on the effects of local conditions and a strongly increasing amount of wastes for the modeling outcomes, changes in the availability of treatment sites and application in developing cities in general. The research showed that a host of factors may affect the results of the tool.

Firstly, the quality of the results obtained depends strongly on the accuracy of the input data. In particular, the costs information in this thesis contains considerable uncertainties, which has influenced the outcomes. In order to reduce costs of MSW management:

(1) A policy should be applied that stimulates to reduce the moisture content of MSW (such a policy could lead to lower costs of transport, separation, drying and incinerationand higher energy production per ton of waste);
(2) The focus should be on the recovery of valuable products like biogas and electricity, and
(3) An efficient policy should be developed regarding the short and long term availability of land for treatment of MSW.

The strategies elaborated in this thesis were modelled using the estimated average flow of MSW over a period of 20 years. It may be argued that this approach could lead to sub-optimal, possibly cheaper, choices given the reality of a rapidly increasing flow of wastes. Such a rapidly increasing flow of MSW requires making capacity extension plans regularly at not too long time intervals. This would lead to a further optimization of technology choices.

The present thesis could be an adequate tool for the preparation of investment decisions in developing cities in general. It has presented the methodology and a broad package of data on technologies and costs and could in its present form deliver a first approximation of a suitable MSW management strategy for other cities as well. However, the more the situation in such cities deviates from the conditions in HCMC, or how farther in the future, the more adaptation of SURMAT would be needed, in particular with respect to appropriate and innovative technologies, their land use and costs.

Finally, on the basis of the experiences with SURMAT and the outcomes of this thesis SURMAT can be judged a useful, applicable and easily adjustable decision support tool for MSW management. The results of SURMAT give detailed insight in the logistics of MSW transport from discharge sources to treatment zones and treatment plants. SURMAT selects treatment technologies, their capacities, production of recovered products and costs within predefined system boundaries. Therefore, SURMAT can help to generate guidelines or master plans for solid waste management for specific case studies. Besides the most appropriate logistics, treatment technologies, the tool may give additional information for the situation under study. For example, it can calculate the costs of alternative strategies. Therefore, it can be used to make a clear comparison among strategic options, under the premises that relevant input data is reliable and available.

Samenvatting

Het hoofddoel van het onderzoek in deze dissertatie is een betere besluitvorming rondom duurzaam en kosteneffectief afvalbeheer in steden in ontwikkelingslanden, in het bijzonder in Vietnam. Voor dit doel werd een instrument, genaamd SURMAT, ontwikkeld en gevalideerd met behulp van een case-study in Ho Chi Minh City (HCMC) in Vietnam. Deze grote stad kampt met een snel toenemende stroom afval en in de toekomst een schaarste aan land voor storten, de belangrijkste afvalverwerkingsmethode tot op heden. Het besluitvormingsinstrument dat in deze dissertatie is ontworpen is daarom zeer welkom in deze stad.

De dissertatie omvat zeven hoofdstukken. Hoofdstuk 1 introduceert doel, vragen en methoden van het onderzoek. Hoofdstuk 2 beschrijft de huidige situatie van het stedelijk afvalsysteem in HCMC als een voorbeeld van de situatie van steden in ontwikkelingslanden en levert de invoergegevens voor het model in hoofdstuk 6. Hoofdstuk 3 onderzoekt met name de mogelijkheden van batchgewijze anaërobe vergisting van stedelijk afval afzonderlijk en gemengd met varkensmest. Van dit laatste is in de omgeving van HCMC veel aanwezig. Hoofdstuk 4 maakt een selectie van haalbare vast-afval-verwerkingstechnieken voor steden in ontwikkelingslanden. Hoofdstuk 5 is een kostenanalyse van elk van de technieken voorgesteld in hoofdstuk 4. Hoofdstuk 6 formuleert het mathematische model dat de kern vormt van het SURMAT instrument. Dit model is opgebouwd en toegepast met de informatie afkomstig uit de hoofdstukken 2 tot en met 5. De uitkomsten zijn potentiële strategieën voor het toekomstige afvalbeheer in HCMC. Op grond van deze uitkomsten is een gevoeligheidsanalyse uitgevoerd teneinde de effecten van variaties van de invoergegevens op de uitkomsten van het model te onderzoeken. Hoofdstuk 7 betreft discussies, conclusies en aanbevelingen. De volgende secties presenteren de belangrijkste resultaten van elk van de hoofdstukken.

Afvalbeheer in ontwikkelingslanden

Aan de hand van de case-study van HCMC werden de volgende knelpunten van het stedelijk afvalbeheer in ontwikkelingslanden geïdentificeerd:

1. De hoge en toenemende hoeveelheid vast afval ten gevolge van de groei van bevolking en economie;
2. De noodzaak ongescheiden afval te verwerken met een hoog gehalte aan organische stof en vocht, een laag gehalte aan recyclebare materialen en een lage warmtewaarde;
3. Een ontoereikende infrastructuur van inzameling en transport en een gebrek aan land voor nieuwe afvalverwerkingszones;
4. Het gebrek aan publiek bewustzijn met betrekking tot afvalbeheer en hygiëne en een urgente behoefte aan capaciteitsontwikkeling op het gebied van afvalbeheer en verwerking;
5. Een overmatig ingewikkeld en dikwijls inefficiënt institutioneel kader. De taken en verantwoordelijkheden van organisaties zijn in sommige gevallen overlappend en in andere slecht gedefinieerd;
6. Het gebrek aan relevante en toereikende regelgeving en een zwakke implementatie van regels;
7. Ontoereikend overheidsbudget en kleine bijdrage van de gebruikers in de kosten, hetgeen in het bijzonder problematisch is gezien de behoefte aan nieuwe geavanceerde verwerkingsinstallaties en striktere eisen op het gebied van de milieuveiligheid;
8. Het grote maar slecht toegeruste informele systeem van afvalrecycling;
9. Ongeschikte afvalverwerkingstechnologie.

De strategieën die in deze dissertatie zijn uitgewerkt richten zich in het bijzonder op de logistiek en de verwerking van de snel toenemende hoeveelheden nat organisch afval onder de omstandigheden van beperkte overheidsbudgetten en verwerkingstechnieken (de knelpunten 1,2,3,7 en 9).
Gedurende de laatste tien jaar heeft de overheid in HCMC veel initiatieven genomen op het gebied van afvalbeheer. Successen kunnen worden genoemd bij verbetering van de afvalinzameling, stafontwikkeling en de deelname van buitenlandse en private partijen. Dat laatste heeft tot op zekere hoogte de inzameling en verwerking versterkt. Minder succesvol tot op heden waren de pogingen tot afvalscheiding aan de bron en tot herstructurering van de inzamelingstarieven.

Anaërobe vergisting van stedelijk afval (hoofdstuk 3)

Dankzij haar relatief lage kosten en de productie van biogas uit stedelijk afval is anaërobe vergisting een veelbelovende technologie. Aangezien anaërobe vergisting van vast afval in de meeste ontwikkelingslanden nieuw is, en Vietnam is daarop geen uitzondering, presenteert hoofdstuk 3 experimenteel onderzoek waarin batchgewijze anaërobe vergisting onder lokale omstandigheden werd getest. Het onderzoek toont aan dat toevoeging van varkensmest aan de organische fractie van stedelijk afval leidde tot een aanzienlijke toename van de biogasproductie, terwijl de pH stabieler bleef wanneer aan het afval digestaat werd toegevoegd. De maximale geaccumuleerde biogasproductie bedroeg 59 m^3/ton van een mengsel van organisch stedelijk afval, digestaat en varkensmest in een verhouding van 10:1:1. Om economische redenen dient een vergistingsduur van 20 dagen aangehouden te worden. compostering van het digestaat gedurende 7 dagen werd als nabehandelings-technologie gebruikt. Dit resulteerde in goede compost in termen van de Vietnamese kwaliteitseisen. Men dient rekening te houden met de reductie van het vochtgehalte bij de digestaat en de compostverwerking, aangezien een hoog vochtgehalte leidt tot stank. De compostproductie bedroeg 0,2-0,25 ton/ton stedelijk afval. Dit onderzoek toonde de haalbaarheid aan van droge batchgewijze anaërobe vergisting voor het afval van HCMC in termen van toepasbaarheid, reductie van milieuproblemen en productie van biogas en compost.

Afvalverwerkingstechnologieën voor ontwikkelingslanden (hoofdstuk 4)

Een beoordeling van afvalverwerkingstechnologieën voor ontwikkelingslanden en speciaal voor HCMC is gemaakt op basis van de eigenschappen van technologieën, met inbegrip van processchema's en massabalansen, en technische, milieukundige, sociale en economische criteria. Dit leverde een lijst op van acht mogelijk haalbare technologieën, namelijk geforceerde aërobe compostering, *in-vessel* compostering, *batch*-anaërobe vergisting, continue anaërobe vergisting, verbranding met energiewinning, verbranding zonder energiewinning, de sanitaire stortplaats en de bioreactorstortplaats. Dit hoofdstuk leverde ook de belangrijkste gegevens over het landgebruik van de verschillende technieken voor het SURMAT instrument.

Relatief lage kosten en de mogelijkheid alle soorten afval te storten, maken de sanitaire stortplaats tot een veel toegepaste verwerkingsmethode in ontwikkelingslanden. Hij wordt gewoonlijk beschouwd als een onvermijdelijk element van een afvalbeheerssysteem. Landgebrek, toenemende milieueisen en hoge kosten van *leachate* behandeling doen de waardering voor deze methode echter dalen. Dientengevolge is de bioreactorstortplaats een aantrekkelijk alternatief geworden. In vergelijking met de sanitaire stortplaats zijn de kapitaalslasten en complexiteit van de bioreactorstortplaats hoger, maar hij vraagt minder land, produceert meer biogas en de *leachate* behandelingskosten zijn lager.

Naast storten is compostering de twee keuze van afvalverwerking in ontwikkelingslanden. Het is een eenvoudige, goedkope en bewezen techniek, maar haar succes hangt echter sterk af van de effectieve vraag naar compost. Bij een toenemende nadruk op energieproductie wint anaërobe vergisting het van compostering vanwege haar productie van groene energie en de waarde van het digestaat als grondstof voor de productie van een bodemverbeteraar. Deze technologie moet echter aangepast worden voor toepassing in ontwikkelingslanden.

Het doel van verbranding is reductie van het volume en het vervuilingspotentieel van afval en eventueel productie van energie uit afval. In ontwikkelingslanden wordt verbranding nauwelijks als verwerkingsmethode gekozen, onder meer vanwege haar hoge investerings- en operationele kosten, hoge eisen die gesteld worden aan de bekwaamheid van bedieningspersoneel en gevoeligheid voor een hoog vochtgehalte van het afval. Een belangrijk deel van de kosten kan echter gedekt worden door de verdiensten uit de energiewinning. Aangezien de prijs van elektriciteit in ontwikkelingslanden meestal nog laag is, zal verbranding alleen aantrekkelijk worden, indien de beschikbaarheid van land voor afvalverwerking een cruciale factor is en/of er aanzienlijk verdiensten zijn via de verkoop van koolstofcertificaten (CERs).

Analyse van kosten van afvaltechnologieën in ontwikkelingslanden

De kostenschattingen in hoofdstuk 5 zijn gebaseerd op gegevens van bestaande verwerkingsinstallaties in HCMC, aangepaste gegevens over Europese installaties en gedetailleerde ontwerpen. De geschatte kosten van de acht geselecteerde verwerkingstechnieken, onderverdeeld in bruto verwerkingskosten, inkomsten en netto verwerkingskosten zijn weergegeven in tabel 1 (zie ook figuur 5.17). De inkomsten zijn afkomstig uit de verkoop van energie (biogas en elektriciteit), compost, plastics en metalen. De schattingen tonen aanzienlijke schaaleffecten voor alle verwerkingstechnieken in het bestudeerde gebied van 100.000 tot 1,1 miljoen ton afval/jaar. Het effect van kostenreductie bij hogere capaciteiten was in het bijzonder sterk voor geforceerde aërobe compostering, *in-vessel* compostering, *batch*-anaërobe vergisting en continue anaërobe vergisting. Het effect was kleiner voor verbranding met en zonder energiewinning en voor sanitaire en bioreactorstortplaatsen.

Tabel 1. Analyse van kosten van afvalverwerking in Ho Chi Minh City (schaal 100.000 – 1,1 miljoen ton/jaar) (USD/ton afval).

Technologieën	Bruto verwerkingskosten	Inkomsten	Netto verwerkingskosten
Geforceerde aërobe compostering	22,3 – 33,1	12,7 – 13,7	8,0 – 19,9
In-vessel compostering	26,2 – 42,1	12,7 – 13,7	13,0 – 28,9
Batch-anaërobe vergisting	25,3 - 40,5	17,6 – 20,7	6,1 – 21,3
Continue anaërobe vergisting	33,2 – 54,7	19,3 – 29,9	8,6 -30,1
Verbranding met energiewinning	45,7- 58,6	15,7 – 52,9	11,4 – 24,3
Verbranding zonder energiewinning	38,6 – 49,3	0	38,6 – 49,3
Sanitaire stortplaats	20,0 – 28,0	11,8 – 16,0	6,1 – 14,1
Bioreactor stortplaats	23,6 – 33,4	15,5 – 20,2	5,7 – 15,5

Opmerking: bruto verwerkingskosten zijn de som van vaste, operationele en residuverwerkingskosten.

De inkomsten uit afvalverwerking blijken zeer gevoelig voor lokale omstandigheden. De inkomsten uit producten uit afval staan bloot aan veel variatie en onzekerheid en hebben daarom veel invloed op de netto verwerkingskosten.

Onder de acht technieken kent sanitair storten de laagste bruto verwerkingskosten. Echter, bij inbegrip van de inkomsten uit de verhoogde biogasbenutting, heeft bioreactor storten de laagste netto verwerkingskosten in het hogere capaciteitsbereik. Verbranding, zowel met als zonder energiewinning, heeft de hoogste bruto kosten in vergelijking met de andere opties. Indien echter de inkomsten uit verkoopbare energie meegenomen worden, nemen de verwerkingskosten van verbranding met energieterugwinning aanzienlijk af in afhankelijkheid van de energieopbrengst en prijs.

Modelleren met SURMAT (hoofdstuk 6)

Het besluitvormingsinstrument SURMAT bevat een optimalisatieraamwerk waarvan de kern bestaat uit een geïntegreerd *mixed integer linear programming* (MILP) model. Het instrument werd gebruikt om strategieën voor afvalbeheer in HCMC voor te stellen. Hierbij werden als doelen gesteld: (1) minimalisatie van kosten van afvaltransport en verwerking en (2) maximalisatie van elektriciteitsproductie uit afval. De gegevens uit de hoofdstukken 2 tot en met 5 werden als invoer voor het instrument gebruikt. Het instrument levert informatie over de distributie van afval vanuit de bronnen naar de verwerkings-bedrijven, de optimale combinatie van technologieën en hun capaciteit in afhankelijkheid van het beschikbaar landoppervlak en een overzicht van kosten.

Vijf strategieën zijn gemodelleerd gericht op minimalisatie van kosten van transport en verwerking van afval in HCMC. Voor elke strategie waren er drie opties die verschilden voor wat betreft de beschikbaarheid van land. In optie 1 was land niet beperkend, in optie 2 was er respectievelijk 276 en 233 ha beschikbaar in de verwerkingszones 1 en 2 en in optie 3 werd de helft van het landoppervlak van optie 2 verondersteld.

Om het doel van minimale kosten te bereiken selecteert SURMAT de goedkoopste technologieën onder de gegeven condities van landbeschikbaarheid. Onder de vijf strategieën was strategie 1 met standaardcondities de goedkoopste. De standaardcondities waren de huidige condities in HCMC zonder specifieke eisen.

Strategieën met meer eisen zijn vanzelfsprekend duurder dan de standaardstrategie aangezien de eisen de strategische keuzen beperken. Deze extra eisen betroffen de graad van biologische verwerking van afval (strategie 2), het deel van het afval dat naar zone 2 gebracht moet worden (strategie 3) en een gereduceerde marktvraag naar compost (strategie 4). Optie 1 was altijd de goedkoopste, terwijl optie 3 altijd de duurste was, aangezien toenemende landbeperking (oppervlakte optie 3 < optie 2 < optie 1) resulteerde in de selectie van land-besparende maar dure technologieën. Een gevoeligheidsanalyse liet zien dat veranderingen in de invoergegevens, zoals de hoeveelheid en prijs van elektriciteit en verkoopbare compost, de resultaten van de modellering sterk beïnvloedden.

Zes beheersopties werden gemodelleerd om het effect van uitgaven op het gebied van afvalbeheer op de maximale elektriciteitsproductie te achterhalen. Met de standaardstrategie voor HCMC als uitgangspunt varieerden de uitgaven van ongeveer 14.0 USD/ton afval (optie E1) tot 20.7 USD/ton afval (optie E6). Bij toenemende uitgaven kon de elektriciteitsproductie uit afval stijgen naar een maximale waarde van 323 kWh/ton afval. De elektriciteitsproductie nam toe door een groter aandeel van verbranding met energiewinning in de technologiecombinatie. De technologiekeuze verschoof van *batch*-anaërobe vergisting (E1) naar bioreactor storten (E1-E4) en vervolgens naar verbranding (E3-E6). De berekening liet ook zien dat, bij uitgaven van 15.3 USD/ton en hoger, verbranding met energie-terugwinning toegepast kon worden.

Eindconclusies (hoofdstuk 7)

Hoofdstuk 7 bekijkt de resultaten van het SURMAT instrument nog eens kritisch en richt zich vervolgens op de effecten op de uitkomsten van lokale condities en een sterk toenemende hoeveelheid afval, van veranderingen in de beschikbaarheid van verwerkingszones en op de toepassing in ontwikkelingslanden in het algemeen. Het onderzoek heeft aangetoond, dat heel veel factoren de resultaten van het instrument kunnen beïnvloeden. Allereerst hangt de kwaliteit van de uitkomsten sterk af van de nauwkeurigheid van de invoergegevens. In het bijzonder bevat de kosteninformatie in deze dissertatie aanzienlijke onzekerheden, hetgeen de uitkomsten heeft beïnvloed. Om de kosten van afvalbeheer te verminderen moet:

1. Een beleid toegepast worden, dat een reductie van het vochtgehalte in afval stimuleert. Zulk een beleid kan leiden tot lagere kosten van transport, scheiding, drogen en verbranding en een hogere energieopbrengst per ton afval;
2. Het accent liggen op terugwinning van waardevolle producten zoals biogas en elektriciteit;
3. Een effectief beleid ontwikkeld worden met betrekking tot de beschikbaarheid van land voor afvalverwerking op de korte en lange termijn.

De in deze dissertatie uitgewerkte strategieën werden gemodelleerd op basis van de gemiddelde afvalstroom over een periode van 20 jaar. Men kan beredeneren, dat deze benadering leidt tot suboptimale, mogelijk te goedkope, keuzen gezien de realiteit van een snel toenemende stroom afval. Zo een toenemende afvalstroom vraagt om het van tijd tot tijd en met niet te grote tussenpozen opstellen van uitbreidingsplannen van de verwerkingscapaciteit. Dat zou kunnen leiden tot een verdere optimalisatie van de technologiekeuzen.

De gemodelleerde strategieën leverden technologievoorstellen op die in staat waren om al het in de planperiode geproduceerde afval te verwerken op het beschikbare land. Door de toenemende afvalstroom en de hoge daarvoor vereiste verwerkingscapaciteit aan het einde van de 20 jaar periode zal een deel van de installaties, bijvoorbeeld *batch*-anaërobe vergisters, niet lang voor het einde van de projectperiode (2032) in bedrijf genomen worden. Zij moeten na die tijd verder functioneren om hun ontwerpleeftijd te bereiken en voortijdige afwaardering te voorkomen. Deze installaties produceren residuen die niet kunnen worden gestort op het oorspronkelijk aanwezige land aangezien dat land volledig in gebruik is in het jaar van de projecthorizon. Daarom moeten rondom het jaar van de project-horizon een of meer nieuwe afvalverwerkingsterreinen geopend worden, zodat er kosteneffectief gewerkt kan blijven worden en alle installaties gedurende tenminste 20 jaar in bedrijf gehouden kunnen worden.

Deze dissertatie kan een geschikt instrument zijn voor de voorbereiding van investeringsbeslissingen in ontwikkelingslanden in het algemeen. Zij heeft een methodologie alsmede een pakket aan gegevens over technologieën en kosten opgeleverd die in de huidige vorm ook voor andere steden een eerste indicatie zou kunnen leveren van geschikte afvalbeheersstrategieën. Hoe meer echter de situatie in zulke steden afwijkt van die in HCMC of hoe verder in de toekomst, hoe meer SURMAT aangepast zou moeten worden, in het bijzonder wat betreft geschikte en innovatieve technologieën, het bijbehorend landgebruik en kosten.

Tenslotte kan op basis van de ervaringen met SURMAT en de uitkomsten van deze dissertatie geconstateerd worden, dat SURMAT een nuttig, bruikbaar en gemakkelijk aan te passen besluitvormingsinstrument voor het stedelijk afvalbeheer is. De resultaten van SURMAT geven gedetailleerd inzicht in de logistiek van het afvaltransport van bronnen naar verwerkingsbedrijven. SURMAT selecteert verwerkingstechnologieën en rapporteert hun capaciteiten, de teruggewonnen producten en kosten. Daarom kan SURMAT helpen bij het opstellen van richtlijnen en plannen op het gebied van afvalbeheer. Behalve de logistiek en de verwerkingstechnieken kan het instrument ook additionele informatie inzake de bestudeerde situatie leveren. Het instrument kan bijvoorbeeld de kosten van alternatieve strategieën berekenen en kan daarom gebruikt worden om een heldere vergelijking tussen strategische opties te maken. Het is ook eenvoudig om een gevoeligheidsanalyse op te stellen met gewijzigde invoergegevens.

Tóm tắt

Giới thiệu

Mục tiêu chính của nghiên cứu này là xây dựng công cụ hỗ trợ các nhà quản lý ở các nước đang phát triển để quản lý chất thải rắn sinh hoạt một cách bền vững về môi trường và hiệu quả về kinh tế. Để đạt được mục tiêu trên đề tài đã xây dựng một công cụ có tên gọi SURMAT (Sustainable URban waste MAnagement Tool: công cụ quản lý chất thải đô thị bền vững) và đã áp dụng vận hành thử nghiệm với cơ sở dữ liệu về chất thải rắn sinh hoạt của thành phố Hồ Chí Minh. Đây là một thành phố có khối lượng và tốc độ xả thải chất thải cao, đồng thời đang đối mặt với các hạn chế về tài nguyên đất đai cần để chôn lấp rác (là công nghệ phổ biến hiện nay của thành phố). Do vậy, một công cụ như trên sẽ mang một ý nghĩa lớn trong việc quản lý hiệu quả chất thải rắn sinh hoạt.

Nghiên cứu gồm có 7 chương. Chương 1 giới thiệu về mục tiêu, phương pháp luận và phương pháp nghiên cứu. Chương 2 nghiên cứu hiện trạng của hệ thống quản lý chất thải rắn sinh hoạt của thành phố Hồ Chí Minh, là một trường hợp nghiên cứu cụ thể ở một thành phố đang phát triển. Số liệu thu thập được ở chương này là số liệu đầu vào của mô hình đã được xây dựng và vận hành ở chương 6. Do thiếu các thông tin liên quan đến công nghệ ủ kị khí chất thải rắn hữu cơ ở các nước đang phát triển, chương 3 nghiên cứu sâu về khả năng ứng dụng của công nghệ ủ kị khí chất thải rắn hữu cơ trong điều kiện về môi trường và thành phần chất thải của thành phố Hồ Chí Minh. Chương 4 lựa chọn công nghệ khả thi để xử lý chất thải rắn sinh hoạt ở các thành phố của các nước đang phát triển. Chương 5 phân tích kinh tế (chi phí và lợi nhuận) cho từng phương án công nghệ đã được lựa chọn ở chương 4. Chương 6 lập trình toán cho công cụ SURMAT. Mô hình toán được xây dựng và vận hành với thông số đầu vào từ chương 2, 3, 4 and 5. Kết quả đầu ra của SURMAT cho thấy hiệu quả (tiềm năng) của từng chiến lược quản lý chất thải rắn trong tương lai. Chương 7 trình bày các thảo luận, kết luận và kiến nghị. Các mục tiếp sau đây trình bày các kết quả chính của từng chương nghiên cứu.

Quản lý chất thải rắn sinh hoạt ở các nước đang phát triển (chương 2)

Các thông tin, số liệu về hệ thống quản lý chất thải rắn được thu thập từ các báo cáo trong và ngoài nước, từ các hội thảo trong nước và quốc tế và từ các dự án nghiên cứu và triển khai liên quan đến quản lý chất thải rắn, một số các đặc điểm chính về hệ thống quản lý chất thải rắn sinh hoạt ở các nước đang phát triển được liệt kê sau:

(1) Khối lượng và tốc độ phát sinh chất thải rắn sinh hoạt tăng nhanh do tăng trưởng kinh tế và gia tăng dân số;
(2) Nhu cầu cao về xử lý chất thải rắn sinh hoạt có tỷ lệ chất hữu cơ và độ ẩm cao, có tỷ lệ chất thải có khả năng tái chế (các loại khác chất hữu cơ có khả năng phân hủy sinh học như: túi nilon, nhựa, giấy, thủy tinh, cao su) thấp và nhiệt trị thấp;
(3) Cơ sở hạ tầng về thu gom và vận chuyển không đồng bộ và còn thiếu. Thiếu diện tích đất để xây dựng khu xử lý chất thải mới;
(4) Nhận thức cộng đồng về quản lý chất thải và vệ sinh môi trường còn yếu kém. Nhu cầu xây dựng lực lượng cán bộ về quản lý và xử lý chất thải là nhu cầu cấp bách;
(5) Hệ thống quản lý kém hiệu quả và cồng kềnh. Vai trò, quyền hạn và chức năng của nhiều tổ chức bị trùng lặp và/hoặc không cụ thể;
(6) Thiếu một số các qui định chi tiết cần thiết trong quản lý và triển khai các qui định, luật về bảo vệ môi trường;
(7) Ngân sách nhà nước dành cho các công tác bảo vệ môi trường không đủ, đặc biệt là ngân sách đầu tư xử lý chất thải, trong khi các yêu cầu về bảo vệ môi trường ngày càng nghiêm ngặt hơn;
(8) Hoạt động của hệ thống tái chế chất thải (nilon, giấy, nhựa, thủy tinh) phát triển rộng. Tuy nhiên công nghệ tái chế còn lạc hậu, khả năng phát thải ô nhiễm cao;

(9) Công nghệ xử lý chất thải rắn sinh hoạt còn lạc hậu, chủ yếu là bãi chôn lấp và nhà máy compost.

Trong thời gian vừa qua, thành phố Hồ Chí Minh đã triển khai nhiều hoạt động về quản lý chất thải rắn sinh hoạt. Thành công đáng kể nhất là việc nâng cao hiệu quả của hệ thống thu gom chất thải, phát triển đội ngũ cán bộ và sự tham gia của thành phần tư nhân và nước ngoài vào hai khâu thu gom và xử lý. Bên cạnh đó, thành phố đã áp dụng một số các chương trình nhằm hoàn thiện hệ thống quản lý chất thải rắn như: chương trình phân loại rác tại nguồn (thí điểm), chương trình tái thiết lập hệ thống thu phí thu gom chất thải rắn sinh hoạt. Bước đầu triển khai và thí điểm các chương trình đã cho thấy một số bất cập, thành phố đang từng bước hoàn thiện.

Phân hủy kị khí chất thải rắn sinh hoạt hữu cơ (chương 3)

Liên quan đến chi phí và khả năng sản xuất biogas từ các công nghệ xử lý chất thải rắn, công nghệ ủ kị khí là một công nghệ có tiềm năng ở các nước đang phát triển. Tuy nhiên công nghệ này còn mới ở các nước đang phát triển, không ngoại trừ ở Việt Nam. Do vậy, chương 3 nghiên cứu quá trình ủ kị khí chất thải rắn sinh hoạt hữu cơ trong điều kiện môi trường (nhiệt độ, độ ẩm, chất lượng chất thải) của một nước đang phát triển. Kết quả nghiên cứu cho thấy khi kết hợp ủ chất thải rắn sinh hoạt hữu cơ với phân heo đã gia tăng hiệu quả sinh khí biogas, trong khi đó nếu kết hợp ủ chất thải rắn hữu cơ với hỗn hợp chất thải sau khi đã ủ kị khí sẽ làm ổn định pH và do đó hiệu quả sinh khí cũng tăng (so với chỉ ủ chất thải rắn sinh hoạt hữu cơ một mình).

Lượng khí biogas sinh ra tối đa đạt được là $59m^3$/tấn hỗn hợp chất thải rắn sinh hoạt hữu cơ, phân heo và hỗn hợp sau ủ kị khí với tỷ lệ khối lượng tươi là 10:1:1. Kết hợp với yêu cầu về kinh tế (cần thời gian lưu ngắn trong khoảng thời gian sinh khí có hiệu quả kinh tế) thì quá trình ủ kị khí cần 20 ngày và quá trình ủ hiếu khí sau đó (post-treatment) là 7 ngày. Compost sau ủ hiếu khí đạt tiêu chuẩn chất lượng compost của Việt Nam[53]. Trong quá trình ủ kị khí và hiếu khí, cần phải lưu ý vấn đề sinh mùi. Khối lượng compost thành phẩm khoảng 0.2-0.25 tấn/tấn hỗn hợp chất hữu cơ đầu vào.

Nghiên cứu cho thấy khả năng ứng dụng cao của công nghệ ủ kị khí khô dạng mẻ có tuần hoàn nước rỉ rác đối với chất thải rắn sinh hoạt hữu cơ trong điều kiện ở các nước đang phát triển.

Công nghệ xử lý chất thải rắn sinh hoạt và khả năng ứng dụng ở các nước đang phát triển (chương 4)

Lựa chọn công nghệ xử lý chất thải rắn sinh hoạt ở các nước đang phát triển được căn cứ vào: đặc điểm của từng công nghệ (gồm quá trình xử lý và cân bằng vật chất), các tiêu chí về công nghệ, môi trường, kinh tế và xã hội của địa phương. Tám công nghệ có tính khả thi cao được đề xuất bao gồm: công nghệ ủ hiếu khí sản xuất compost bao gồm ủ dạng luống thổi khí cưỡng bức (Aerated static pile composting) và ủ dạng container (In-vessel composting), công nghệ ủ kị khí sản xuất biogas và compost bao gồm hai công nghệ điển hình là ủ khô dang mẻ (Biocell technology) và ủ khô dạng liên tục (Valorga technology), công nghệ đốt không thu năng lượng (Incineration without energy recovery) và công nghệ đốt thu hồi năng lượng (Incineration with energy recovery), công nghệ chôn lấp hợp vệ sinh (sanitary landfill) và công nghệ chôn lấp sinh học (Bioreactor landfill).

Kết quả nghiên cứu cho thấy do giá thành hợp lý và khả năng chôn lấp hầu hết các loại chất thải đã làm gia tăng khả năng ứng dụng của công nghệ bãi chôn lấp hợp vệ sinh ở các nước đang phát triển. Công nghệ này được xem là một công nghệ không thể thiếu trong hệ thống quản lý chất thải rắn. Do đất đai ngày càng khan hiếm, sự gia tăng các yêu cầu gắt gao về bảo vệ môi trường, giá thành xử lý nước rỉ rác quá cao đã dẫn đến việc bãi chôn lấp ngày càng bị thay thế. Từ đó phát triển công nghệ bãi chôn lấp sinh học và công nghệ này ngày càng thu hút nhà đầu tư. So với công nghệ bãi chôn

[53] Tiêu chuẩn ngành cho phân hữu cơ vi sinh chế biến từ chất thải rắn sinh hoạt của Bộ Nông nghiệp và Phát triển Nông thôn, 2002.

lấp hợp vệ sinh, bãi chôn lấp sinh học có giá thành xây dựng và điều kiện thi công và vận hành phức tạp hơn. Tuy nhiên, bãi chôn lấp sinh học có nhu cầu đất đai thấp hơn, sản phẩm biogas nhiều hơn và giá thành xử lý nước rỉ rác thấp hơn.

Công nghệ ủ hiếu khí sản xuất compost là lựa chọn thứ hai sau công nghệ bãi chôn lấp vệ sinh ở các nước đang phát triển hiện nay. Đây là một công nghệ đơn giản, không đắt tiền và công nghệ đã được minh chứng bằng thực tế. Tuy nhiên việc ứng dụng công nghệ này có thành công hay không phụ thuộc vào chất lượng compost và nhu cầu sử dụng compost của địa phương. Với xu hướng phát triển các công nghệ sản xuất năng lượng, công nghệ ủ kị khí sản xuất biogas ngày càng được quan tâm do công nghệ này sản xuất khí năng lượng và cả sản phẩm compost. Tuy nhiên, công nghệ này chưa được minh chứng bằng thực tế ứng dụng ở các nước đang phát triển.

Mục tiêu của công nghệ lò đốt là giảm thiểu khối lượng chất thải và hạn chế tiềm năng gây ô nhiễm môi trường của chất thải rắn sinh hoạt. Một mục tiêu mới của công nghệ này còn là thu hồi nguồn năng lượng. Ở các nước đang phát triển, công nghệ lò đốt không được lựa chọn do chi phí đầu tư và vận hành công nghệ này quá cao, yêu cầu về kỹ thuật cũng rất cao và công nghệ này rất nhạy cảm (hạn chế) khi nhiệt trị của chất thải thấp, độ ẩm trong chất thải cao như là trường hợp của chất thải rắn sinh hoạt tại các nước đang phát triển. Một điều quan trọng là chi phí để xử lý bằng lò đốt có thể được bù đắp bằng nguồn lợi từ thu hồi nguồn năng lượng. Ở các nước đang phát triển giá điện thường thấp do được bù lỗ từ chính phủ, vì vậy công nghệ lò đốt chưa được quan tâm. Tuy nhiên, khi địa phương bị hạn chế về nguồn đất đai hoặc địa phương có thể thu lợi từ bán tín chỉ carbon (CERs) thì tính khả thi của công nghệ này ngày càng được cải thiện.

Phân tích chi phí và nguồn thu từ các công nghệ xử lý chất thải rắn sinh hoạt (chương 5)

Việc dự đoán chi phí và nguồn thu cho từng công nghệ xử lý chất thải rắn sinh hoạt ở chương 5 phụ thuộc vào các số liệu về chi phí của các dự án đã triển khai tại thành phố Hồ Chí Minh và tại Việt Nam, cũng như các số liệu thu thập được từ các dự án, bài báo tại Châu Âu. Chi phí cho từng công nghệ được phân ra làm: tổng chi phí (gross), nguồn thu và chi phí ròng (net). Nguồn thu từ việc bán năng lượng (biogas, điện), compost, nhựa và kim loại. Số liệu tính toán cho thấy chi phí bị ảnh hưởng lớn bởi qui mô của nhà máy, nhà máy đầu tư công suất lớn có giá thành xử lý cho một tấn sản phẩm nhỏ hơn các qui mô nhỏ. Qui mô của nhà máy trong nghiên cứu này giao động từ 100.000 đến 1.100.000 tấn /năm. Ảnh hưởng của việc chi phí xử lý giảm khi đầu tư công suất lớn đặc biệt rõ ở công nghệ ủ hiếu khí dạng luống ủ, công nghệ dạng container, công nghệ kị khí dạng mẻ và liên tục. Đối với công nghệ lò đốt ảnh hưởng này không lớn do công nghệ đã được đầu tư ở dạng module.

Bảng 1 Chi phí xử lý chất thải rắn bằng các công nghệ khác nhau ở thành phố Hồ Chí Minh (công suất 100.000 – 1.100.000 tấn chất thải rắn sinh hoạt/năm) (USD/tấn).

Công nghệ	Tổng chi phí	Nguồn thu	Chi phí ròng
Công nghệ compost dạng luống	22,3 - 33,1	12,7 - 13,7	8,0 - 19,9
Công nghệ compost dạng container	26,2 - 42,1	12,7 - 13,7	13,0 - 28,9
Công nghệ kị khí dạng mẻ	25,3 - 40,5	17,6 - 20,7	6,1 - 21,3
Công nghệ kị khí dạng liên tục	33,2 - 54,7	19,3 - 29,9	8,6 - 30,1
Công nghệ lò đốt không thu năng lượng	45,7 - 58,6	15,7 - 52,9	11,4 - 24,3
Công nghệ lò đốt có thu hồi năng lượng	38,6 - 49,3	0	38,6 - 49,3
Bãi chôn lấp vệ sinh	20,0 - 28,0	11,8 - 16,0	6,1 - 14,1
Bãi chôn lấp sinh học	23,6 - 33,4	15,5 - 20,2	5,7 - 15,5

Lưu ý: Tổng chi phí bao gồm phí đầu tư, vận hành và phí chôn lấp chất thải không thể tái chế.

Nguồn thu từ các công nghệ xử lý chất thải rắn sinh hoạt hữu cơ phụ thuộc rất nhiều vào điều kiện địa phương. Giá trị này biến động rất rộng và do đó nó ảnh hưởng lớn đến chi phí ròng. Trong tám công nghệ xử lý đã đề cập ở chương 4, bãi chôn lấp vệ sinh là công nghệ có tổng chi phí nhỏ nhất. Trong khi công nghệ lò đốt có chi phí lớn nhất nhưng nếu tính gộp cả nguồn thu từ bán điện thì chi phí ròng của lò đốt lại giảm đi đáng kể và có sức cạnh tranh với các công nghệ khác.

Mô hình tối ưu hóa (chương 6)

Công cụ hỗ trợ người ra quyết định SURMAT được xây dựng với mục đích tối ưu hóa việc lựa chọn đầu tư. Công cụ sử dụng phần mềm MILP (mixed integer linear programming). Công cụ được sử dụng để đánh giá các chiến lược quản lý chất thải cho thành phố Hồ Chí Minh, ứng dụng để (1) giảm thiểu chi phí ròng (net) vận chuyển và xử lý chất thải rắn sinh hoạt hữu cơ, và (2) tối đa lượng điện được sản xuất từ quá trình xử lý chất thải rắn sinh hoạt. Các số liệu được thu thập và tính toán ở các chương 2, 3, 4 và 5 được sử dụng làm số liệu đầu vào của mô hình. Kết quả đầu ra của mô hình cung cấp thông tin về việc phân bổ khối lượng chất thải từ 24 quận của thành phố Hồ Chí Minh đến từng nhà máy xử lý, loại và công suất của từng công nghệ xử lý, chi phí và nguồn thu của toàn hệ thống.

Năm (5) chiến lược quản lý chất thải rắn sinh hoạt đã được mô hình hóa với mục tiêu giảm thiểu chi phí ròng trong vận chuyển và xử lý chất thải rắn sinh hoạt trên địa bàn thành phố Hồ Chí Minh. Ứng với mỗi chiến lược, có 3 trường hợp liên quan đến đất đai được đề cập. Trường hợp 1, khi đất đai được giả thiết là không thiếu, cần bao nhiêu sẽ được cung cấp đủ. Trường hợp 2, khi đất đai đã được qui hoạch. Hiện nay (2011) thành phố Hồ Chí Minh đã qui hoạch 2 khu vực làm điểm xử lý chất thải rắn sinh hoạt tại Phước Hiệp và Đa Phước với diện tích tương ứng là 276 and 233 ha cho mỗi khu vực. Như vậy trường hợp 2 ứng với diện tích này và theo qui hoạch diện tích này phải được sử dụng ít nhất trong 20 năm. Trường hợp 3 giả sử việc thu hồi giải tỏa của thành phố gặp nhiều khó khăn và thành phố chỉ thu hồi được 50% diện tích so với trường hợp 2.

Để đạt được mục tiêu giảm thiểu chi phí, mô hình sẽ lựa chọn các công nghệ chi phí thấp với điều kiện phù hợp về mặt đất đai. Trong 5 chiến lược đề xuất, chiến lược 1 thực hiện trong điều kiện về hệ thống quản lý chất thải rắn sinh hoạt hiện tại của địa phương sẽ có kết quả về chi phí là thấp nhất. Các chiến lược sau được bổ sung một số yêu cầu gắt gao hơn và do đó chi phí sẽ cao hơn chiến lược 1. Trong đó, chiến lược 2 bổ sung yêu cầu về công nghệ xử lý; chiến lược 3 bổ sung yêu cầu về hạn chế trong giao thông vận chuyển chất thải; chiến lược 4 bổ sung yêu cầu về nhu cầu sản phẩm (khả năng bán sản phẩm compost); chiến lược 5 có điều kiện tương tự chiến lược 1 nhưng đặt giả thiết là thành phố Hồ Chí Minh bán được năng lượng dưới dạng nhiệt và bán được chứng chỉ carbon (CERs).

Trong 3 trường hợp liên quan đến đất đai, trường hợp 1 do đất đai không bị hạn chế luôn cho kết quả về chi phí thấp nhất. Ngược lại trường hợp 3 do rất hạn chế về đất đai, đòi hỏi công nghệ cần ít đất và do đó chí phí là cao nhất. Các phân tích tính nhạy cảm của mô hình cho thấy sự thay đổi thông số đầu vào như là giá điện, khả năng bán compost... rất ảnh hưởng đến kết quả của mô hình.

Sáu trường hợp nghiên cứu đã được thực hiện nhằm phân tích ảnh hưởng của chi phí ròng trong quản lý chất thải rắn đến khả năng tối đa hóa sản phẩm điện. Chi phí xử lý chất thải rắn được nâng lên từ 14 USD/tấn (trường hợp E_1) đến 20.7 USD/tấn (trường hợp E_6). Khi chi phí chi trả để xử lý một tấn chất thải rắn sinh hoạt tăng lên thì khả năng sản xuất điện cũng tăng theo và sản lượng điện tối đa đạt được là 323 kWh/tấn chất thải rắn sinh hoạt. Sản lượng điện gia tăng đồng nghĩa với việc đầu tư nhiều hơn cho công nghệ lò đốt có thu hồi điện năng. Công nghệ được mô hình lựa chọn từ: công nghệ ủ kị khí dạng mẻ (trường hợp E_1) đến công nghệ bãi chôn lấp sinh học (trường hợp $E_{1, 2, 3, 4}$) và đến công nghệ lò đốt ($E_{3, 4, 5, 6}$). Kết quả cho thấy với kinh phí cho phép từ 15.3USD/tấn trở lên, công nghệ lò đốt có thu hồi điện sẽ được đề nghị đầu tư.

Kết luận (chương 7)

Chương 7 thảo luận sâu về hiệu quả của công cụ SURMAT và thảo luận về các ảnh hưởng của điều kiện địa phương, ảnh hưởng khi khối lượng chất thải tăng mạnh qua các năm đến kết quả của mô hình và khả năng ứng dụng của mô hình tại các nước đang phát triển.

Vấn đề đầu tiên là: kết quả của mô hình phụ thuộc rất lớn vào số liệu đầu vào. Đặc biệt là chi phí và nguồn thu của từng công nghệ. Đây là các thông số có biến động lớn và dễ ảnh hưởng đến kết quả của mô hình. Để hạn chế chi phí quản lý chất thải rắn, một số các hoạt động sau cần thực hiện:

(1) Cần phải có chính sách và công nghệ quản lý chất thải rắn sinh hoạt một cách phù hợp để giảm thiểu độ ẩm của chất thải (nhờ vậy sẽ giảm được chi phí vận chuyển, chi phí phân loại, chí phí sấy khô và sản xuất được nhiều năng lượng hơn);
(2) Cần đẩy mạnh các công nghệ thu hồi sản phẩm có giá trị như biogas, điện; và
(3) Các chính sách cần phải phát triển theo từng giai đoạn ngắn hoặc dài hạn tương ứng với khả năng đáp ứng nhu cầu về diện tích đất đai phục vụ trong công tác xử lý chất thải.

Các chiến lược được mô hình hóa trong luận văn này sử dụng khối lượng chất thải rắn trung bình ước tính trong 20 năm. Điều này có thể dẫn đến vấn đề là kết quả của mô hình có thể hơi rẻ hơn trong thực tế ứng dụng khi lượng chất thải tăng dần qua các năm qui hoạch.

Công cụ được trình bày trong luận văn này có thể được sử dụng để đề xuất kế hoạch đầu tư cho các thành phố đang phát triển. Luận văn đã trình bày phương pháp thực hiện, gói số liệu cần thiết về công nghệ cũng như chi phí như là một ví dụ có thể ứng dụng cho các thành phố khác. Tuy nhiên, khi các điều kiện thực tế của các địa phương khác có những khác biệt so với thành phố Hồ Chí Minh, cần phải có một số hiệu chỉnh công cụ SURMAT, đặc biệt những khác biệt như sự đổi mới công nghệ, điều kiện đất đai, chi phí xử lý và nguồn thu tại từng địa phương.

Vấn đề sau cùng là, với kinh nghiệm vận hành SURMAT và kết quả thu được từ nghiên cứu này, có thể kết luận rằng SURMAT là một công cụ hữu hiệu, dễ ứng dụng và dễ hiệu chỉnh trong quản lý chất thải rắn sinh hoạt. Kết quả của SURMAT cung cấp những số liệu chi tiết về vận chuyển chất thải từ nguồn đến nơi xử lý và công nghệ xử lý chất thải. SURMAT lựa chọn công nghệ, đề xuất công suất cho từng công nghệ, loại và lượng sản phẩm được sản xuất, chi phí và nguồn thu. Do vậy, SURMAT có thể được sử dụng để đề xuất các định hướng, qui hoạch tổng thể về quản lý chất thải rắn cho từng trường hợp nghiên cứu. Bên cạnh phương án tối ưu về vận chuyển và công nghệ xử lý, SURMAT còn cung cấp nhiều thông tin liên quan khác. Ví dụ như SURMAT có thể tính toán trong trường hợp kém tối ưu hơn. Do vậy, nó có thể giúp so sánh rõ ràng sự khác biệt giữa các phương án.

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Appendices

Appendix 1: Characteristics of municipal solid waste in Ho Chi Minh City

A.1.1 Solid waste generation in Ho Chi Minh City

The generation of MSW is the starting point within each waste management system. There is no solid waste separation at the source in HCMC and in Viet Nam. Based on recent studies (CENTEMA 2008), commingled MSW in HCMC comes from households, street sweeping, commercial establishments, offices, markets, non-hazardous waste from hospitals and industries. The solid waste from households, markets, offices and commercial areas includes all types of waste even hazardous waste. The solid waste from hospitals is only domestic solid waste. Industrial waste is in fact domestic waste and non-hazardous industrial solid waste. Medical waste from hospitals, hazardous waste from industries, sediments and construction waste are collected and treated separately. Table A.1.1 shows the percentage of MSW per discharge source, excluding domestic waste from hospitals and non-hazardous waste from industry.

Table A.1.1 The percentage of MSW per source in HCMC

Source	Percentage in wet weight (%)
Households	57.91
Market	13.00
Commercial area	12.00
Schools, offices	2.80
Public area and others	14.29
Total	100.00

Source: CITENCO (2010)

A.1.2 Quantities of MSW generated

The amount of solid waste generation per capita strongly depends on the social and economic conditions. This can be illustrated by remarkable differences in the MSW generation within HCMC. The amount of MSW in HCMC increased continuously the past 10 years after implementation of the "Doi moi" policies. These policies rapidly improved the social and economic situation of HCMC. From 1997 - 2007 the waste generation increase rate is about 6 -8% (DONRE HCMCb 2009). This MSW growth rate is corresponding with the growth of urban residents, living standards and economic expansion. Another comparison of economic areas between HCMC and cities in Europe, shows that the economically developed European cities produce much higher amounts of MSW (510 kg/capita/year, (Den Boer et al. 2005) than HCMC (295 kg/capita/year),(CENTEMA 2008). There are some fluctuations in the amounts of MSW collected per year. This could be due to reorganizations of the collection system.

The solid waste management strategy 2003 toward 2010, of HCMC PC, announced that 100% of the MSW from urban districts should be collected and treated with environment-friendly and cost-effective technologies, which includes energy recovery and aerobic composting. However, until now about 10 - 15% of municipal waste is still not collected and is discharged in yards, cannels and empty areas and of the collected MSW more than 90% is still landfilled. Only about 8% of the collected MSW is composted at the Vietstar composting plant. Figure A.2.1 shows the amount of MSW dumped in landfills in the period of 1996 to 2009.

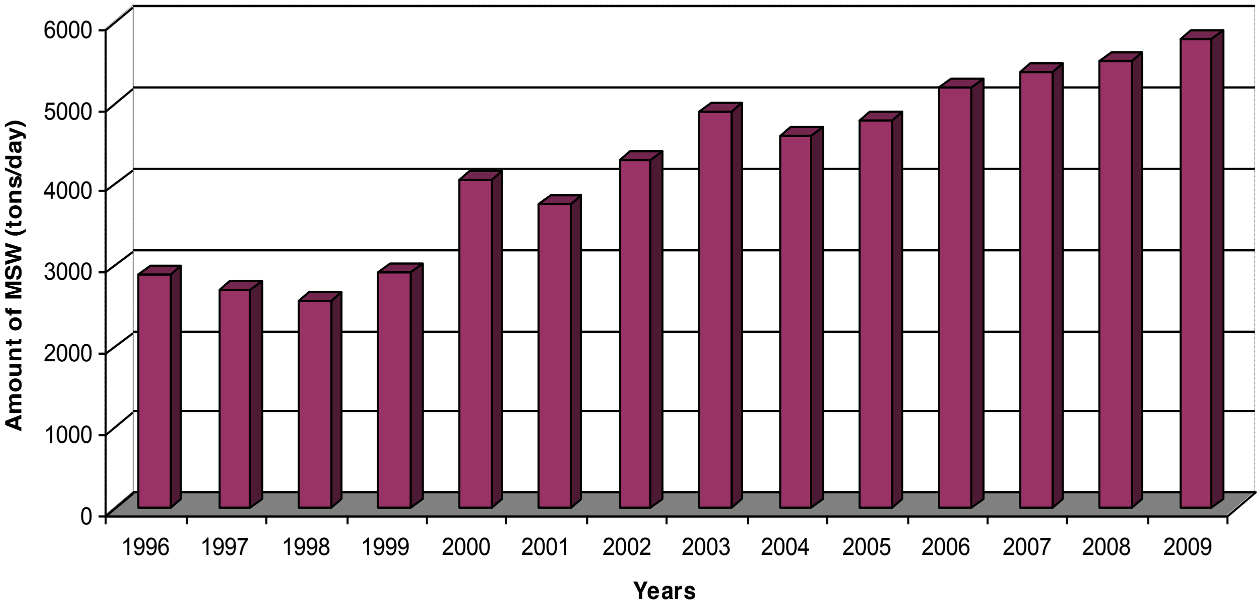

Figure A.1.1 Average amounts of MSW discharged (ton/day) in HCMC from 1996 to 2009.

Table A.1.2 shows the amount of MSW collected in the 24 districts of HCMC in 2008. MSW is collected at day and at night and transported to landfills.

Table A.1.2 Amount of collected MSW from 24 districts of HCMC in 2008.

Name of district	Total amount of MSW		Name of district	Total amount of MSW	
	Ton/year	Ton/day		Ton/year	Ton/day
1	97,632	267	Tan Binh	173,573	476
2	77,115	211	Tan Phu	106,106	291
3	64,374	176	Binh Tan	58,240	160
4	82,628	226	Phu Nhuan	99,772	273
5	108,684	298	Go vap	106,970	293
6	158,963	436	Thu Duc	131,741	361
7	71,665	196	Hoc Mon	82,227	225
8	67,911	186	Binh Thanh	134,666	369
9	78,112	214	Nha Be	11,592	32
10	100,460	275	Can Gio	0	0
11	58,654	161	Binh Chanh	47,320	130
12	80,098	219	Cu Chi	40,404	111
Total	2,038,907	5,586			

Source: Viet (2009)

A.1.3 Composition of MSW

The composition of collected MSW in HCMC is presented in table A.1.3. In this table, the data under "transfer stations" is an average from samples taken at 54 transfer stations in HCMC in 2009. The data of Phuoc Hiep landfill is the average of two samples from Phuoc Hiep landfill in 2007. The differences between the two sets of data are explained below.

The fraction of organic waste in the MSW at transfer stations in HCMC was high, about 80% by wet weight (CENTEMA 2008). The high weight fraction is also due to the high moisture content of food waste, which is about 65% (CENTEMA 2008). The composition of MSW at transfer stations and at Phuoc Hiep landfill shows that fraction of food and paper waste are lower at the landfill and all other types of wastes higher compared to the transfer stations. This can be due to: (1) no dry weight data are available which makes comparison inaccurate. (2) MSW in the landfill might be older by a few days compared to MSW in the transfer stations. Therefore, more of the organic fraction in MSW at the landfill is biodegraded and is settled inside the heap. Therefore plastic are available on the top of the heap for sampling; (3) the time of sampling of the relatively fresh MSW at the landfill and at the transfer stations were 2 years apart. Within this period the collection of recyclable waste had decreased due to economic reasons; (4) the price of recyclable waste strongly declined in 2007. As a consequence people were no longer interested to collect this type waste; (5) water leaked out from the MSW and organic matter digested during the time of transferring from transfer station to landfill unlikely that this would lead to such big differences; (6) digested organic matter is attached to inorganic matter and is difficult to separate; (7) the degree of accuracy of the data with sample masses of only 93.6 and 96.2 kg per sample is questionable.

Table A.1.3 Composition of MSW measured in HCMC

Component	Transfer station 2009* (% by wet weight)	Phuoc Hiep landfill 2007** (% by wet weight)
Organic		
Food wastes	85.81	38.1
Paper	4.18	1.7
Cardboard	0.66	Included in paper
Plastics and nylon	5.7	30.4
Textiles	0.83	10.3
Rubber	0.12	2.4
Leather	0.07	0.2
Yard wastes	0.38	13.3
Wood	0.34	0.5
Misc. organics	0.36	0.6
Inorganic		
Glass	0.24	0.3
Tin cans	0.37	nd
Aluminum	nd	nd
Other metal	0.02	1
Dirt, ash, etc.	0.99	1.2
Total	100	100

*Sources: * CENTEMA (2009) and **DONRE HCMCb (2009)*
Note: nd: no data.

A.1.4 Composition of compost from aerated composting plants in Viet Nam

Table A.1.4 Analytical results of compost product from plants in Viet Nam

Name composting plant	Samples	pH	Soluble salt	Moisture content	Organic carbon	Ash	Kjeldahl Nitrogen	P_2O_5	Cd	Cr	Pb	Salmo-nellla
		-	g/kg dw	%	% dw	% dw	% dw	% dw	mg/kg dw	mg/kg dw	mg/kg dw	CFU/25g
Tan Thanh		8.09	8.56	17.8	15.5	72.1	0.92	0.85	1.37	nd	33	0
Nam Thanh	Sample 1	8.76	8.08	14.8	18.6	66.6	1.10	0.14	0.66	nd	11	0
	Sample 2	8.59	3.46	21.7	19.9	64.1	1.90	0.40	-	-	-	0
Nam Dinh		7.74	4.36	16.3	17.6	68.4	1.17	0.18	2.44	-	10	0
Thuy Phương	Product type 1	8.43	6.18	28.8	14.8	55.3	1.27	0.09	0.88	-	69	0
	Product type 2	7.85	6.52	22.5	20.9	62.4	1.20	0.20	-	-	-	0
Vietnamese standard 10-TCN 526-2002[54]	-	6.0 – 8.0	-	35	≥ 13	-	2.5	2.5	2.5	200	250	0

Source: Giac Tam et al (2006)
Note: dw: dry weight
nd: not detected

Appendix 2: National legal framework

At the national level, there are a series of legal instruments stipulating solid wastes management to protect the environment. We only mention here in chronological order the documents regarding MSW.

- Some Articles in the "Environmental Protection Law" (issued in 1993 and reissued in 2005), e.g. Legislation no. 52/2005/QH11 dated 29/12/2005, stipulate the generalities of solid waste management;
- Inter-Ministerial Circular No. 29/1999/QD-BXD dated 22/10/1999 promulgates the regulations of environmental protection applied for the construction sector;
- Inter-Ministerial Circular No. 10/2000/TTBXD dated 8/8/2000 guides the preparation of EIA reports for the planning of construction projects, including solid waste management during and after construction;
- Inter-Ministerial Circular No. 01/2001/TTLT-BKHCNMT-BXD dated 18/1/2001 guides the regulations and environmental protection applied for the spatial planning of the sites, construction and operation of landfills;
- Ordinance No. 38/2001/PL-UBTVQH dated 28/8/2001 of the Standing Committee of the National Assembly on Proscribing Fees and Charges. This is generally supported by local regulations issued by People's Councils or Committees;
- Governmental Decree No. 57/2002/ND-CP dated 3/6/2002 provides the details on the implementation of ordinance No. 38/2001/PL-UBTVGH on fees and charges;
- Circular No. 63/2002/TT-BTC dated 24/7/2002 of the Ministry of Finance guides the implementation of provisions on fees and charges;

[54] Vietnamese standard for organic bio-fertilizer from MSW, issued by the Ministry of Agriculture and Rural Development. Go to appendix 2

- Circular No. 45/2006/TT-BTT dated 30/7/2003 of the Ministry of Finance guides the implementation of the provisions of the fees and charges for solid waste collection and treatment;
- Decision no. 256/2003/QD-TTG dated 2/12/2003 by the Prime Minister on approving the National Strategy Framework on general environmental improvement in the period of 2000 - 2010, vision 2020". The document covers all the components and sectors (domestic, industrial wastewater, coastal area, MSW, hazardous waste, etc.). The strategy framework is divided into 23 programs, issued by MONRE Viet Nam (MONREd Viet Nam 2009). It contains among other things recycling and reuse of waste and the application of new technologies and the reduction of the amount of waste going to landfills by 30-50%;
- Decision No. 03/2004/QD-BTNMT dated 2/4/2004 of the Ministry of Natural Resources and Environment on importing waste as materials for domestic production;
- Decree no. 80/2006/ND-CP dated 9/8/2006 stipulates and gives guidelines to implement some of the articles of the Environmental Protection Law, with 25 articles and 2 references and decree no. 21/2008/ND-CP dated 28/2/2008 which modifies and adds some articles of Decree no. 80/2006/ND-CP;
- Decision no. 81/2006/ND-CP dated 09/8/2006 by the Prime Minister on the official fines on environmental pollution. Here, article 14 deals with solid waste discharges, article 15 deals with solid waste management, transport and treatment, and article 16 deals with import of equipment, material, fuel and waste;
- Announcement no. 50/TB-VPCP dated 17/3/2007, on the conclusion of Prime Minister Nguyen Tan Dung at the seminar on the local technology for solid waste treatment: "The Vietnamese government encourages investors to apply local technologies for solid waste treatment. The government contributes the clearance fee and infrastructure up to the land boundary and also pays for technology copyrights. The investors can borrow with special low interest from the Environmental Protection Fund and the Viet Nam Developing Bank. All related Ministries, Departments and local Organizations must provide good conditions for investors building solid waste treatment factories based on local technologies";
- Decree no. 59/2007/ND-CP dated 9/4/2007 of the Government promulgates the regulations on solid waste management. It includes 8 chapters, in which Chapter 1 is general information such as: scope and object of application, principles and content of management and forbidden behaviors, Chapter 2 is about solid waste management planning and investment, Chapter 3 is about solid waste separation, Chapter 4 is about collection, storage and transportation, Chapter 5 is on solid waste treatment, Chapter 6 is on financial aspects for solid waste management, Chapter 7 is about monitoring and inspection and Chapter 8 is about execution provision;
- Decision no 13/2007/QD-BXD dated 23/4/2007 by the Ministry of Construction about expenditure norms for MSW collection, transportation treatment, landfilling;
- Decree no. 174/2007/ND-CP dated 29/11/2007 on environmental protection fees for solid waste and Circular guide no. 39/2008/TT-BTC dated 19/5/2008 to implement the Decree no. 174/2007/ND-CP dated 29/11/2007 about the environmental protection fees for solid waste;
- Announcement no. 08/2008/TT-BTC dated 29/1/2008 about changing and improving Announcement no. 108/2003/TT-BTC dated 7/11/2003 on the guideline for ODA funds used for MSW and urban solid waste projects;
- Decision no. 21/2008/ND-CP dated 28/2/2008 on changing and improving some articles in decision no. 80/2006/ND-CP dated 9/8/2006 which details guidelines to implement some articles of the Environmental Law. Herein, MOSTE provides guidelines to check, monitor, and approve waste treatment facilities;
- Decision no. 1440/QD-TTg dated 6/10/2008 on approving the master plan for solid waste treatment zones for 3 key economic zones North, Middle and South Viet Nam until 2020. In the decision, the government encourages technologies suitable for local conditions. It encourages to use certified local and foreign technologies for landfilling, composting, recycling and incineration;

- Decision No. 2149/QD-TTg, dated 17/12/2009 by the Prime Minister about approving the national strategy for integrated management of solid waste up to 2025, with a vision to 2050. The objectives of the strategy are: (1) to raise the effectiveness of integrated management of solid waste in order to improve environmental quality, assure community health and contribute to sustainable national development; (2) to formulate a system of integrated management of solid waste where solid waste will be sorted at the source, collected, reused, recycled and thoroughly treated with advanced and appropriate technologies to minimize the burying of waste, save land resources and mitigate environmental pollution; (3) to raise community awareness on integrated management of solid waste and develop an environmentally friendly lifestyle; (4) to provide necessary infrastructure, financial and human resource conditions for integrated management of solid waste.

Appendix 3: Data input to the model

A.3.1 Amount of MSW input

Table A.3.1 and A.3.2 show the average amount of MSW per year in each period of planning based on the amount of MSW in 2008 and the grow rates of 7, 6.5, 6, 5.5, 5%/year for each period of 5 years (2008-2012), (2013-2017), (2018-2022), (2023-2028), and (2029-2032).

Taking into account the current 2 composting plants (with capacity of each composting plants is 400,000 ton/year) in treatment zone 1 are operating until 2029 and 2030, and 1 sanitary landfill (1,100,000 ton/year) in treatment zone 2 are operating until 2029, the amount of MSW to put into the model will be the result of the total amount of MSW per year (ton/year) minus the amount of MSW need for these current plants.

Table A.3.1 Estimated amount of MSW per year in HCMC (ton/year) and estimated population in HCMC.

Year	Total MSW (tons/year)	MSW need to be treated (ton/year)**	Population	MSW discharge (kg/person/day)
2008	2,038,907*	-	6,917,968	0.81
2009	2,181,630	-	7,162,864	0.83
2010	2,334,345	-	7,416,429	0.86
2011	2,497,749	-	7,678,971	0.89
2012	2,672,591	772,591	7,950,807	0.92
2013	2,846,310	946,310	8,232,265	0.95
2014	3,031,320	1,131,320	8,523,687	0.97
2015	3,228,355	1,328,355	8,825,426	1.00
2016	3,438,199	1,538,199	9,137,846	1.03
2017	3,661,682	1,761,682	9,461,326	1.06
2018	3,881,382	1,981,382	9,796,257	1.09
2019	4,114,265	2,214,265	10,143,044	1.11
2020	4,361,121	2,461,121	10,502,108	1.14
2021	4,622,789	2,722,789	10,873,882	1.16
2022	4,900,156	3,000,156	11,258,818	1.19
2023	5,169,664	3,269,664	11,657,380	1.21
2024	5,453,996	3,553,996	12,070,051	1.24
2025	5,753,966	3,853,966	12,497,331	1.26
2026	6,070,434	4,170,434	12,939,737	1.29
2027	6,404,308	4,504,308	13,397,803	1.31
2028	6,724,523	4,824,523	13,872,086	1.33
2029	7,060,749	5,160,749	14,363,157	1.35
2030	7,413,787	7,013,787	14,871,613	1.37
2031	7,784,476	7,784,476	15,398,068	1.39
2032	8,173,700	8,173,700	15,943,160	1.40
Total amount of MSW need to be treated in 20 years (ton)		71,395,181		
Average amount of MSW need to be treated in 20 years planning (ton/year)		3,569,759		

** Source: DONRE, 2009*

Note:

*** The actual amount of MSW need to be treated (After minus 1,900,000 ton/year for the available plants).*

Population growth rate of 3.54%/year.

Table A.3.2 Estimated the average amount of MSW per year of 24 districts (ton/year) in 20 years planning.

Districts	Amount (ton)	Districts	Amount (ton)	Districts	Amount (ton)
1	170,936	9	136,760	Go vap	187,285
2	135,014	10	175,887	Thu Duc	230,655
3	112,707	11	102,693	Hoc Mon	143,965
4	144,667	12	140,237	Binh Thanh	235,776
5	190,286	Tan Binh	303,895	Nha Be	20,296
6	278,316	Tan Phu	185,773	Can Gio	0
7	125,473	Binh Tan	101,968	Binh Chanh	82,849
8	118,900	Phu Nhuan	174,683	Cu Chi	70,740
Total	3,569,759 ton wet commingled MSW/year				

A.3.2 The distance from districts to treatment zones and transport costs

Table A.3.3 shows the distance from the 24 districts to the 2 treatment zones (DONRE, 2009). We assume these distances to be the shortest distances. The transport costs from the 24 districts to the 2 treatment zones are calculated based on the distances and the unit transport costs (0.21 and 0.27 USD/ton to treatment zone 1 and 2, respectively) which had been settled by DONRE, 2009.

Table A.3.3 Transport distance and transport cost of each distance from 24 districts to 2 treatment zones.

Districts	Distance to zone 1	Distance to zone 2	Transport costs to zone 1	Transport costs to zone 2	Districts	Distance to zone 1	Distance to zone 2	Transport costs to zone 1	Transport costs to zone 2
	km		USD/ton			km		USD/ton	
1	50.4	24.4	10.6	6.6	Tan Binh	36.5	38.9	7.7	10.5
2	69.4	24.0	14.6	6.5	Tan Phu	43.0	37.0	9.0	10.0
3	44.8	21.9	9.4	5.9	Binh Tan	42.5	23.3	8.9	6.3
4	52.0	21.7	10.9	5.9	Phu Nhuan	43.0	25.7	9.0	6.9
5	46.7	20.5	9.8	5.5	Go vap	47.5	27.0	10.0	7.3
6	48.6	24.4	10.2	6.6	Thu Duc	57.0	31.0	12.0	8.4
7	57.9	27.0	12.2	7.3	Hoc Mon	36.8	45.0	7.7	12.2
8	55.3	22.1	11.6	6.0	Binh Thanh	50.5	24.0	10.6	6.5
9	67.7	28.0	14.2	7.6	Nha Be	90.0	49.4	18.9	13.3
10	53.4	21.7	11.2	5.9	Can Gio	100.0	50.0	21.0	13.5
11	42.8	26.0	9.0	7.0	Binh Chanh	48.0	24.9	10.1	6.7
12	43.5	40.0	9.1	10.8	Cu Chi	23.76	73.0	5.0	19.7

A.3.3 The costs of MSW treatment technologies.

Table A.3.4 shows the costs analysis of the 9 technologies. The detailed analysis of the costs of the 9 technologies is presented in chapter 5. Table A.3.5 presents the detailed average benefit (income) of the 9 sub-technologies (USD/ton MSW input).

Table A.3.4 The costs analysis of the 9 technologies at different capacity (ton MSW input or ton residue in case of Residue landfill).

Plants	Capacity (ton/year)	Fixed costs (USD)	Fixed costs (USD/ton)	Operation costs (USD/ton)	Gross treatment costs (USD/ton)	Negative costs (USD/ton)	Net treatment costs (USD/ton)
Aerated compost	100,000	1,210,000	12.1	16.8	28.9	13.2	15.7
	200,000	1,760,000	8.8	14.0	22.8	13.2	9.6
	300,000	2,200,000	7.3	12.1	19.4	13.2	6.2
	400,000	2,750,000	6.9	11.2	18.1	13.2	4.9
	500,000	3,300,000	6.6	10.4	17.0	13.2	3.8
In-vessel compost	100,000	1,936,000	19.4	18.5	37.8	13.2	24.6
	200,000	2,816,000	14.1	15.4	29.5	13.2	16.3
	300,000	3,520,000	11.7	13.3	25.0	13.2	11.8
	400,000	4,400,000	11.0	12.3	23.3	13.2	10.1
	500,000	5,280,000	10.6	11.4	22.0	13.2	8.8
Batch anaerobic digestion	100,000	1,815,000	18.2	18.1	36.3	19.2	17.1
	200,000	2,640,000	13.2	15.1	28.3	19.2	9.1
	300,000	3,300,000	11.0	13.1	24.1	19.2	4.9
	400,000	4,125,000	10.3	12.1	22.4	19.2	3.2
	500,000	4,950,000	9.9	11.2	21.1	19.2	1.9
Continuous Anaerobic digestion	100,000	3,025,000	30.3	20.2	50.4	24.6	25.8
	200,000	4,400,000	22.0	16.8	38.8	24.6	14.2
	300,000	5,500,000	18.3	14.5	32.9	24.6	8.3
	400,000	6,875,000	17.2	13.4	30.6	24.6	6.0
	500,000	8,250,000	16.5	12.5	29.0	24.6	4.4
Incineration with energy recovery	200,000	6,900,000	34.5	22.4	56.9	34.3	22.6
	300,000	9,600,000	32.0	19.9	51.9	34.3	17.6
	400,000	12,000,000	30.0	18.3	48.3	34.3	14.0
	500,000	14,400,000	28.8	17.3	46.1	34.3	11.8
	600,000	16,600,000	27.7	16.3	44.0	34.3	9.7
Incineration without energy recovery	200,000	5,700,000	28.5	19.1	47.4	0.0	47.4
	300,000	8,000,000	26.7	17.1	43.4	0.0	43.4
	400,000	10,000,000	25.0	15.7	40.4	0.0	40.4
	500,000	12,000,000	24.0	14.8	38.6	0.0	38.6
	600,000	13,800,000	23.0	13.9	36.9	0.0	36.9
Sanitary landfill	100,000	2,000,000	20.0	8.0	28.0	13.0	15.0
	300,000	5,550,000	18.5	7.5	26.0	13.0	13.0
	500,000	8,500,000	17.0	7.0	24.0	13.0	11.0
	800,000	12,400,000	15.5	6.5	22.0	13.0	9.0
	1,100,000	15,400,000	14.0	6.0	20.0	13.0	7.0
Bioreactor landfill	100,000	2,600,000	26.0	7.2	33.2	18.0	15.2
	300,000	7,215,000	24.1	6.8	30.8	18.0	12.8
	500,000	11,050,000	22.1	6.3	28.4	18.0	10.4
	800,000	16,120,000	20.2	5.9	26.0	18.0	8.0
	1,100,000	20,020,000	18.2	5.4	23.6	18.0	5.6
Residue landfill	100,000	1,400,000	14.0	5.6	19.6	0.0	19.6
	300,000	3,885,000	13.0	5.3	18.2	0.0	18.2
	500,000	5,950,000	11.9	4.9	16.8	0.0	16.8
	800,000	8,680,000	10.9	4.6	15.4	0.0	15.4
	1,100,000	10,780,000	9.8	4.2	14.0	0.0	14.0

Note: All costs are calculated based on the costs of 2009. In the costs data of the individual treatment technologies the costs of disposal of the residue in the residue landfill is NOT included. However in the costs calculations, made by the model, the costs of residue is included.

Table A.3.5 The detailed average benefit (income) of the 9 sub-technologies (USD/ton MSW input).

	Compost	PE plastic	Recycla-ble waste	Electrici-ty	Heat	Alumin-um	Iron	Total
Aerated static pile and In-vessel composting	6.5	5.8	0.9	0	0	0	0	13.2
Continuous anaerobic digestion	6.5	5.8	0.9	11.4	0	0	0	24.6
Batch anaerobic digestion	6.5	5.8	0.9	6	0	0	0	19.2
Incineration with energy recovery	0	0	0	25.8	0	0.8	7.7	34.3
Incineration without energy recovery	0	0	0	0	0	0	0	0
Sanitary landfill	0	0	0	13.9	0	0	0	13.9
Bioreactor landfill	0	0	0	18	0	0	0	18
Residue landfill	0	0	0	0	0	0	0	0

A.3.4 Land requirement

- *The land requirement for process-oriented technologies:*

SURMAT will select the technologies to treat the average amount of MSW of 3.6 million ton MSW/year. At the end of 2032, the estimated amount of MSW will be about 8.2 million ton MSW/year which is 2.3 times higher than the average. In the calculations with SURMAT with a constant average amount of waste over 20 years this factor (factor 2.3) has already been incorporated. We now assume that the treatment capacity ratio of the required technologies in 2032 is similar to the ratio proposed for the average amount of MSW, and that the same technologies are used. Then the capacity of each technology in 2032 will be 2.3 times higher than that in average. Therefore, the land use of process- oriented technologies in 2032 is also 2.3 times higher than the average. For example, if the SURMAT proposed 1 aerated static pile composting with capacity of 100,000 ton/year, it needs 5 ha. Then in 2032, it needs 11.4 ha (= 5*2.3). The data of the needed land area for process- oriented technologies are given in appendix 3, table A.3.6a.

- *The land requirement for sanitary landfill, bioreactor landfill and residue landfill:*

SURMAT calculate with average amount of MSW of 3.6 million ton/year with in 20 years planning. Therefore, at the end of 20 years planning, the amount of land use of sanitary landfill is equal to 20 times of average amount. It means, if the model proposes 1 sanitary landfill with 100,000 ton/year is 0.8 ha, then at the end of 2032 it needs 16 ha (= 0.8*20). The land use for residue landfill is calculated in the same way.

The way to calculate land use for bioreactor landfill is similar to sanitary landfill. Beside that the life time of bioreactor landfill is 10 year. Therefore, in the calculation of bioreactor landfill, this recovery of land was taken into account. So that, over 20 year's period, a bioreactor landfill required less land than a sanitary landfill. For example, for a capacity of 100,000 ton/year, the sanitary landfill needs 16 ha while the bioreactor needs only 12 ha.

Table A.3.6a presents the land requirement of the 6 process-oriented technologies and table A.3.6b presents the land requirement of sanitary landfill, bioreactor landfill and residue landfill.

Table A.3.6a Land use of the process- oriented technologies.

Plants	Capacity	Land need to set up the	Land need in the case
Aerated static pile composting	100,000	5.0	11.4
	200,000	10.0	22.9
	300,000	15.0	34.3
	400,000	20.0	45.8
	500,000	25.0	57.2
In-vessel composting	100,000	3.3	7.6
	200,000	6.7	15.3
	300,000	10.0	22.9
	400,000	13.3	30.5
	500,000	16.7	38.2
Batch anaerobic digestion	100,000	2.3	5.2
	200,000	4.6	10.5
	300,000	6.8	15.7
	400,000	9.1	20.9
	500,000	11.4	26.1
Continuous anaerobic digestion	100,000	1.3	3.1
	200,000	2.7	6.1
	300,000	4.0	9.2
	400,000	5.3	12.2
	500,000	6.7	15.3
Incineration with energy recovery	200,000	1.8	4.0
	300,000	2.6	6.0
	400,000	3.5	8.0
	500,000	4.4	10.0
	600,000	5.3	12.1
Incineration without energy recovery	200,000	1.4	3.2
	300,000	2.1	4.8
	400,000	2.8	6.4
	500,000	3.5	8.0
	600,000	4.2	9.6

Table A.3.6b Land use of sanitary landfill, bioreactor landfill and residue landfill in 20 years planning.

Plants	Capacity	Land use in 1 year	Total land use at the end
Sanitary landfill	100,000	0.8	16.5
	300,000	2.5	49.4
	500,000	4.1	82.3
	800,000	6.6	131.7
	1,100,000	9.1	181.1
Bioreactor landfill	100,000	0.7	12.0
	300,000	2.1	42.9
	500,000	3.6	71.6
	800,000	5.7	114.5
	1,100,000	7.9	157.5
Residue landfill	100,000	1.0	19.8
	300,000	3.0	59.3
	500,000	4.9	98.8
	800,000	7.9	158.0
	1,100,000	10.9	217.3

<u>Appendix 4:</u> Results of the model

A.4.1 Distribution of MSW from 24 districts to 2 treatment zones and to treatment plants or landfill.

The calculated amount of MSW of each district that is transported to the 2 treatment zones for the 5 strategies of the minimization net cost model are given in table A.4.1.

Table A.4.1 Distribution the amount MSW (ton/year) from 24 districts to 2 treatment zones of 3 options of the 5 strategies. Total annual average amount of MSW that has to be treated is 3.6 million ton/year.

Districts	**Amount**	**Strategy 1**					
		Option 1		**Option 2**		**Option 3**	
		Zone 1	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**
1	170,936	0	170,936	0	170,936	0	170,936
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	0	112,707	75,672	37,035	0	112,707
4	144,667	0	144,667	0	144,667	0	144,667
5	190,286	0	190,286	0	190,286	0	190,286
6	278,316	0	278,316	0	278,316	0	278,316
7	125,473	0	125,473	0	125,473	0	125,473
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	175,887	0	175,887
11	102,693	102,693	0	102,693	0	102,693	0
12	140,237	140,237	0	140,237	0	140,237	0
T. Binh	303,895	303,895	0	303,895	0	303,895	0
Tan Phu	185,773	185,773	0	185,773	0	185,773	0
B. Tan	101,968	0	101,968	101,968	0	101,968	0
P.Nhuan	174,683	122,457	52,226	174,683	0	174,683	0
Go vap	187,285	0	187,285	187,285	0	65,806	121,479
T. Duc	230,655	0	230,655	0	230,655	0	230,655
H. Mon	143,965	143,965	0	143,965	0	143,965	0
B.Thanh	235,776	0	235,776	0	235,776	0	235,776
Nha Be	20,296	0	20,296	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	0	82,849	82,849	0	0	82,849
Cu Chi	70,740	70,740	0	70,740	0	70,740	0

Table A.4.1 Distribution the amount MSW (ton/year) from 24 districts to 2 treatment zones of 3 options of the 5 strategies. Total annual average amount of MSW that has to be treated is 3.6 million ton/year. (continuous)

Districts	Amount	Strategy 2					
		Option 1		Option 2		Option 3	
		Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
1	170,936	0	170,936	0	170,936	0	170,936
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	0	112,707	0	112,707	0	112,707
4	144,667	0	144,667	0	144,667	0	144,667
5	190,286	0	190,286	0	190,286	0	190,286
6	278,316	0	278,316	0	278,316	0	278,316
7	125,473	0	125,473	0	125,473	0	125,473
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	175,887	0	175,887
11	102,693	0	77,543	25,149	77,543	102,693	0
12	140,237	140,237	0	140,237	0	140,237	0
T. Binh	303,895	303,895	0	303,895	0	303,895	0
Tan Phu	185,773	185,773	0	185,773	0	185,773	0
B. Tan	101,968	0	101,968	0	101,968	101,968	0
P.Nhuan	174,683	0	174,683	0	174,683	174,683	0
Go vap	187,285	0	187,285	0	187,285	187,285	0
T. Duc	230,655	0	230,655	0	230,655	230,655	0
H. Mon	143,965	143,965	0	143,965	0	143,965	0
B.Thanh	235,776	0	235,776	0	235,776	0	235,776
Nha Be	20,296	0	20,296	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	0	82,849	0	82,849	58,521	24,328
Cu Chi	70,740	70,740	0	70,740	0	70,740	0
Districts	**Amount**	**Strategy 3**					
		Option 1		**Option 2**		**Option 3**	
		Zone 1	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**
1	170,936	0	170,936	0	170,936	0	170,936
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	112,707		112,707		112,707	
4	144,667	0	144,667		144,667		144,667
5	190,286	0	190,286		190,286		190,286
6	278,316	132,310	146,005	132,310	146,005	232,310	46,005
7	125,473	0	125,473	0	125,473	0	125,473
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	10,840	0	175,887
11	102,693	102,693	0	102,693	0	102,693	0
12	140,237	140,237	0	140,237	0	140,237	0
T. Binh	303,895	303,895	0	303,895	0	303,895	0
Tan Phu	185,773	185,773	0	185,773	0	185,773	0
B. Tan	101,968	101,968	0	101,968	0	101,968	0
P.Nhuan	174,683	174,683	0	174,683	0	174,683	0
Go vap	187,285	187,285	0	187,285	0	187,285	0
T. Duc	230,655	230,655	0	230,655	0	230,655	0
H. Mon	143,965	0	0	143,965	0	143,965	0
B.Thanh	235,776	0	235,776	0	235,776	0	235,776
Nha Be	20,296	0	20,296	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	82,849	0	82,849	0	82,849	0
Cu Chi	70,740	70,740	0	70,740	0	70,740	0

Table A.4.1 Distribution the amount MSW (ton/year) from 24 districts to 2 treatment zones of 3 options of the 5 strategies. Total annual average amount of MSW that has to be treated is 3.6 million ton/year. (continuous)

Districts	Amount	Strategy 4					
		Option 1		Option 2		Option 3	
		Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
1	170,936	0	170,936	0	170,936	0	170,936
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	0	112,707	112,707	0	0	112,707
4	144,667	0	144,667	0	144,667	0	144,667
5	190,286	0	190,286	0	190,286	0	190,286
6	278,316	0	278,316	232,310	46,005	0	278,316
7	125,473	0	125,473	0	125,473	0	125,473
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	175,887	0	175,887
11	102,693	102,693	0	102,693	0	102,693	0
12	140,237	140,237	0	140,237	0	140,237	0
T. Binh	303,895	303,895	0	303,895	0	303,895	0
Tan Phu	185,773	185,773	0	185,773	0	185,773	0
B. Tan	101,968	0	101,968	101,968	0	0	101,968
P.Nhuan	174,683	22,457	152,226	174,683	0	52,698	121,985
Go vap	187,285	0	187,285	187,285	0	0	187,285
T. Duc	230,655	0	230,655	230,655	0	0	230,655
H. Mon	143,965	143,965	0	143,965	0	143,965	0
B.Thanh	235,776	0	235,776	0	235,776	0	235,776
Nha Be	20,296	0	20,296	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	0	0	82,849	0	0	82,849
Cu Chi	70,740	70,740	0	70,740	0	70,740	0
Districts	Amount	Strategy 5					
		Option 1		Option 2		Option 3	
		Zone 1	Zone 2	Zone 1	Zone 2	Zone 1	Zone 2
1	170,936	0	170,936	0	170,936	0	170,936
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	0	112,707	0	112,707	0	112,707
4	144,667	0	144,667	0	144,667	0	144,667
5	190,286	0	190,286	0	190,286	0	190,286
6	278,316	0	278,316	0	278,316	0	278,316
7	125,473	0	125,473	0	125,473	0	125,473
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	175,887	0	175,887
11	102,693	102,693	0	102,693	0	0	102,693
12	140,237	140,237	0	140,237	0	81,400	58,837
T. Binh	303,895	303,895	0	303,895	0	303,895	0
Tan Phu	185,773	185,773	0	185,773	0	0	185,773
B. Tan	101,968	0	303,895	0	303,895	0	101,968
P.Nhuan	174,683	122,457	52,226	152,698	21,985	0	174,683
Go vap	187,285	0	187,285	0	187,285	0	187,285
T. Duc	230,655	0	230,655	0	230,655	0	230,655
H. Mon	143,965	143,965	0	143,965	0	143,965	0
B.Thanh	235,776	0	235,776	0	235,776	0	235,776
Nha Be	20,296	0	20,296	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	0	82,849	0	82,849	0	82,849
Cu Chi	70,740	70,740	0	70,740	0	70,740	0

The calculated amount of MSW of each district that is transported to the 2 treatment zones for the 6 options of the maximization of energy production model are given in table A.4.2.

Table A.4.2 Transport of the amount MSW (ton/year) from 24 districts to 2 treatment zones of 6 options E_1,E_2, E_3, E_4, E_5,E_6 ,

		Option E_1		Option E_2		Option E_3	
Districts	**Amount**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**
1	170,936	19,582	151,354	0	170,936	0	170,936
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	0	112,707	0	112,707	0	112,707
4	144,667	56,090	88,576	0	144,667	0	144,667
5	190,286	0	190,286	0	190,286	0	190,286
6	278,316	0	278,316	0	278,316	0	278,316
7	125,473	0	125,473	0	125,473	44,352	81,120
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	175,887	0	175,887
11	102,693	102,693	0	102,693	0	0	102,693
12	140,237	140,237	0	140,237	0	140,237	0
T. Binh	303,895	303,895	0	303,895	0	303,895	0
Tan Phu	185,773	185,773	0	185,773	0	66,570	119,203
B. Tan	101,968	101,968	0	101,968	0	0	101,968
P.Nhuan	174,683	174,683	0	174,683	0	0	174,683
Go vap	187,285	187,285	0	165,278	22,007	0	187,285
T. Duc	230,655	0	230,655	0	230,655	0	230,655
H. Mon	143,965	143,965	0	143,965	0	143,965	0
B.Thanh	235,776	235,776	0	0	235,776	0	235,776
Nha Be	20,296	20,296	0	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	82,849	0	0	82,849	0	82,849
Cu Chi	70,740	70,740	0	70,740	0	70,740	0
		Option E_4		**Option E_5**		**Option E_6**	
Districts	**Amount**	**Zone 1**	**Zone 2**	**Zone 1**			**Zone 1**
1	170,936	0	170,936	0	170,936	170,936	0
2	135,014	0	135,014	0	135,014	0	135,014
3	112,707	112,707	0	0	112,707	0	112,707
4	144,667	0	144,667	0	144,667	0	144,667
5	190,286	0	190,286	0	190,286	0	190,286
6	278,316	0	278,316	0	278,316	0	278,316
7	125,473	0	125,473	0	125,473	0	125,473
8	118,900	0	118,900	0	118,900	0	118,900
9	136,760	0	136,760	0	136,760	0	136,760
10	175,887	0	175,887	0	175,887	0	175,887
11	102,693	102,693	0	0	102,693	0	102,693
12	140,237	140,237	0	140,237	0	0	140,237
T. Binh	303,895	286,161	17,734	303,895	0	131,438	172,457
Tan Phu	185,773	185,773	0	0	185,773	0	185,773
B. Tan	101,968	101,968	0	0	101,968	101,968	0
P.Nhuan	174,683	174,683	0	174,683	0	0	174,683
Go vap	187,285	187,285	0	0	187,285	0	187,285
T. Duc	230,655	210,940	19,715	0	230,655	0	230,655
H. Mon	143,965	143,965	0	143,965	0	143,965	0
B.Thanh	235,776	0	235,776	0	235,776	0	235,776
Nha Be	20,296	0	20,296	0	20,296	0	20,296
Can Gio	0	0	0	0	0	0	0
B.Chanh	82,849	82,849	0	0	82,849	0	82,849
Cu Chi	70,740	70,740	0	70,740	0	51,694	19,046

A.4.2 Optimal treatment technologies, location and its capacity

The results of model in table A.4.3 show the treatment technologies and its capacity for the 3 options of each strategy, in the case of the average amount of MSW input to the model is 3.6 million ton/year and takes into account the additional constraints for each strategy.

Table A.4.3 Selected MSW treatment plants and its capacity in each treatment zones for 3 options of each strategy.

Options	Strategy 1	
	Treatment zone 1	**Treatment zone 2**
1	o Bioreactor landfill (31%): 1,100,000 ton/year x 1plant	o Batch anaerobic digestion (8%): 300,000 ton/year x 1 plant o Bioreactor landfill (61%): 1,100,000 ton/year x 2 plant o Residue landfill: 100,000 ton/year x 1 plant
2	o Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant o Bioreactor landfill (30%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 2 plant	o Batch anaerobic digestion (56%): 500,000 ton/year x 4 plant o Residue landfill: 500,000 ton/year x 1 plant
3	o Batch anaerobic digestion (33%): 500,000 ton/year x 2 plant 200,000 ton/year x 1 plant o Sanitary landfill (3%): 100,000 ton/year x 1 plant o Residue landfill: 300,000 ton/year x 1 plant	o AD continues (14%): 500,000 ton/year x 1 plant o Incineration with energy recovery (50%): 600,000 ton/year x 3 plant o Residue landfill: 300,000 ton/year x 1 plant
Options	**Strategy 2**	
	Treatment zone 1	**Treatment zone 2**
1	o Batch anaerobic digestion (25%): 400,000 ton/year x 1plant 500,000 ton/year x 1plant o Residue landfill: 300,000 ton/year x 1 plant	o Batch anaerobic digestion (42%): 500,000 ton/year x 3 plant o Incineration with energy recovery (33%): 600,000 ton/year x 2 plant o Residue landfill: 500,000 ton/year x 1 plant
2	o Batch anaerobic digestion (25%): 400,000 ton/year x 1plant 500,000 ton/year x 1plant o Residue landfill: 300,000 ton/year x 1 plant	o Batch anaerobic digestion (42%): 500,000 ton/year x 3 plant o Incineration with energy recovery (33%): 600,000 ton/year x 2 plant o Residue landfill: 500,000 ton/year x 1 plant
3	o Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant o AD continues (28%): 500,000 ton/year x 2 plant o Residue landfill: 300,000 ton/year x 1 plant 100,000 ton/year x 1 plant	o Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant o Incineration with energy recovery (44%): 600,000 ton/year x 2 plant 400,000 ton/year x 1 plant o Residue landfill: 300,000 ton/year x 1 plant

Table A.4.3 Selected MSW treatment plants and its capacity in each treatment zones for 3 options of each strategy (continuous).

Options	Strategy 3	
	Treatment zone 1	**Treatment zone 2**
1	o Batch anaerobic digestion (56%): 500,000 ton/year x 4 plant o Residue landfill: 500,000 ton/year x 1plant	o Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant o Bioreactor landfill (30%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 2 plant
2	o Batch anaerobic digestion (56%): 500,000 ton/year x 4 plant o Residue landfill: 500,000 ton/year x 1plant	o Batch anaerobic digestion (14%): 500,000 ton/year x 1 plant o Bioreactor landfill (30%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 2 plant
3	o Batch anaerobic digestion (11%): 400,000 ton/year x 1 plant o AD continues (14%): 500,000 ton/year x 1 plant o Incineration, energy recovery (33%): 600,000 ton/year x 2 plant o Residue landfill: 300,000 ton/year x 1 plant 100,000 ton/year x 1 plant	o Batch anaerobic digestion (25%): 400,000 ton/year x 1 plant 500,000 ton/year x 1 plant o Incineration with energy recovery (17%): 600,000 ton/year x 1 plant o Residue landfill: 300,000 ton/year x 1 plant
Options	**Strategy 4**	
	Treatment zone 1	**Treatment zone 2**
1	o Batch anaerobic digestion (28%): 500,000 ton/year x 2 plant o Residue landfill: 300,000 ton/year x 1 plant	o Batch anaerobic digestion (10%): 400,000 ton/year x 1 plant o Bioreactor landfill (62%): 1,100,000 ton/year x 2 plant o Residue landfill: 100,000 ton/year x 1 plant
2	o Batch anaerobic digestion (28%): 500,000 ton/year x 2 plant o Bioreactor landfill (31%): 1,100,000 ton/year x 1 plant o Residue landfill: 300,000 ton/year x 1plant	o Batch anaerobic digestion (10%): 400,000 ton/year x 1 plant o Bioreactor landfill (31%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 1 plant
3	o Batch anaerobic digestion (28%): 500,000 ton/year x 2 plant o Residue landfill: 300,000 ton/year x 1 plant	o Batch anaerobic digestion (6%): 200,000 ton/year x 1 plant o Incineration with energy recovery (66%): 600,000 ton/year x 4 plant o Residue landfill: 300,000 ton/year x 1 plant

Table A.4.3 Selected MSW treatment plants and its capacity in each treatment zones for 3 options of each strategy (continuous).

<table>
<tr><th rowspan="2">Options</th><th colspan="2">Strategy 5</th></tr>
<tr><th>Treatment zone 1</th><th>Treatment zone 2</th></tr>
<tr><td>1</td><td>o Bioreactor landfill (31%):
1,100,000 ton/year x 1 plant</td><td>o Bioreactor landfill (69%):
1,100,000 ton/year x 2 plant
300,000 ton/year x 1 plant</td></tr>
<tr><td>2</td><td>o Bioreactor landfill (31%):
1,100,000 ton/year x 1 plant</td><td>o Batch anaerobic digestion (6%):
200,000 ton/year x 1 plant
o Incineration with energy recovery (33%):
600,000 ton/year x 2 plant
o Bioreactor landfill (30%):
1,100,000 ton/year x 1 plant
o Residue landfill:
100,000 ton/year x 2 plant</td></tr>
<tr><td>3</td><td>o Incineration with energy recovery (17%):
600,000 ton/year x 1 plant
o Residue landfill:
100,000 ton/year x 1 plant</td><td>o Incineration with energy recovery (83%):
600,000 ton/year x 5 plant
o Residue landfill:
300,000 ton/year x 1 plant</td></tr>
</table>

Table A.4.4 shows the selected technologies for 6 options in case of maximum energy production.

Table A.4.4 Optimal MSW treatment for 6 options.

Options	Treatment zone 1	Treatment zone 2
E_1 (Budget ≤ 50.1 million USD/year)	o Batch anaerobic digestion (11%): 400,000 ton/year x 1 plant o Bioreactor landfill (33%): 1,100,000 ton/year x 1 plant 100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 1 plant	o Batch anaerobic digestion (56%): 500,000 ton/year x 4 plants o Residue landfill: 500,000 ton/year x 1 plant
E_2 (Budget ≤ 54.4 million USD/year)	o Bioreactor landfill (39%): 1,100,000 ton/year x 1 plant 300,000 ton/year x 1 plant	o Continuous anaerobic digestion (14%): 500,000 ton/year x 1 plant o Incineration with energy recovery (17%): 600,000 ton/year x 1 plant o Bioreactor landfill (30%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 2 plants
E_3 (Budget ≤ 59.4 million USD/year)	o Bioreactor landfill (22%): 800,000 ton/year x 1plant	o Incineration with energy recovery (47%): 600,000 ton/year x 2 plants 500,000 ton/year x 1 plant o Bioreactor landfill (31%): 1,100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 2 plants
E_4 (Budget ≤ 64.3 million USD/year)	o Incineration with energy recovery (50%): 600,000 ton/year x 3 plants o Residue landfill: 100,000 ton/year x 2 plants	o Incineration with energy recovery (17%): 600,000 ton/year x 1 plant o Bioreactor landfill (33%): 1,100,000 ton/year x 1 plant 100,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 1 plant
E_5 (Budget ≤ 69.3 million USD/year)	o Incineration with energy recovery (17%): 600,000 ton/year x 1 plant o Residue landfill: 100,000 ton/year x 1 plant	o Incineration with energy recovery (83%): 600,000 ton/year x 5 plants o Residue landfill: 100,000 ton/year x 3 plants
E_6 (Budget ≤ 74.2 million USD/year)	o Incineration with energy recovery (17%): 600,000 ton/year x 1 plan o Residue landfill: 100,000 ton/year x 2 plants	o Incineration with energy recovery (83%): 600,000 ton/year x 5 plants o Residue landfill: 100,000 ton/year x 3 plants

A.4.3 Costs analysis

Table A.4.5 show the costs analysis of the three options of each strategy.

Table A.4.5 Costs analysis of the 3 options of each strategy with the total annual average amount of MSW input (3.6 million ton/year).

	Strategy 1			Strategy 2		
	Option 1	**Option 1**	**Option 2**	**Option 3**	**Option 2**	**Option 3**
Total net costs	47,384,899	54,909,412	54,909,412	62,235,316	49,464,255	61,539,552
Total net costs	13.3	15.4	15.4	17.4	13.9	17.2
Total net costs/person	5.0	5.8	5.8	6.6	5.2	6.5
Transport costs	7.2	7.1	7.1	7.5	7.6	7.3
Fixed costs	18.1	18.8	18.8	22.6	15	22.5
Operation costs	6.1	13.1	13.1	14.2	9.5	14.1
Negative costs	18.3	24.4	24.4	27.6	19	27.4
Extra operation costs	0.1	0.86	0.86	0.8	0.7	0.7
	Strategy 3			**Strategy 4**		
	Option 1	**Option 1**	**Option 2**	**Option 3**	**Option 2**	**Option 3**
Total net costs	50,904,220	47,793,299	51,226,510	62,510,435	50,904,220	63,909,910
Total net costs	14.3	13.4	14.4	17.5	14.3	17.9
Total net costs/person	5.5	5.1	5.5	6.7	5.5	6.9
Transport costs	8.0	7.1	8.1	7.1	8.0	8.1
Fixed costs	15.0	16.6	16.6	24.3	15.0	22.5
Operation costs	9.5	7.8	7.8	14.8	9.5	14.3
Negative costs	19.0	18.6	18.6	29.4	19.0	27.7
Extra operation costs	0.7	0.4	0.4	0.6	0.7	0.8
	Strategy 5					
	Option 1	**Option 2**	**Option 3**			
Total net costs	1,374,058	3,751,576	4,824,485			
Total net costs	0.4	1.1	1.4			
Total net costs/person	0.15	0.40	0.52			
Transport costs	7.2	7.2	7.1			
Fixed costs	18.9	22	29.4			
Operation costs	5.5	9.5	16.3			
Negative costs	31.1	37.9	51.9			
Extra operation costs	0	0.2	0.4			

Table A.4.6 Costs analysis of the 6 options with the aim of maximum electricity production. The average amount of MSW input is 3.6 million ton/year.

	Option E_1	Option E_2	Option E_3	Option E_4	Option E_5	Option E_6
Total budget (million USD/year)	50.0	54.4	59.4	64.3	69.3	74.2
Total net costs (USD/ton)	14	15.2	16.6	18.0	19.4	20.8
Total net costs per person (USD/person/year)	5.4	5.8	6.4	6.9	7.4	8.0
Transport costs (USD/ton)	7.6	7.4	7.1	7.8	7.1	7.62
Fixed costs (USD/ton)	15.1	21	24.2	26.1	29.9	30.7
Operation costs (USD/ton)	10.1	8.5	11	13.1	16.7	16.7
Negative costs (USD/ton)	18.8	21.6	25.8	29	34.3	34.3

A4.4 Products

Table A.4.7 show the total products of 3 options of each strategy. It shows the amount of each product is produced per year and per ton of MSW treated.

Table A.4.7 Calculated total products per year and per ton in each strategy with total annual average amount of waste input of 3.6 million ton/year.

Products	***Units***	**Strategy 1**					
		Option 1		**Option 2**		**Option 3**	
		per year	*per ton*	*per year*	*per ton*	*per year*	*per ton*
Compost	*ton*	$60*10^3$	$17*10^{-3}$	$500*10^3$	$140*10^{-3}$	$340*10^3$	$95*10^{-3}$
Biogas	*m^3*	$348*10^6$	98	$210*10^6$	59	$75*10^6$	21
Electric	*kWh*	0	0.0	0	0.0	$581*10^6$	163
Heat	*kWh*	0	0.0	0	0.0	$1,163*10^6$	326
PE	*ton*	$9.6*10^3$	$2.7*10^{-3}$	$80*10^3$	$22.4*10^{-3}$	$54*10^3$	$15*10^{-3}$
Rec. waste	*ton*	$5.4*10^3$	$1.5*10^{-3}$	$45*10^3$	$12.6*10^{-3}$	$31*10^3$	$9*10^{-3}$
Aluminum	*ton*	0	0.0	0	0.0	$1.6*10^3$	$4*10^{-2}$
Iron	*ton*	0	0.0	0	0.0	$28*10^3$	$8*10^{-3}$
Products	***Units***	**Strategy 2**					
		Option 1		**Option 2**		**Option 3**	
		per year	*per ton*	*per year*	*per ton*	*per year*	*per ton*
Compost	*ton*	$480*10^3$	$135*10^{-3}$	$480*10^3$	135.10^{-3}	$400*10^3$	$112*10^{-3}$
Biogas	*m^3*	$94*10^6$	26	$94*10^6$	26	$111*10^6$	31
Electric	*kWh*	$388*10^6$	109	$388*10^6$	109	$517*10^6$	145
Heat	*kWh*	$775*10^6$	217	$775*10^6$	217	$1,034*10^6$	290
PE	*ton*	$77*10^3$	$22*10^{-3}$	$77*10^3$	22.10^{-3}	$64*10^3$	$18*10^{-3}$
Rec. waste	*ton*	$43*10^3$	$12*10^{-3}$	$43*10^3$	12.10^{-3}	$36*10^3$	$10*10^{-3}$
Aluminum	*ton*	$1*10^3$	$3*10^{-3}$	$1*10^3$	3.10^{-4}	$1.4*10^3$	$4*10^{-4}$
Iron	*ton*	$19*10^3$	$5*10^{-3}$	$19*10^3$	5.10^{-3}	$25*10^3$	$7*10^{-3}$

Table A.4.7 Calculated total products per year and per ton in each strategy with total annual average amount of waste input of 3.6 million ton/year (continuous).

Products	Units	Strategy 3					
		Option 1		Option 2		Option 3	
		per year	*per ton*	*per year*	*per ton*	*per year*	*per ton*
Compost	*ton*	$500*10^3$	$140*10^{-3}$	$500*10^3$	$140*10^{-3}$	$360*10^3$	$101*10^{-3}$
Biogas	*m^3*	$210*10^6$	58.7	$210*10^6$	58.7	$87*10^6$	24.3
Electric	*kWh*	0	0.0	0	0.0	$581*10^6$	162.9
Heat	*kWh*	0	0.0	0	0.0	$1,163*10^6$	325.7
PE	*ton*	$80*10^3$	$22.4*10^{-3}$	$80*10^3$	$22.4*10^{-3}$	$58*10^3$	$16*10^{-3}$
Rec. waste	*ton*	$45*10^3$	$12.6*10^{-3}$	$45*10^3$	$12.6*10^{-3}$	$32*10^3$	$9*10^{-3}$
Aluminum	*ton*	0	0.0	0	0.0	$1.6*10^3$	$0.4*10^{-3}$
Iron	*ton*	0	0.0	0	0.0	$27.7*10^3$	$7.8*10^{-3}$
Products	***Units***	**Strategy 4**					
		Option 1		**Option 2**		**Option 3**	
		per year	*per ton*	*per year*	*per ton*	*per year*	*per ton*
Compost	*ton*	$280*10^3$	$78*10^{-3}$	$280*10^3$	$78*10^{-3}$	$240*10^3$	$67*10^{-3}$
Biogas	*m^3*	$279*10^6$	78	$279*10^6$	78	$46.8*10^6$	13.1
Electric	*kWh*	0	0.0	0	0.0	$755.2*10^6$	217
Heat	*kWh*	0	0.0	0	0.0	$1,550*10^6$	434
PE	*ton*	$44.8*10^3$	$12.5*10^{-3}$	$44.8*10^3$	$12.5*10^{-3}$	$38.4*10^3$	$11*10^{-3}$
Rec. waste	*ton*	$25.2*10^3$	$7.1*10^{-3}$	$25.2*10^3$	$7.1*10^{-3}$	$21.6*10^3$	$6*10^{-3}$
Aluminum	*ton*	0	0.0	0	0.0	$2.1*10^3$	$0.6*10^{-3}$
Iron	*ton*	0	0.0	0	0.0	$37*10^3$	$10*10^{-3}$
Products	***Units***	**Strategy 5**					
		Option 1		**Option 2**		**Option 3**	
		per year	*per ton*	*per year*	*per ton*	*per year*	*per ton*
Compost	*ton*	0	0.0	$40*10^3$	$11.2*10^{-3}$	0	0.0
Biogas	*m^3*	$367*10^6$	102.9	$232*10^6$	65.0	0	0.0
Electric	*kWh*	0	0.0	$388*10^6$	108.6	$1,163*10^6$	325.7
Heat	*kWh*	0	0.0	$775*10^6$	217.2	$2,326*10^6$	651.5
PE	*ton*	0	0.0	$6.4*10^3$	$1.8*10^{-3}$	0	0.0
Rec. waste	*ton*	0	0.0	$3.6*10^3$	$1.0*10^{-3}$	0	0.0
Aluminum	*ton*	0	0.0	$1.1*10^3$	$0.3*10^{-3}$	$3.2*10^3$	$0.9*10^{-3}$
Iron	*ton*	0	0.0	$18.5*10^3$	$5.2*10^{-3}$	$55.4*10^6$	$15.5*10^{-3}$

Note: The heat product from Incineration process is used for drying MSW not for sale. Biogas from biological process can be converted into electricity and heat. The heat from biogas can be sold.

Appendix 5. Application of SURMAT in case of strongly increasing annual amount of MSW - An example of an investment planning

Under standard conditions of HCMC (S_1O_2), SURMAT has selected the technologies to treat the average amount of MSW of 3.6 million ton MSW/year. These technologies are batch anaerobic digestion (total capacity of 2,500,000 ton/year) and bioreactor landfill (total capacity of 1,100,000 ton/year). At the end of 2032, the estimated amount of MSW will be 8,173,000 ton/year which is 2.29 times higher than the average. In the calculations with SURMAT with a constant average amount of waste over 20 years this factor has already been incorporated. We now assume that the treatment capacity ratio of the required technologies in 2032 is similar to the ratio proposed for the average amount of MSW, and that the same technologies are used. Then the capacity of each technology in 2032 will be batch anaerobic digestion technology for treating 5,725,000 ton/year (= 2,500,000 x 2.29) and bioreactor landfill for treating 2,519,000 ton/year (=1,100,000 x 2.29). Taking into account the defined scales of technology, we assume that in 2032 the technologies will be batch anaerobic digestion technology for treating 6,000,000 ton/year and bioreactor landfill for treating 2,200,000 ton/year. Based on these capacities, on the selection of the mix of technologies and the amount of MSW per year (ton/year) we can make a capacity plan for each period of five years as is given in table A. 5.1.

Table A.5.1 Proposed capacity plan (from 2012 – 2032) for four five-year periods.

Year of investment	2013- 2017	2017- 2022	2022- 2027	2027- 2032
Amount to be treated (ton/year)	1,762,000	3,000,000	4,500,000	8,173,000
Investment in Treatment zone 1	o 1 Bioreactor landfill (in 2013): Capacity: 1x1,100,000 ton/year	o 1 Bioreactor landfill (in 2021): Capacity 1x1,100,000 ton/year	o No investment	o 1 AD batch (in 2031): Capacity; 1x500,000 ton/year o 1 Residue landfill: Capacity: 250,000 ton/year.
Investment in Treatment zone 2	o 2 AD batch plants (in 2015 and 2017): Capacity: 2x500,000 ton/year o 1 Residue landfill(in 2015 and 2017): Capacity: 125,000 and 250,000 ton/year.	o 1AD batch plants (in 2019): Capacity: 1x500,000 ton/year o 1 Residue landfill(in 2019): Capacity: 375,000 ton/year	o 2 AD batch plant (in 2025 and 2027): Capacity: 2x500,000 ton/year o 1 Residue landfill(in 2025 and 2027): Capacity: 500,000 and 625,000 ton/year	o 6 AD batch (1 in 2028, 4 in 2030 and 1 in 2031): Capacity: 6x 500,000 ton/year o 1 Residue landfill(in 2028, 2030 and 2031): Capacity: 750,000, 1,250,000 and 1,375,000ton/year.

Note:

- *The year of having a plant available between parentheses.*
- *Bioreactor landfill receives every year the same amount of waste.*
- *The capacities of residue landfill are related to the capacities of the batch anaerobic digestion plants.*

Based on this overview of the required treatment capacity plan for the four five-year periods we can elaborate a more detailed investment scheme. This more detailed scheme is given below.

<u>*Period 2013-2017.*</u>

- The total amount of waste to be treated in the years 2013 until 2017 increases from about 1 to 1.8 million ton MSW/year (table A.3.1 in appendix 3);
- With respect to 1 million ton MSW to be treated in 2013 and considering the results of the technology selection with SURMAT for the standard situation S_1O_2, one bioreactor landfill with a capacity of 1.1 million ton/year in treatment zone 1 should be built. The construction should be completed at the end of 2012. This investment is sufficient to treat the MSW in the years 2013 and 2014;
- In 2015 a second treatment plant should be made available to treat 1.3 million ton MSW/year. Therefore, a batch anaerobic digestion plant with a capacity of 500,000 ton/year should be installed at the end of 2014 at treatment zone 2. Because bioreactor landfill is a flexible technology in terms of capacity, it is possible to treat the extra amount of MSW (in 2015 about 200,000 ton/year more than in 2014) in the existing bioreactor landfill. Its capacity would rise

from 1.1 to 1.3 million ton/year. In this case, the investment in a batch anaerobic digestion plant can be postponed to have the plant ready for the year 2016.
- In order to treat 1.8 million ton MSW/year in 2017, another batch anaerobic digestion plant with a capacity of 500,000 ton/year will be built in treatment zone 2. Or similar to the previous paragraph, the extra amount of 200,000 ton/year could be treated in the bioreactor landfill. In that case, the investment in batch anaerobic digestion would be moved to 2018;
- Beside the investment in batch anaerobic digestion, a residue landfill should be made available to dispose the residue from the separation process of anaerobic digestion technology. Residue landfill is more flexible in terms of capacity compared to batch anaerobic digestion. Therefore, the capacity of the residue landfill will have to be adapted to the capacity of the batch anaerobic digestion plant.

Periods 2018-2022, 2023-2027 and 2028-2032

For these next three periods a similar procedure was developed as follows:
- The amount of MSW to be treated per year is estimated;
- Based on the results of SURMAT in the case of the standard situation S_1O_2 and based on the investment activities of the previous periods additional investments for the next five-year periods could be executed until the end of the entire planning period (2032);
- Based on the existing plants from the previous periods and the new investment it is possible to calculate the capacity needed for residue landfills and to propose the investments in them.

Based on the capacity plan proposed above the land requirements were calculated and are shown in table A.5.2. The total land requirements for treatment zone 1 and 2 are 267 and 227 ha, respectively. These data fit the planned areas of the two treatment zones (276 and 233 ha, respectively).

The proposal elaborated above regarding the investment procedure for MSW treatment technologies at increasing amount of MSW to be treated is partly arbitrary. The decision makers can chose the length of the investment intervals. More fine-tuning is possible. However, if we keep the assumption that the most appropriate technologies in this case are batch anaerobic digestion and bioreactor landfill and assuming the same ratio of the treatment capacity of these technologies applied over the entire 20-year period then the results are more or less the same.

The procedure elaborated above deals with the investment in capacity only. The net costs of bioreactor landfill are lower compared to batch anaerobic digestion. Therefore, to minimize total net costs, bioreactor landfill would be the first choice. However, the choice also depends on the land availability. As bioreactor landfill needs more land compared to batch anaerobic digestion, a trade-off between land use and costs has to be made.

Minimization of the costs means that all installed treatment capacities of the process-oriented treatment technologies composting, anaerobic digestion and incineration, will be in operation for a period of 20 years. All these process-oriented treatment technologies produce residues that have to be disposed in a residue landfill. To that aim a new site has to be opened. Since the last extension of treatment plants proposed in table A.5.2 takes place in 2030, and treatment plants have to work for 20 years to reach their assumed design life time, this new site should be in operation at least until 2050.

Table A.5.2 Land requirement for the investment plan proposed in table A.5.1.

Treatment zone 1				
Year of investment	Technologies	Land requirement for installing the technology for AD batch or for running the technology in case of bioreactor landfill	Land requirement for disposal of residue in residue landfill	Total land use until the end of 2032
2013	1 Bioreactor landfill	7.9[55] ha/year x 20 years	0.0	158
2021	1 Bioreactor landfill	7.9 ha/year x 12 years	0.0	94.8
2031	1 AD batch	11.4[56] ha/plant	1.25[57] ha/year/plant x 2 years	13.9
Total land requirement in Treatment zone 1				**267**
Treatment zone 2				
Year of investment	Technologies	Land requirement for installing the technology for AD batch	Land requirement for disposal of residue in residue landfill	Total land use until the end of 2032
2015	1 AD batch	11.4	1.25ha/year/plant x 18 year x 1 plant	33.9
2017	1 AD batch	11.4	1.25ha/year/plant x 16 year x 1 plant	31.4
2019	1 AD batch	11.4	1.25ha/year/plant x 14 year x 1 plant	28.9
2025	1 AD batch	11.4	1.25ha/year/plant x 8 year x 1 plant	21.4
2027	1 AD batch	11.4	1.25ha/year/plant x 6 year x 1 plant	18.9
2028	1 AD batch	11.4	1.25ha/year/plant x 5 year x 1 plant	17.7
2030	4 AD batch	45.6	1.25ha/year/plant x 3 year x 4 plants	60.6
2031	1 AD batch	11.4	1.25 ha/year/plant x 2 years	13.9
Total land requirement in Treatment zone 2				**227**

[55] 7.9 ha is the land use for bioreactor landfill with a capacity of 1.1 million ton MSW /year.
[56] 11.4 ha is the land use for batch anaerobic digestion plant with a capacity of 500,000 ton MSW/year.
[57] 1.25 ha is the land use for disposal residue from AD batch with capacity of 500,000 ton/year.