Sustainable Municipal Solid Waste Management Systems for Small and Medium Sized Cities in Thailand

by

Rotchana Intharathirat

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Examination Committee:	Dr. P. Abdul Salam (Chairperson) Prof. Sivanappan Kumar Dr. Shobhakar Dhakal Prof. Athapol Noomhorm
External Examiner:	Prof. Kurian Joseph Centre for Environmental Studies Anna University, Chennai India
Nationality:	Thai
Previous Degree:	Master of Engineering in Environmental Engineering Khon Kean University Thailand
Scholarship Donor:	HM King HRD Project-AIT Fellowship

Asian Institute of Technology
School of Environment, Resources and Development
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Abstract

Municipal solid waste management (MSWM) has become a crucial issue worldwide, not only because of the increase of waste generation, but also due to its improper disposal. Improper management of MSW, typically through landfills and open dumping, has caused serious environmental impacts. To evaluate the most appropriate MSWM system, several models have been developed to support a decision making process. These models were mostly practiced for large cities, while only a few were found for medium and small cities. There is no single optimal MSWM system that can be applied to both large and small cities since they have different characteristics. It is, therefore, vital to evaluate the most suitable MSWM system for medium and small cities, as decisions made at an early stage can have significant impacts to MSWM in later phases as cities grow. Selecting the most effective MSWM requires consideration of various parameters. For instance, it is complicated for developing countries, such as Thailand, due to the lack of reliable data, including the status of MSWM, characteristics of technologies used and applied, and present and future MSW generation and composition.

Firstly, this study aims to assess the status of MSWM systems in Thailand to clarify existing decision making processes and to propose appropriate alternatives. The implementation of waste-to-energy (WTE) and other treatment systems invested and operated by the private sector were also comprehensively assessed. Due to the lack of data on MSW treatment systems in medium and small cities, this assessment was carried out at the country level and was used to represent alternative treatment systems for medium and small cities. Secondly, this study attempts to fill a gap where traditional forecasting models of MSW quantity (i.e., regression analysis, time-series analysis, and econometric models) are challenging to implement given their data requirements. The innovative models, grey models (GM), are developed by using limited data and consider influencing factors to achieve greatest accuracy. In most developing countries, it is difficult to collect reliable data on MSW quantities in large, medium and small cities. Therefore, this study utilized time-series data of MSW collected countrywide for developing alternative models. Despite sources of MSW generation identified in various sectors (residential, commercial, institution, and municipal services), a few studies investigated factors affecting MSW generated from only two sectors (residential and commercial). Hence, this study considers these factors in developing MSW forecasting models to address the lack of data. Thirdly, based on the outcomes obtained above, the MSWM systems for medium and small cities were evaluated involving relevant participatory stakeholders. Given the lack of data, this study focuses on front-end and end-pipe treatment systems, excluding separation at source and collection systems. Group meetings or workshops were not conducted in this study due to the unavailability of stakeholders at the top of each organization

The assessment of MSWM systems was carried out based on a review of available literature, interviews, and site visits focusing on existing general MSW management systems and WTE treatment systems, including consideration of pre-treatment, treatment and disposal systems. This study assessed the details of WTE systems: anaerobic digestion (AD), incineration (IC), gasification (GF), landfill gas (LFG) and refuse derived fuel (MBT-RDF). Results show that the current annual amount of MSW generated treated is 2.54 Mt (9.5% of total 26.8 Mt generated in 2013), which generates 66 MW of electricity, as well as 78.26 ktoe of heat. It is estimated that about 8.17 Mt of MSW (30.5%) will be treated, 319 MW of electricity generated, as well as 78.26 ktoe of heat, when the plants presently under construction and planning start operation. Eight systems consisting of three general MSWM systems

(composting (MBT-CP), recycling (MT-Re) and landfill (LF)) and five WTE treatment systems (AD, IC, GF, MT-RDF and LFG) were proposed as MSWM alternatives for further decision making process.

A methodological framework for MSW forecasting was developed considering traditional and innovative grey models. The forecasting framework could be distinguished as having four main steps: i) identifying and selecting influencing factors, ii) developing alternative models, iii) verifying models, and iv) forecasting the amount of MSW quantity at country level with prediction intervals. Fifteen models were developed by using time series data from 2000 to 2012. Results show that GM with convolution integral, GMC (1, 5), is the best fit model and used to forecast MSW collected with the least error of 1.16% MAPE. This model indicates that the amount of MSW collected would increase by 1.40% per year, which is in the range from 43,435–44,994 t/d in 2013 to 47,735–49,293 t/d in 2020, and 55,177–56,735 t/d in 2030. The increase of MSW collected may reflect representative factors of the commercial sector (population density, urbanization and proportion employment) rather than that of the residential sector (household size). It was also observed that demographic factors are more important than socio-economic factors.

The evaluation of MSWM systems was conducted by using the Analytical Hierarchy Process (AHP) method through assigning weights in pair-wise comparison matrices by 11 stakeholders from five groups of organization such as governmental, academic, technical, local authority and NGOs. This study identified four main criteria (environmental, social, economic and technical), and 12 sub-criteria (diversion from landfill, GHG emissions, environmental impacts, capital cost, O&M cost, revenue & benefit, public acceptance, creation of jobs, simplicity, maturity, and local equipment) to be simultaneously considered for selecting the most suitable MSWM systems among eight alternatives mentioned above. Results indicate that stakeholders preferenced the environmental aspect as being the most important, followed by social consideration, whereas economic and technical aspects were considered equal for both medium and small cities. It can be concluded that in the context of Thailand, stakeholders focus more on strong sustainability. The preferences of stakeholders on sub-criteria show that public acceptance is the most important, followed by environmental impacts and diversion from landfill. As per this study, the most suitable MSWM system is the mechanical biological treatment combined with composting (MBT-CP) for medium city and mechanical treatment combined with RDF (MT-RDF) for small city, while both landfilling and landfill gas were identified as the worst options. Stakeholders prefer the waste-to-resource (WTR) scheme than waste-to-energy (WTE) to achieve sustainable MSW management in Thailand.

This study presents a systematic methodology for MSW forecasting that addresses the limited availability of data in a developing country. It also offers wider application and encouragement to researchers in other developing countries and fields of study. The evaluation of MSWM systems that engage relevant stakeholders and thus reflect their preferences, can assist decision makers and local authorities in tackling the issue of MSWM in other regions of the study area.

Keywords: municipal solid waste management, sustainability, MSW Forecasting, Analytic Hierarchy Process, Thailand

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List of Abbreviations

AD	Anaerobic digestion
AdCONEXP	The adjusted value of consumption expenditure
AEDP	Alternative Energy Development Plan
AGO	Accumulated generating operation
AHP	Analytical Hierarchy Process
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
ANP	Analytical Network Process
ANOVA	Analysis of Variance
ARIMA	Autoregressive Integrated Moving Average
ASR	Automotive Shredder Residue
ASTM	American Standards for Testing of Materials
BFB	Bubbling fluidized bed
BMA	Bangkok Metropolitan Administration
BOCR	Benefits Opportunities Costs and Risks
BOE	Bureau of Epidemiology
BOI	Thailand's Board of Investment
BORA	Bureau of Registration Administration
BOT	Bank of Thailand
CA	Correlation analysis
CAM	Consensus Analysis Model
CBA	Cost benefit analysis
CCGT	Combined cycle gas turbine
CDM	Clean Development Mechanism
CERs	Certified Emission Reduction
CFB	Circulating Fluidized Bed
CH_4	Methane
CI	Consistency index
CNG	Compressed natural gas
C/N	Carbon/nitrogen ratio
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CP	Composting
COP21	21th Conference of Parties (COP), also known as Paris Climate Conference
CPI	Consumer Price Index
CR	Consistency ratio
CTA	Cluster Analysis
DASTA	Designated Areas for Sustainable Tourism Administration (Public Organization)
DEDE	Department of Alternative Energy Development and Efficiency
DDS	Decision Support System
DMT	Decision making tool
EC	Economic criteria
ECNEQ	Enhancement and Conservation of National Environmental Quality Plan
EfW	Energy from waste
EGAT	Electricity Generating Authority of Thailand
EKC	Environmental Kuznets Curve Hypothesis

List of Abbreviations (Cont'd)

ELECTRE	Elimination Et Choix Traduisant la Realité
EMPLOY	Proportion employment
EQM	Environmental Quality Management Plan
EV	Environmental criteria
ERC	Energy Regulatory Commission
FA	Factor analysis
FGLS	Feasible General Least Square
FiT	Feed-in-Tariff
GDP	Gross Domestic Product
GF	Gasification
GFM	Grey fuzzy dynamic model
Gg/year	Gigagrams per year
GHG	Greenhouse gas
GIM	Grey index model
GIS	Geographical information system
GLPM	Grey logarithm power model
GM	Grey model
GMC	Grey model with convolution integral
GMM	Geometric mean method
GPPM	Grey parabola power model
GRA	Grey relational analysis
GRNN	General regression neural network
GW	Global weight
HCl	Hydrogen Chloride
HHSIZE	Household size
I-AGO	1th derivative of accumulated generating operation
IC	Incineration
IPCC	Intergovernmental Panel on Climate Change
ISWM	Integrated Solid Waste Management System
ktoe	Kilotonne of oil equivalent
kWh	Kilowatt hour
LAOs	Local authority organizations
LCA	Life cycle assessment
LCS	Low Carbon Society
LES	Linear Expenditure System
LF	Landfill
LFG	Landfill gas
LHV	Lower heating value
LPG	Liquid petroleum gas
MAPE	Mean Absolute Percentage Error
MBT	Mechanical Biological Treatment
MBT-CP	Mechanical biological treatment integrated with composting
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
MDGs	Millennium Development Goals
ME	Mass and Energy balance
MEA	Metropolitan Electricity Authority
MFA	Material Flow Analysis

List of Abbreviations (Cont'd)

MJ/kg	Megajoules per kilogram
MJ/m^3	Megajoules per cubic meter
MNL	Multinomial Logit
MoNRE	Ministry of Natural Resources and Environment
MRA	Multiple regression analysis
MRF	Materials recovery facility
MSW	Municipal solid waste
MSWM	Municipal solid waste management
Mt	Million tonnes
MT	Mechanical Treatment
MT-RDF	Mechanical treatment system- Refuse Derived Fuel
MT-Re	Mechanical treatment system used for sorting recyclable materials
MW	Megawatt
NESDB	Office of the National Economic and Social Development Board
NGOs	Non-governmental organization
NO_x	Nitrogen oxide
NSO	National Statistical Office
OAT	One-at-a-time
OECD	Organization for Economic Co-operation and Development
OLS	Ordinary least square method
O&M	Operational and maintenance
PC	Pair-wise comparison
PCA	Principal Component Analysis
PCD	Pollution Control Department
PDP	Power Development Plan
PEA	Provincial Electricity Authority
PI	Prediction intervals
PJT	PJT Company
PLS-SVM	Hybrid Partial Least Square and Support Vector Machine
POPDEN	Population density
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
r	Pearson correlation coefficient
R^2	Coefficient of determination
RA	Regression analysis
RDF	Refuse Derived Fuel
Re	Recycling
RE	Renewable energy
REDP	Renewable Energy Development Plan
RI	Random index
SA	Sensitivity analysis
SAO	Sub-district Administrative Organization
SARIMA	Seasonal Autoregressive Integrated Moving Average
SAT	Sustainability Assessment of Technologies
SAW	Simple Additive Weight
SC	Social criteria
SCCC	Siam City Cement Public Company
SCG	Siam Cement Group Company
SEM	Spatial error model

List of Abbreviations (Cont'd)

SES	Seasonal exponential smoothing
SESY	Simultaneous Equation System
SO_x	Sulfur oxide
SRA	Single regression analysis
SRF	Solid recovered fuel
SVM	Support Vector Machine
SWOT	Strength, Weakness, Opportunity and Threats
TAS	Technology Assessment
tCO_2eq	Tonnes of carbon dioxide equivalent
TGO	Thailand Greenhouse Gas Management Organization (Public Organization)
TN	Technical criteria
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPI	TPI Polene Company
TSA	Time series analysis
TWh	Terawatt-hour
t/d	Tonne per day
UK	United Kingdom
US	United States
USA	United States of America
USD	United States Dollar
URBAN	Urbanization
VSPP	Very small power producer
WAMM	Weighted arithmetic mean method
WTE	Waste-to-Energy
WEEE	Waste electrical and electronic equipment
WTR	Waste-to-Resource
WT-SVM	Hybrid Wavelet Transform-Support Vector Machine
WT-ANFIS	Hybrid Wavelet Transform-Adaptive Neuro-Fuzzy Inference System
WT-ANN	Hybrid Wavelet Transform-Artificial Neural Network
3Rs	Reduce, Reuse, Recycle

Symbols

a	Grey control parameter
a_{ij}	Relative importance between indicator i and indicator j
A_k	Actual observations
b	Control variable
b_i	Associated coefficients
$e_k(h)$	Forecast error
$\tilde{F}_k$	Forecasted value
$\tilde{F}_k(h)$	Point forecast of the value at time h
$h(t)$	Unit impulse response function
l_{ij}	Local priority
u	Developmental coefficient

List of Abbreviations (Cont'd)

w_j	Weight of criterions
z	Back ground value
$z_{\alpha/2}$	Appropriate (two-tailed) percentage point of a standard normal distribution
$\gamma(y_0(k), y_i(k))$	Grey relational coefficient
$\gamma(y_0, y_i)$	Grey relational grade
$\lambda_{\max}$	Maximum eigenvalue

Chapter 1

Introduction

1.1 **Background of the Study**

Urbanization is one of the most powerful and irreversible forces in the world that has accompanied large-scale improvements in developing countries towards the Millennium Development Goals (MDGs). It has brought many important benefits to economic, cultural and social development and transformations (UNCTAD, 2015; United Nations, 2014). In 2014, 54% of the world's population resided in urban areas and this is expected to increase to 66% by 2050, with nearly 90% of the increase concentrated in Africa and Asia (United Nations, 2014). Rapidly increasing population density in unplanned urban areas can create severe problems, such as urban sprawl, informal settlements, impacts on climate change and other global environmental issues (UNCTAD, 2015). Global urban areas currently occupy less than 5% of the world's land covered, consume over two-thirds of its energy, and create up to 80% of global greenhouse gas (GHG) emissions (STAP, 2014; UNCTAD, 2015). In addition, urbanization directly contributes to waste generation, and poor waste handling causes health hazards and urban environmental degradation (Vij, 2012).

Generation of municipal solid waste (MSW) is increasing worldwide due to a boom in population, urbanization, industrialization, improvement in living standards and development of the global economy. The rate of MSW generation is faster than the rate of urbanization. The annual global MSW generation is estimated to increase from approximately 1.3 billion tonnes in 2012 to 2.2 billion tonnes by 2025 (World Bank, 2012). Among these, OECD countries will generate almost half of the waste in the world, while South Asia and Africa regions generate the least amount.

Municipal solid waste management (MSWM) has become a crucial issue worldwide, not only due to rapidly increasing waste generation, but also from improper disposal of waste. Improper management of MSW, typically in landfills and open dumping, have caused serious pollution to air, soil, surface water, underground water, as well as destroying the ecological environment and negatively impacting land use and may present an explosive risk (Demirbas et al., 2011). MSW's contribution from anthropogenic activities is approximately 5% of total GHG emissions (IEA, 2014). Landfill without biogas collection is identified as the biggest source of anthropogenic methane, accounting for 34% of all methane emissions in the USA (DoE, 2008).

The use of energy worldwide is set to grow by one-third by 2040. Pledges made at the UN climate summit in Paris (also known as COP21) promise a move towards lower carbon emissions and more energy efficiency, but do not alter the picture of rising global needs for energy. The COP21 brings the share of non-fossil fuels or renewable energy (RE) up from 19% of the global mix today to 25% in 2040 (IEA, 2015). Energy from waste (EfW) has been identified as a source of renewable energy and 'green electricity', and has been used as a way of reducing GHG emissions (El Hanandeh and El Zein, 2011). Also, changing product design, re-use, recycling, energy-intensive products, and efficient use offers huge potential for energy saving (IEA, 2015).

According to the Pollution Control Department (PCD) of Thailand, MSW generation increased from 23.9 million tonnes (Mt) in 2008 to 26.2 Mt in 2014 (PCD, 2001-2014,

2015a). For MSWM and recovery EfW implementation in Thailand, the government has announced a target of RE contributing at least 25% of final energy consumption by 2021. It is expected that 400 MW of electricity and 200 ktoe of heat will be generated from MSW by 2021 (DEDE, 2014). Also, a MSWM plan targeting 40% proper disposal of waste generation and 30% recovery (for material and energy) was introduced by the government in the 10th National Economic and Social Development Plan (NESDB, 2007-2011), but these targets have not been achieved (Vanapruk, 2012). The targets have been replaced by the 11th National Economic and Social Development Plan (NESDB, 2012-2016), i.e. 30% recovery and 50% proper disposal (PCD, 2014d).

In developing countries including Thailand, local authorities are rarely able to manage MSW effectively because it is complicated and it uses the largest budget. Local authorities are relying on uncontrolled landfill and open dumping to cope with MSWM demands, and these present numerous problems for residents and the municipality (World Bank, 2012). These improper disposal sites are normally located far from civic areas where waste is generated, which entail higher costs of waste collection and transportation. An average of 20-50% of the annual municipality's budget is spent on MSWM, of which up to 80-90% is spent on the collection system alone (World Bank, 2012). As MSWM is given low priority in developing countries, the current practice of processing and disposing represents defective implementation, particularly for rural areas and small cities where the taxation system is insufficiently developed, and therefore there are limited funds for MSWM and public services are very poor (World Bank, 2011).

Therefore, it is necessary to evaluate appropriate MSWM systems in medium and small cities, as the improper use of MSW treatment facilities will cause environmental impacts, which may become critical as cities grow. Attempts to consider the sustainability of MSWM have been made in decision making processes. In practice, evaluation of appropriate MSW treatment options has been reported, but these are limited to country level, large cities and administrative areas in a few countries such as Cornwall and Warwickshire in UK, Boston in USA, Bandung in Indonesia, and Johor Bahru in Malaysia, where sufficient data are available (Abba et al., 2013; Contreras et al., 2008; Longden et al., 2007; Martowibowo and Riyanto, 2011). Among these evaluations, the availability of reliable data, e.g., the status of MSWM, characteristics of technologies used and applied, and present and predicted future MSW generation and composition should be investigated and addressed in decision making. Both a robust evaluation model for MSW treatment and an accurate forecasting model of MSW generation should play a key role for MSWM; these will present a great opportunity to increase the proportion of MSW treated properly and thereby decrease associated environmental impacts.

1.2 **Rationale of the Research and Problem Statement**

The long term key challenges for waste management are energy use and climate change, linking MSW systems with GHG emissions reduction and the enhancement of energy recovery (Pires et al., 2011b). Scarcity of resources and the impacts of global climate changes have motivated new strategies of waste management policies in European countries by decoupling waste generation from economic growth (EEA, 2011). For these reasons, they have improved their legislation by preventing biodegradable waste being landfilled for methane emission reduction, promoting composting as mineral fertilizers for improving energy recovery efficiency, enhancing recycling implementation and raising material utility. This shows that (Pires et al., 2011b). To address these issues, many models, for example,

forecasting, optimization, system analysis, and multi-criteria decision models, have been devised as supporting tools to help decision makers recognize criteria and evaluate the best MSW system for achieving sustainable development.

Several evaluating methods and models have been developed to support decision making in MSWM. These methods, such as cost-benefit analysis (CBA), life cycle assessment (LCA) and multi-criteria decision analysis (MCDA), are used to study waste streams and compare existing waste management options to guide decision makers in selecting the best available and applicable option(s) (Dewi et al., 2010; Morrissey and Browne, 2004). MCDA considers and integrates conflicting criteria from various dimensions and therefore gives more robust decisions than the other two methods (Morrissey and Browne, 2004). These methods were mostly practiced for large cities as mentioned in the previous section, while only a few of which were found for medium and small cities, such as Phetchaburi in Thailand and Baja California in Mexico (Suthapanich, 2014; Taboada-Gonzalez et al., 2014).

There is no single solution to the problem since each city has different characteristics, and while MSW treatment plans have already been developed, there are several environmental drawbacks associated with them (Pires et al., 2011b). Large cities are centers of economics, development and research and high technology, and have highly skilled workers. The characteristics of a large city differs from medium and small cities in terms of urbanization, production patterns (in manufacturing and service composition), income, population and population density, potential of labor force, health, entertainment, and education and public services (Henderson, 2014). In Thailand, in 2015, there were 7,777 local authority organizations (LAOs), comprising Bangkok and Pattaya city, 30 large cities, 178 medium cities, 2,233 small cities, and 5,334 sub-district administration organizations (SAO) (Department of Local Administration, 2015). This means that only 32% of total MSW generated countrywide were treated properly, mostly in large cities, while a large amount of MSW generated in other LAOs was disposed of improperly (PCD, 2015a). Therefore, it is vital to evaluate suitable MSW systems for medium and small cities, as decisions made at an early stage of development have significant impacts in MSWM in later phases when small cities expand.

Evaluating the most appropriate MSWM requires consideration of various parameters (Achillas et al., 2013). In the developing world, selecting a suitable MSW system is complicated due to the lack of reliable data, for example, the existing status of MSW management, pros and cons of each treatment technology and their operations in the particular area, and the existing and increasing composition and generation of waste (Dewi et al., 2010). The potential performance of existing waste treatment alternatives should be investigated in order to adopt the most appropriate system (Antonopoulos et al., 2014). It is, therefore, necessary to assess existing MSWM and characteristics of technologies for identifying MSW treatment alternatives.

To address the issue of MSW generation forecasting, a number of forecasting models have been developed (Ali Abdoli et al., 2012; Beigl et al., 2008; Noori et al., 2009a; Xu et al., 2013). Most of these are statistics-based models requiring reliable data, and some are mathematics-based models that can use limited data for training the models without considering influencing factors. Since traditional forecasting models such as regression analysis, time-series analysis, and econometric models require sufficient reliable data, an innovative model using limited data is preferred for forecasting of MSW generation (herein

after called MSW quantity) in developing countries, which include consideration of socio-economic, demographic, and geographic factors, to achieve the most accuracy.

It is expected that results from this study will help policy makers better understand the management of MSW and selection of the most suitable MSWM for medium and small cities. Innovative models to forecast MSW quantity can also help policy makers in developing countries who face an issue of limited data. This methodology can be applied not only in MSW management, but also in other fields of study. With such expectation, the following details the problem statements and rationale of the research in terms of assessing MSWM, forecasting of MSW generation, and decision making for evaluating appropriate MSWM systems.

a) Assessment of MSWM

The assessment of general MSWM systems is widely studied worldwide. For instance, a review and assessment of five existing MSW-to-energy technologies, i.e., landfill gas (LFG), anaerobic digestion (AD), incineration (IC), refuse derived fuel (RDF) and gasification (GF), were investigated in India (Nixon et al., 2013). The status, challenges and issues of MSW management in China were also reviewed (Zhang et al., 2010). In Thailand, many studies related to anaerobic digestion, incineration, gasification, landfill gas, RDF, and sustainable MSW management were carried out (Ali et al., 2012; Chaiprasert, 2011; Chiemchaisri et al., 2010; Kaosol, 2009; Liamsanguan and Gheewala, 2007; Menikpura et al., 2012; Nithikul, 2007; Thamavithya and Dutta, 2008; Wang-Yao et al., 2006).

A comprehensive assessment of overall commercial MSW treatment systems and comparative analysis of these technologies, as well as their barriers and challenges in the context of Thailand, could not be found. Also, information on waste-to-energy (WTE), and other treatment systems invested and operated by the private sector are not available officially because they have not been comprehensively assessed (Intharathirat and Abdul Salam, 2016). Thus, a study on this assessment would be useful for a clearer understanding of the extrinsic situation of MSWM systems and for proposing appropriate alternatives in the decision making process.

b) Forecasting of MSW quantity in medium and small cities

The amount of MSW generation in the future can be estimated by using different models depending on the available data, type of information, influencing factors and expected changes in MSW management policy (Rimaityte et al., 2011). Beigl et al. (2008) reviewed around 45 models for forecasting MSW. Among these, regression analysis was widely used (Xu et al., 2013) and this requires complete historical data of MSW generated and the factors affecting them. Nevertheless, all factors affecting waste generation cannot be considered in regression analysis (Noori et al., 2009b). Several studies used time series analysis to forecast MSW generation, and this analysis has higher accuracy than regression analysis (Chung, 2010; Rimaityte et al., 2011), but it requires the number of data (Beigl et al., 2008; Xu et al., 2013). Artificial Neural Network (ANN) also has been used to forecast MSW generation, and this has higher accuracy than regression and traditional time series analyses (Ali Abdoli et al., 2012; Batinic et al., 2011; Noori et al., 2009a; Ordonez-Ponce et al., 2004; Patel and Meka, 2013). However, it also requires considerable data.

To overcome the scarcity of historical data for modeling and the complexity of the forecasting model, the grey model (GM) has been implemented successfully to forecast long-term periods with higher accuracy than conventional time series analyses and ANN (Pai et al., 2008; Srivastava and Nema, 2006; Xu et al., 2013). The grey model is usually represented as GM (m, n) for dealing with the order 'm' of the differential equation and using 'n' variables (Hsu and Wang, 2009). At least four years of time-series data can be used in the grey model, which offers a simple procedure providing reliable results and an applicable methodology for other developing countries.

A few studies identified and quantified influencing factors affecting MSW quantities in different sectors (i.e., residential, commercial, institution, and municipal services) using regression analysis and geographical information system (GIS) approaches (Buenrostro et al., 2001; Lebersorger and Beigl, 2011; Purcell and Magette, 2009). Several studies forecasted MSW quantity in Thailand using regression and time series analyses associated with few influencing factors, such as population, GDP and expenditure (DEDE, 2009; Luanratana, 2003; Mongkoldhumrongkul and Thanarak, 2012; TGO, 2010; Vanapruk, 2012). These results might be inaccurate due to insufficient data. Also, none of the models provide explanatory factors affecting waste generated from various sectors.

Therefore, this study attempts to fill this gap by identifying, quantifying and selecting suitable factors affecting MSW quantity, and aims to develop alternative models to forecast MSW quantity with the uncertainty of the forecasting approach.

c) Decision making of MSWM systems

Morrissey and Browne (2004) reviewed literature on waste management models and concluded that it is necessary to simultaneously consider all the three aspects of environment, society and economy, and involve relevant stakeholders, namely the government, technical experts, local authority and community. They also highlighted that the models considering three such criteria could not be found and none can be revealed to be completely sustainable. Several studies then evaluated sustainable waste management by using multi-criteria decision making (MCDM) approaches, simultaneously considering the three sustainability criteria in medium and large cities in both developed and developing countries, such as Johor Bahru in Taiwan, Cornwall and Warwickshire, Niš, Phetchaburi and Baja California (Abba et al., 2013; Antonopoulos et al., 2014; Hung et al., 2007; Longden et al., 2007; Milutinović et al., 2014; Pires et al., 2011a; Suthapanich, 2014; Taboada-Gonzalez et al., 2014). Results showing the performance of each criterion that play a key role in decision making were highlighted in a number of studies. The engagement of stakeholders plays an important role in decision making, with some literature describing their preferences regarding sustainability criteria and alternative options (Begum et al., 2012; Contreras et al., 2008; Longden et al., 2007; Suthapanich, 2014; Taboada-Gonzalez et al., 2014). Among these, a few studied large cities in developed countries that focused on stakeholders' preferences regarding solid waste management (Contreras et al., 2008; Longden et al., 2007). In fact, stakeholders evaluated different criteria not only based on their own opinions, but also based on the opinions of others. Studying the preferences of stakeholders allows the incorporation of their concerns into decision making. This is the fact that more desirable alternatives are difficult obtain in this case (Soltani et al., 2015). In developed countries, consideration of stakeholders on the three pillars of sustainability criteria illustrated that environmental performance is viewed as the most important, followed by social and economic aspects for large cities (Contreras et al., 2008; Longden et al., 2007). In contrast, in developing countries, economic considerations

are viewed as the most important criteria, followed by social and environmental aspects (Martowibowo and Riyanto, 2011; Samah et al., 2010). However, stakeholders' preferences have mostly been simultaneously investigated for large cities (Contreras et al., 2008; Longden et al., 2007; Samah et al., 2010; Taboada-Gonzalez et al., 2014) but are still limited concerning medium and small cities.

The Analytical Hierarchy Process (AHP) is one method of MCDA that has been applied as a supporting tool to define the most suitable alternative and to carry out stakeholder groups' opinions or preferences in many cases, such as the forest planning (Ananda and Herath, 2003), fisheries management (Soma, 2003), industrial projects (Agha et al., 2012), wetland management (Herath, 2004), wastewater systems (Bao et al., 2013) and MSW management (Contreras et al., 2008; Longden et al., 2007). Therefore, this study attempts to identify and select the criteria, stakeholders and alternatives for consideration in the AHP approach and to develop the AHP model to incorporate stakeholders' preferences. Especially, this study aims to evaluate the most suitable MSW mangement system focusing on medium and small cities instead of large cities as seen in most previous studies. The national government provides funds to large cities, which may have had a large commercial and industrial base to support finance for public services and had high performance to attract investment from the private sector. In small cities, demand for financial support for MSWM has become a rapidly increasing budget category for local authories. Therefore, this study aims to help better understanding regarding appropriate MSWM in medium and small cities in developing countries.

1.3 **Objectives of the Study**

The major objective of the study is to evaluate municipal solid waste management, including general waste treatment systems and energy recovery from waste or waste-to-energy treatment systems of medium and small cities using Thailand as the case study. Specific objectives are:

Objective 1: To assess general MSW management and MSW-to-energy treatment systems that currently exist in Thailand.

Objective 2: To forecast long-term MSW quantities based on limited data using alternative multivariate grey models.

Objective 3: To evaluate general MSW management and waste-to-energy treatment systems for medium and small cities by using the analytic hierarchy process (AHP).

1.4 **Scope and Limitations**

The scope and limitations of this research can be divided into three aspects related to the objectives of the study: the assessment of MSWM systems, forecasting of MSW quantity, and evaluation of MSWM systems for medium and small cities as presented below.

1) Scope and limitations of assessing MSWM systems

The purpose of the assessment and review of the status of MSWM and WTE implementation in this study is to propose alternative MSWM systems. This assessment was implemented based on a review of available literature, interviews, and site visits. The MSW characteristics,

overall MSWM and policies related to WTE implementation were accessed from various sources, such as PCD, Bangkok Metropolitan Administration (BMA), Thailand Greenhouse Gas Management Organization (Public Organization) (TGO), Provincial Electricity Authority (PEA), Electricity Generating Authority of Thailand (EGAT), Energy Regulatory Commission (ERC), and entrepreneurs. This study focuses on existing general MSW management systems (composting, recycling and landfilling) and WTE treatment systems (landfill gas, anaerobic digestion, incineration, gasification and refuse derived fuel), and considers only pre-treatment, treatment and disposal systems. Also, for WTE treatment, only those systems generating electricity and heat are included, while oil and char produced from pyrolysis are not considered due to its insufficient maturity and development.

Given the lack of available information on MSW treatment systems in medium and small cities in Thailand, the assessment of these systems in this study is carried out at a country level and represented as alternative treatment systems for medium and small cities.

2) Scope and limitations of forecasting MSW quantity

Municipal solid waste is defined as discarded materials that have no value and are not useful to the waste generator. The major fractions of MSW comprise food waste, paper, plastic, metal, rags, glass, and some hazardous wastes such as waste electrical and electronic equipment (WEEE) and batteries. Despite the physical components of MSW, it typically includes wastes generated from various sources including residential, commercial, institutional and municipal services, as presented in **Table 1.1** (UNEP, 2015); no literature addresses MSW generation from all of these sectors. Information on factors that were identified in only residential and commercial sectors are available (Buenrostro et al., 2001; Lebersorger and Beigl, 2011; Purcell and Magette, 2009). Therefore, the identification of factors affecting MSW generation in forecasting models considers two sources: residential and commercial sectors.

Table 1.1: Sources and major types of MSW

Sources	Definitions	Fractions of wastes
Residential	Waste generated from livelihood of people who live in single and multifamily dwellings.	Food waste, plastic, paper, cardboard, glass, textiles, metals, ashes, household hazardous waste and special wastes (e.g., WEEE, oil, tires and bulky items)
Commercial	Waste generated from stores, restaurants, markets, hotels and office buildings	Paper, cardboard, plastic, wood, glass, food waste, metal, special waste and hazardous waste
Institutional	Waste generated from schools, hospitals, government centers and prisons	Paper, cardboard, plastic, food waste, wood, glass, metal, special waste and hazardous waste
Municipal services	Waste generated from street cleaning, beaches, management of parks and recreational areas	Street sweeping, tree trimming and landscape, wastes from beaches, parks, and other recreational areas

(Source: UNEP (2015))

As described above, in many developing countries such as Thailand, it is difficult to collect reliable data on MSW generation and composition for large, medium and small cities. Therefore, in this study, time series data were used for training alternative models of MSW forecasting based on MSW collected countrywide as reported by the PCD. The rate of MSW

quantity during 2013-2030 is assumed to be the same as for medium and small cities. In addition, as front-end and end-pipe treatments are considered in this study, it is therefore considered appropriate to describe MSW results as 'MSW quantity' in this study.

3) Scope and limitations of the evaluation of MSWM systems for medium and small cities

The Thai Government has introduced a centralized MSW management system, unlike the Japanese Government who permits authorities to manage their MSW at city level, which have strong regulation. In Japan, the transportation of MSW from city to city is not allowed. In contrast, the Thai Government encourages local authorities to manage solid waste via centralized or clustered treatment systems; this is not considered in this study. The MSWM system in each civic area is the focus of this study, as local authorities in middle income countries spend approximately 80-90% of their total annual budget for MSWM, which is related to the high cost of waste collection and transportation (World Bank, 2012).

The management of waste stream generation, such as reducing, reusing and sorting at source, collection and transportation are excluded from this study because its analysis is difficult due to the lack of data, and these aspects do not affect GHG emissions compared to end-pipe treatment systems (Antonopoulos et al., 2014). Given the availability of data on waste separation at source and its implementation are very limited, this study focuses on front-end and end-pipe treatment systems. Since a centralized treatment system policy seems unable to achieve sustainable waste management due to high collection and transportation costs, it would be useful to rethink a decentralized treatment system approach and push effort backwards to sorting waste at source. It should be highlighted that this study attempts to involve relevant stakeholders in decision making to understand their preferences.

To evaluate MSWM systems, it is necessary to present information of alternative MSWM systems to stakeholders for weighting in pair-wise comparisons (PC). In this study, this information is assumed as an overview of MSWM systems. For example, the gasification system represents its overall characteristics, not only its specific type such as plasma arc, down draft gasification and so on.

Regarding the decision making process, a group meeting and/or workshop was not conducted in this study due to the difficulty in inviting senior organizational stakeholders. The knowledge and background of stakeholders on clustering of MSWM systems as mentioned above were also outside the scope of this study.

1.5 **Organization of the Dissertation**

Figure 1.1 provides an overview of the research organization and the outputs of this study. Based on the research gaps identified in **section 1.2**, the overall methodology and research questions are detailed in **Chapter 2**. As shown in **Figure 1.1**, the study is organized into six chapters. **Chapter 1** provides an introduction to the research, comprising the background and rationale of the research, problem statement, research objectives, research contribution, scope and limitations, and the organization of the dissertation. **Chapter 2** documents the methodological framework of this research and briefly describes the overall and specific methodologies used. **Chapter 3** describes the assessment of MSW management and WTE treatment systems, using a case study of Thailand: sections include a review of legislation, opportunities and challenges in Asian countries, background of the study area, MSW management in Thailand, specific methodology of this chapter and results. Formulation of

alternative forecasting models is addressed in **Chapter 4**. The latter chapter presents an introduction of its formulation, followed by an overview of MSW forecasting models, identification and quantification of influencing factors, developing and verifying of alternative models and forecasting of MSW quantity in Thailand. **Chapter 5** evaluates the most suitable MSW system for medium and small cities, giving an introduction to the study; an overview of decision making tools, analytical hierarchy process (AHP) methodology, and sensitivity analysis (SA); implementation of AHP; results of evaluating MSW management systems; a discussion on problems faced and limitations in the AHP model; and recommendations related to MSW management policies.

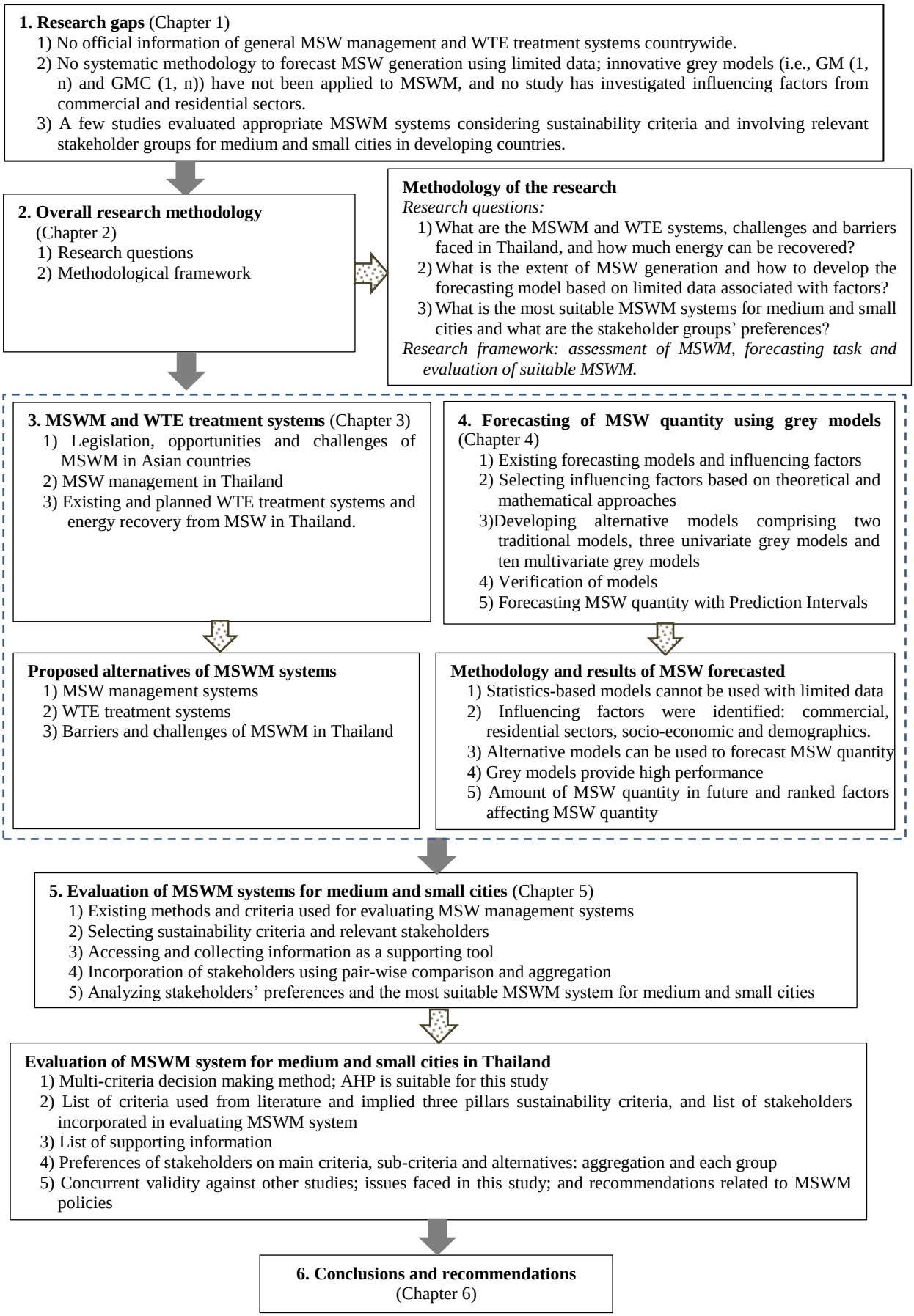


Figure 1.1: Overview of organization of the research and outputs

Chapter 2

Overall Research Methodology

This chapter describes the overall methodology adopted in this research. It presents three stages of the research methodology: assessment of MSWM systems (general MSW treatment and WTE treatment systems); development of MSW forecasting models; and evaluating the most suitable MSWM systems by using the Analytic Hierarchy Process (AHP) method for medium and small cities in Thailand. Results from the assessment of general MSW treatment and WTE treatment systems are proposed as MSWM alternatives in the AHP method. Similarly, results from MSW quantity forecasts are also used, through soft linking, as one of the data inputs in a supporting tool for stakeholders' decision making in the AHP method.

2.1 **Research Framework**

The overall research framework for evaluating the most appropriate MSW management systems for medium and small cities by using the AHP method is presented in **Figure 2.1**. This illustrates the structure of the research, methods used and formulated objectives of the study, and stepwise analyses to achieve all objectives. This also describes the identification of issues and research questions as detailed below.

2.1.1 Identification of Issues and Research Questions

The need for addressing the issue of limited data in evaluating MSWM systems for the reasons described in **section 1.2** leads to the following research questions. These research questions include three main subjects: i) assessment of MSWM systems, general MSW treatment and WTE treatment systems; ii) development of MSW quantity (hereinafter called MSW collected) forecasting models; and iii) evaluation of the most suitable MSWM systems for medium and small cities.

1) What are the general MSW treatment and WTE treatment systems and their challenges and barriers faced in Thailand, and how much energy is recovered from MSW?

2) How to develop models to forecast MSW generation by using limited data and consideration of influencing factors?
    a. What is the annual rate of MSW generation in Thailand?
    b. How to develop an optimal MSW forecasting model?
    c. What factors, representing residential and commercial sectors, affect MSW generation?

3) Which options support the most suitable MSWM systems for medium and small cities and what are the opinions of stakeholder groups regarding MSWM sustainability criteria?

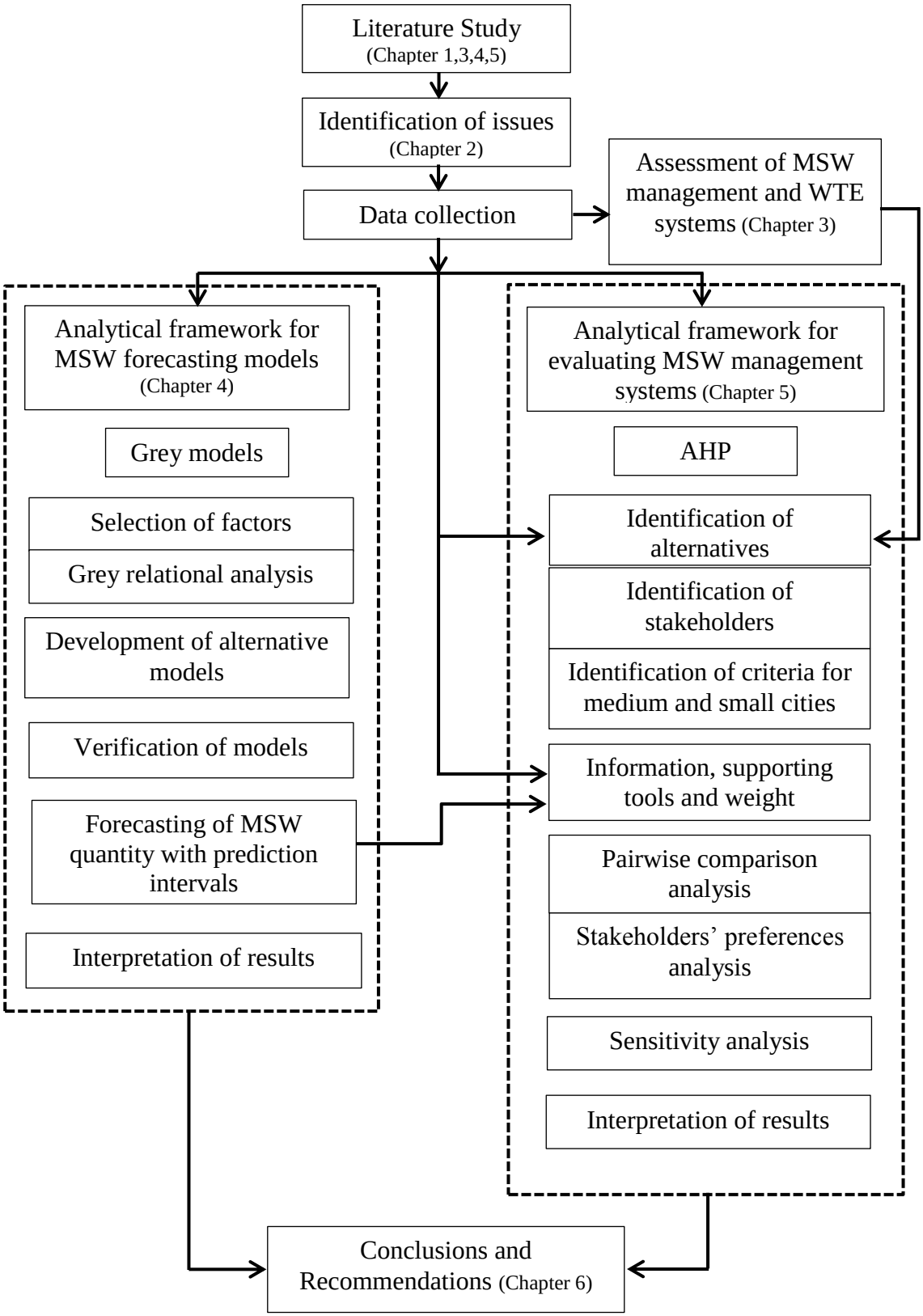


Figure 2.1: Overall analytical framework of the study

2.1.2 Analytical framework development

The analytical framework involves assessing general MSW and WTE treatment systems, forecasting of MSW quantity based on limited data availability in Thailand, and evaluating appropriate MSW management systems for medium and small cities. The assessment framework of MSWM systems was developed to investigate existing general MSW treatment and WTE treatment systems countrywide, as described in **Chapter 3**. Results are proposed as MSWM alternatives in the decision making framework, using the AHP method to evaluate appropriate MSWM systems for medium and small cities. Similarly, information on existing and forecast MSW characteristics that have been widely used as a supporting tool, also play a key role in decision making. The framework of innovative mathematical model approaches, grey theory and grey forecasting model, are developed to forecast MSW quantity from 2013 to 2030 based on limited data using the case study of Thailand. Details of grey theory and grey forecasting models (hereinafter called Grey models (GM)), which can be used to quantify factors affecting waste quantity based on statistics and mathematics, are discussed in **Chapter 4**. Consequently, the framework for evaluating MSWM systems is developed by using the AHP method by carrying out three aims under specific objective 3 of this study: i) identifying criteria, stakeholders and alternatives; ii) quantifying stakeholders' preferences on criteria, sub-criteria and alternatives; and iii) evaluating the most suitable waste management systems for medium and small cities in Thailand. Details of the results and discussion on formulation of the AHP method are presented in **Chapter 5**. Conclusions are provided in **Chapter 6.**

2.1.3 Assessment of MSW management and WTE systems

Besides identification of MSWM systems, which represents one of several steps in the decision making process and plays a crucial role, the status, challenges and prospects of waste planning and management needs to be assessed. To address the issue of limited data of existing general MSW treatment and WTE treatment systems, the framework of the assessment was developed. The details of this framework is provided in **Chapter 3,** and comprises a literature study, methodological steps (the development of a questionnaire for gathering information related to WTE plants, interviewing MSWM experts and the owners of the plants, and sites visited), and results and discussion. This information, especially from commercial WTE plants in Thailand, was compared in a similar manner to other countries. This illustrates MSWM options that will be proposed as alternatives in the decision making framework as discussed further in **section 5.5.1**.

2.1.4 Forecasting of MSW quantity

Other prerequisite information required as input to the supporting tool in the AHP method concerns current and future MSW quantity. The framework of the MSW forecasting methodology is created for developing countries to forecast amounts of MSW accurately based on limited data by considering influencing factors as illustrated in **Figure 2.2**. Influencing factors were identified, classified and quantified based on a literature review, and statistical and mathematical (grey system theory) approaches. It was found that influencing factors representing residential and commercial sectors were major sources of MSW generated. In this study, multivariate grey models were developed and their accuracies compared with traditional forecasting models such as Naïve and Trend curve analysis. Mean Absolute Percentage Error (MAPE) was used to validate the accuracy of alternative models. The most accurate model was selected and used as a representative model to forecast MSW

quantity during 2013–2030. Results then informed further development of the framework for the evaluation of MSWM systems, as discussed in **Chapter 5**.

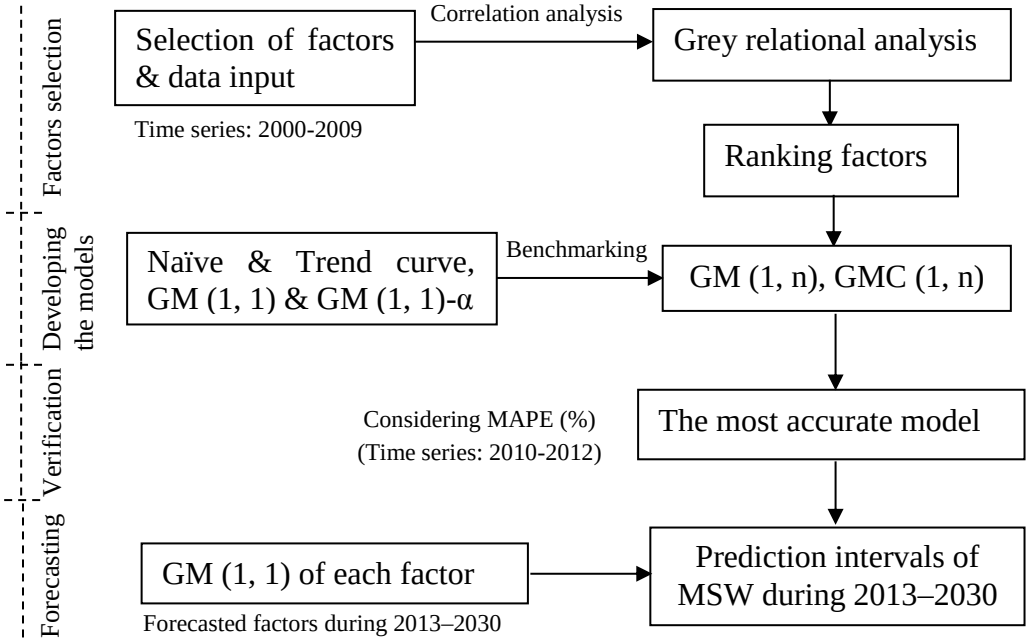


Figure 2.2: Procedure for MSW quantity forecasting.

2.1.5 Multi-criteria decision making approach for MSW management systems

Outputs from **Section 2.1.3** and **2.1.4** were used for developing the AHP method. Other inputs were gathered from literature that is widely available in reports, research articles, master theses and dissertations, and from stakeholders' experiences and opinions. Evaluation of the MSW management systems framework included the following details: i) identification of the problem and alternatives, stakeholders, and criteria; ii) preparing information as a supporting tool; iii) analysis of pairwise comparisons and stakeholders' preferences; and iv) sensitivity analysis as described in **Chapter 5**. The discussion on evaluating MSW management systems and interpretation of results obtained in the context of medium and small cities in Thailand are presented in section 5.6.

2.2 Summary

Key findings from the three main objectives are presented: comprehensive assessment of MSWM systems in Thailand; the development of grey models; factors affecting MSW quantity; and preferences of stakeholders with regard to sustainable MSWM. The impacts of representative factors from residential and commercial sectors affecting MSW quantity are briefly described, identified and quantified. Major contributions of the study in terms of development of grey models and analysis of stakeholders' preferences in medium and small cities, using Thailand as a case study, are also highlighted in the conclusions (**Chapter 6**).

Chapter 3

MSW management and WTE treatment systems*

The objective of this chapter is to assess the status of MSW management, including MSW characteristics and existing treatment systems, challenges and policies, and to identify possible options of MSW management (MSWM) systems, focusing on general MSW management and waste-to-energy (WTE) treatment systems that are suitable for medium and small cities in Thailand. This chapter is structured as follows to achieve the stated objective. **Section 3.1** presents the introduction and the hierarchy of sustainable waste management. **Section 3.2** reviews literature related to the assessment of MSWM and provides a scope of the study. **Sections 3.3 and 3.4** describe the methodology of assessment and the definition of MSWM used in the study respectively. **Sections 3.5 and 3.6** provide the management of MSW and WTE systems in Thailand and other Asian countries respectively. The subsequent sections present results and discussions, followed by a summary of this chapter in **sections 3.7** and **3.8** respectively.

3.1 **Introduction**

Effective MSWM is challenged by inadequate financial resources, and existing management and technical skills within government authorities and municipalities. Environmental issues of MSWM have become a global concern because of increasing population, which results in increasing amounts of waste. MSW generation per capita in Thailand is the highest in the Asia Pacific Region (Troschinetz and Mihelcic, 2009). MSW in Asia generally or in Thailand normally contains a high organic fraction and combustible materials that have potential for energy production. However, almost all MSW is being dumped into landfill sites where they subsequently release high levels of pollutants and greenhouse gases (GHG) into the environment. This has caused serious environmental pollution, destroying the ecological environment, negatively impacting land use, and it may also present an explosive risk. For instance, fires broke out at several dump sites in Thailand in 2014 and displaced more than two hundred residents due to the release of poisonous gases (Fredrickson, 2014). Also, landfill without biogas collection is identified as the biggest source of anthropogenic methane, contributing around 115.4 Gigagrams per year (Gg/year) of methane released from 95 landfills and 330 open dumps in Thailand (Chiemchaisri et al., 2007).

Sustainable solid waste management has been recognized as an environmentally friendly approach for reducing MSW generation and for reusing valuable materials contained in solid waste (Annepu, 2012). Reduction at source and reusing materials at the initial level of the waste management hierarchy prevents MSW generation (see **Figure 3.1**). Materials recovery from recycling and composting is known as the most effective way for MSWM. Recycling has numerous benefits for sustainable waste management by reducing environmental impacts and use of natural resources (Ittiravivongs, 2012). For instance, recycling of an average size aluminum can (about 375 ml) saves up to 95% of energy needed for producing a new can, which is equal to saving the amount of energy needed for 4 hours use of a 100 W light bulb or 3 hours use of a television set. Also, one tonne of recycled aluminium can conserve five tonnes of bauxite. Similarly, every tonne of paper recycled can save 17 trees (Ittiravivongs,

* Part of the work described in this chapter has been published as follows: 'Valorization of MSW-to-Energy in Thailand: Status, Challenges and Prospects' Intharathirat R. and Abdul Salam, P., Waste and Biomass Valorization, Volume 7, 2016, pp. 31-57.

2012; Planet Ark Environmental Foundation, 2013). However, in developing countries, the lack of technical and economic supported separation at source, and sufficient markets, means that MSW ends up in landfills (Annepu, 2012). A sustainable way to handle non-recyclable solid waste is to convert them to energy, which uses waste as fuel; however this strategy is less efficient than composting and materials recovery.

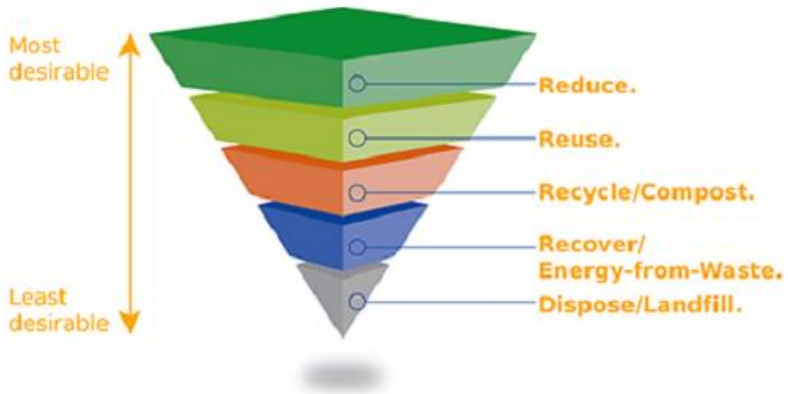


Figure 3.1: The hierarchy of MSW management
(Source: Hedberg and Danielsson (2010))

Achieving sustainable waste management through the WTE process, particularly thermal treatment, has become more attractive as it can reduce up to 70 to 90% of MSW, especially by incineration and gasification (Arena, 2011; EESI, 2009). Waste treatment processes have shifted towards a more sustainable and efficient use of resources worldwide. The use of waste as raw materials to produce energy (heat and/or electricity) is able to reduce primary energy demand (Chanchampee, 2010; Rada et al., 2009).

Waste recovery, such as recycling and waste-to-energy, is an integral part of the waste hierarchy concept for meeting global standards by increasing the recycling rate and providing a safe waste disposal option (Castaldi and Themelis, 2010). Recycling, which is known as an environmentally friendly strategy, makes significant positive influences by preventing GHG emissions and environmental pollution; saves energy by replacing alternative virgin production chains; as well as diverting solid waste from landfill and incineration (Agarwal et al., 2005). Energy recovery from biomass and waste is being actively promoted and can reduce 50% of GHG emissions by 2050 (Kothari et al., 2010). Energy recovery from waste (or WTE) systems consist of biochemical processes (e.g., fermentation, anaerobic digestion (AD) and landfill gas (LFG)) and thermal processes (e.g., incineration (IC), gasification (GF), pyrolysis and refuse derived fuel (RDF)) (Kalyani and Pandey, 2014; Zheng et al., 2014). MSW treatment systems and disposal in developing countries normally consists of open dumping, composting, landfilling and WTE systems.

Decision making on the selection of proper MSWM is mainly influenced by factors such as existing policies, waste management methods, energy supply and use, as well as technologies (Guziana et al., 2013). Furthermore, a consolidated database on recycling, resources recovery from solid waste and WTE practices can be utilized for planning purposes at the national level and for strategy formulation at regional level. Landfilling is equivalent to discarding natural resources that are contained in solid waste, which could be instead used as fuel for

production of energy or as secondary raw materials. In current society, landfilling is required for small fractions of waste that cannot otherwise be used or recovered and need to be buried (Annepu, 2012). Unsanitary landfill, called open dumping, is not recommended and considered as an alternative for MSW management in sustainable development or in this study. To effectively plan MSW management, it is therefore important to assess and understand the current application of MSWM and highlight issues, problems, as well as initiatives undertaken. This understanding highlights the role of proposing options of general MSW management and WTE treatment systems. The practices of these systems and national planning has therefore been reviewed and surveyed as described in the following section.

3.2 **Review of literature**

To adopt appropriate waste management systems that address sustainability, the performance of existing waste treatment systems should be assessed (Antonopoulos et al., 2014). Assessment of MSWM systems have been widely studied worldwide. Ahsan et al. (2014) studied MSWM systems in six major cities of Bangladesh to identify the strengths and weakness of solid waste management systems, examining storage at source, separation, collection and transportation, treatment, recycling, and ultimate disposal, through field survey, public consultation, literature review, and other appropriate means. Masood et al. (2014) investigated current MSWM systems in Lahore, Pakistan, by reviewing available official reports, legal documents and scientific literature, and collected data in the field, including interviewing operators of MSWM systems. Observational data and public surveys were also conducted in their study. To address serious inadequacies of MSW in Sri Lanka, Eheliyagoda and Prematilake (2016) assessed the current status of waste management scenarios and highlighted strengths and weaknesses to understand system sustainability that would help local authorities to improve MSWM. The main methodology used in their study was to analyze information obtained from field observation, literature, reports, questionnaires and interviews with major stakeholders. In addition, an assessment of MSW-to-energy treatment systems (LFG, AD, IC, RDF and GF) were investigated in India (Nixon et al., 2013), and the issues, status and challenges of MSWM in China were illustrated by Zhang et al. (2010).

These assessments were mostly conducted for evaluating appropriate MSWM systems at country level or for large cities, as mentioned in **section 1.1 and 1.2**, while only a few studies such as those in Baja California, Mexico and Phetchaburi, Thailand, were carried out for medium and small cities (Suthapanich, 2014; Taboada-Gonzalez et al., 2014). However, these studies widely assessed MSWM in terms of mixed systems, including landfilling, recycling, incineration and composting (Abba et al., 2013) or one type of system in a WTE scheme (i.e., IC, GF, RDF and AD) (Suthapanich, 2014). The assessment of MSWM systems that were grouped into the two categories of general MSW management and WTE treatment systems could not be found.

In developing countries including Thailand, one of the problems in dealing with solid waste management is a dearth of global data, and even when data is available, it is in various formats and is often not comparable. The absence of reliable MSWM data is also an issue in Thailand (Intharathirat and Abdul Salam, 2016). Previous studies of MSW management in Thailand were mostly focused on the physical components of the systems (anaerobic digestion, incineration, gasification, landfill gas, RDF, and sustainable MSW management) rather than providing a comprehensive analysis including overall commercial MSW management and WTE treatment systems associated with their barriers and challenges (Ali et

al., 2012; Chaiprasert, 2011; Chiemchaisri et al., 2010; Kaosol, 2009; Liamsanguan and Gheewala, 2007; Menikpura et al., 2012; Nithikul, 2007; Thamavithya and Dutta, 2008; Wang-Yao et al., 2006). Also, in Thailand, information on WTE and other treatment systems that were invested and operated by the private sector were not available officially because they have not been comprehensively assessed (Intharathirat and Abdul Salam, 2016).

According to the Pollution Control Department (PCD), a number of existing MSW management systems (459 landfills, 7 incineration without energy recovery, two incineration with energy recovery, two MBT systems and 12 Integrated Solid Waste Management System (ISWM)) as further discussed in **section 3.4,** were initially surveyed in all municipalities in 2012 and 2013 and published in 2014 and 2015 respectively (PCD, 2001-2014, 2014d, 2015a, 2015b). However, reliable data were unavailable in the study period from 2012 to 2013. From PCD's reports, some types and number of treatment systems were missing, particularly countrywide WTE plants. Also, past studies do not provide sufficient information on selecting suitable options for addressing the crisis of MSW management in Thailand. The well-known Analytical Hierarchy Process (AHP) method has been used for selecting suitable options by several researchers (Abba et al., 2013; Antonopoulos et al., 2014; Samah et al., 2010), but it is necessary to clarify the situation of MSW management systems, especially WTE, and to identify options to be represented in the AHP analysis.

As demonstrated above, it is necessary to assess existing MSWM systems for addressing information gaps to obtain a clearer understanding of the extrinsic situation of MSWM systems and for proposing appropriate alternatives in decision making. This chapter attempts to provide an account of the situation of MSWM and WTE implementation in Thailand based on available literature, interviews, and site visits. This chapter helps to ascertain that the subsequent selection of alternatives is informed and avoids the development of a haphazard collection of alternatives. Therefore, this study focuses on two existing waste management systems, namely general MSW management and WTE treatment systems (generating electricity and heat). Pyrolysis, Fischer–Tropsch processes and so on are excluded in this study due to their insufficient maturity and development in Thailand as detailed below.

3.3 **Methodology of the study*:* assessment of MSWM systems**

Based on the overall analytical framework illustrated in **Figure 2.1**, methodological steps of a comprehensive assessment of MSWM systems are presented here. Firstly, a review of literature related to general MSW management systems and WTE treatment systems in Thailand and other countries was conducted. Data on these systems were then collected from various sources as described in **step 1**. Secondly, a questionnaire was developed and distributed to responsible organizations to elicit information on MSW treatment systems, as presented in **step 2**. Thirdly, several treatment sites of general MSW management and WTE treatment systems were classified and visited (**step 3**). In this step, empirical observational data acquired from observation were collected and noted. In addition, governmental authorities, experts, technicians and entrepreneurs were interviewed in-depth and personally consulted so as to develop a deep understanding of general MSWM and WTE treatment systems. Therefore, these systems were identified and proposed as appropriate MSW alternatives to be input to the decision making process, as further described in **section 5.5**. The final judgment of the proposed alternatives was conducted through stakeholder participation using an evaluation form, as further discussed in **section 5.5.4**.

Step 1: Data collection

In this step, information on MSWM was collected from two main sources. Firstly, information was acquired from governmental organizations, including the PCD, Bangkok Metropolitan Administration (BMA), Energy Regulatory Commission (ERC) and Provincial Electricity Authority (PEA). They provided information related to MSW characteristics and management, and WTE implementation countrywide and in Bangkok. Information collected from PCD and BMA was retrieved from their websites, news articles, and from interviewing PCD and BMA officials. Similarly, information on selling electricity permitted to the grid was collected from ERC's website, and from interviewing PEA officials and owners for rechecking and updating the status of such plants. Secondly, details on technological facilities and equipment used, operational and maintenance costs, and the barriers and challenges of each plant, were collected by distributing questionnaires, visiting the sites, and interviewing plant operators and owners.

Step 2: Questionnaire development and distribution

Information on MSWM systems can be easily accessed on PCD's website as most of these systems are under the responsibility of local authorities. However, information on WTE treatment systems was unavailable as they are under private sector control. As a result, there is no organization that consolidates all relevant information. Therefore, it was necessary to contact existing WTE plants for data collection. Once the available literature was reviewed, the next step was to develop the questionnaire and distribute to municipalities and private companies with responsibility for managing WTE and MSW management systems. The questionnaire was developed to elicit information related to existing MSWM systems and WTE plants, gathering essential information about financial, operational, maintenance, barriers and challenges, and suggestions to government and other stakeholders for improvement.

Appendix A shows the questionnaire developed for collecting data related to the systems and management (investment and operation) of MSW. These data were useful for further comparative analysis of MSWM systems and their characteristics to identify MSW management alternatives.

Step 3: Visiting general MSWM and WTE treatment systems

The selection of general MSWM and WTE treatment systems to visit was based on information contained in literature from non-governmental organization and governmental websites, reports and seminars. Few plants were visited to permit comparative studies without statistical analysis. Seven plants were selected as representative case studies of each type of MSWM system, which were grouped into two categories: i) integrated systems (hereafter referred to as general MSWM systems); and ii) WTE treatment systems. These are detailed as follows:

- Integrated systems comprising mechanical biological treatment (MBT) combined with composting (CP) and anaerobic digestion (AD), located in Rayong and Nakornratchasrima municipalities; and

- WTE treatment systems comprising two landfill gas (LFG) plants in Kamphaengsan, Nakornprathom, AD in Rayong and Nakhon Ratchasima municipalities, incineration

(IC) in Phuket, gasification (GF) in Had Yai, Songkla, and mechanical treatment (MT) produced from refuse-derived fuel (RDF) in Rayong.

Information on other general MSWM systems (landfill and recycling) and WTE treatment systems were collected from available sources and personally by calling and interviewing operators and owners of the plants. The consolidated information of these plants are discussed in three phases: currently operating, under construction and under planning, as detailed in Intharathirat et al. (2015) and summarized in the next section.

3.4 **Definitions related to MSW and assessment in this study**

A MSWM system addresses the management of waste generated, storage, collection and transportation, treatment and final disposal. It is a basic and necessary service provided by the local authority. Proper MSWM involves the collection and separation of different types of waste, called source sorted waste collection. It is commonly used in developed countries as in Europe, Japan and North America, where the infrastructure of separated transportation is available (Annepu, 2012). Most developing countries like Thailand collect mixed MSW because of the lack of public awareness and infrastructure.

As per the definition of MSW's physical components, as described in **Table 1.1**, the major fractions of MSW in this chapter comprise food waste, paper, plastic, metal, rags, glass and some hazardous wastes. These includes wastes generated from various sources including residential, commercial, institutional and municipal services (UNEP, 2015).

Managing municipal solid waste typically involves planning, financing, constructing and operating treatment/disposal facilities for waste recycling, collection and transportation and final disposal. However, this study focuses on pretreatment and treatment/disposal systems of MSW as a part of the overall MSW management. This means that the management of waste generated at source and the collection and transportation of MSW are excluded in this study.

In assessing waste management, this study considers all types of MSWM options available and chooses the most appropriate. Many factors can influence the selection process, such as waste generation and waste composition, and both of these factors are major factors for planning waste management. Thus, this study can assess management options such as source reduction, energy recovery, and landfilling that reflect the needs and goals of national policies and sustainable development. The criteria for assessing management options comprises consideration of the potential performance of existing systems, policies related to MSWM, costs, potential to divert waste from disposal, technical capabilities, ability to maintain local control, compatibility of the option with the current system, flexibility, the extent of change to the existing system required, and public acceptance.

3.5 **MSW in Thailand*:* A background**

Thailand, a Southeast Asian country, consists of 77 provinces in 5 regions, excluding Bangkok, which is the capital city and the center of country's political, industrial, commercial, and cultural activities. Thailand experienced gross domestic product (GDP) growth of 2.8% in 2015. The total area of Thailand is about 513,120 square kilometers and the population is approximately 67.96 million (The World Bank, 2015).

3.5.1 Definition of cities in Thailand

In Thailand, municipalities are defined by the Municipality Act, 1953 (Office of the Council of State of Thailand, 1953), and grouped into three categories of city municipality, town municipality, and township or sub-district municipality. For the purpose of this study, three levels of city are considered: large, medium and small cities representing city municipality, town municipality, and township or sub-district municipality respectively, which are classified by the number of population and population density. A large city or city municipality must have a population of at least 50,000 and population density of 3,000 per km^2. A medium city or town municipality has a population of at least 10,000 with a density of 1,000 persons per km^2. A small city or sub-district municipality has a population of at least 5,000 with density of 1,500 persons per km^2 as well as 5 million Baht of gross income (Office of the Council of State of Thailand, 1953).

3.5.2 MSW generation and composition in Thailand

Based on information of MSW generation reported by PCD and presented in **section 1.1**, the increase of MSW generated, changes to the amount of MSW disposed of properly and improperly, and the proportion of waste recovered is illustrated in **Figure 3.2** (PCD, 2001-2014, 2015a). This illustrates that the generation rate has increased from 1 kg/capita/day in 2008 to 1.11 kg/capita/day in 2014 (PCD, 2015a), which is similar to Malaysia (1.0 kg/capita/day) (APO, 2007), Indonesia (1.12 kg/capita/day) (MoE, 2008 cited from Meidiana, 2010), and Japan (1.1 kg/capita/day). However, this is much higher than that of China (0.8 kg/capita/day), Lao (0.6 kg/capita/day) and Myanmar (0.5 kg/capita/day) (PCD, 2014c). In 2011, a large amount of MSW was generated (25.35 Mt) that resulted from the huge flood event in Thailand.

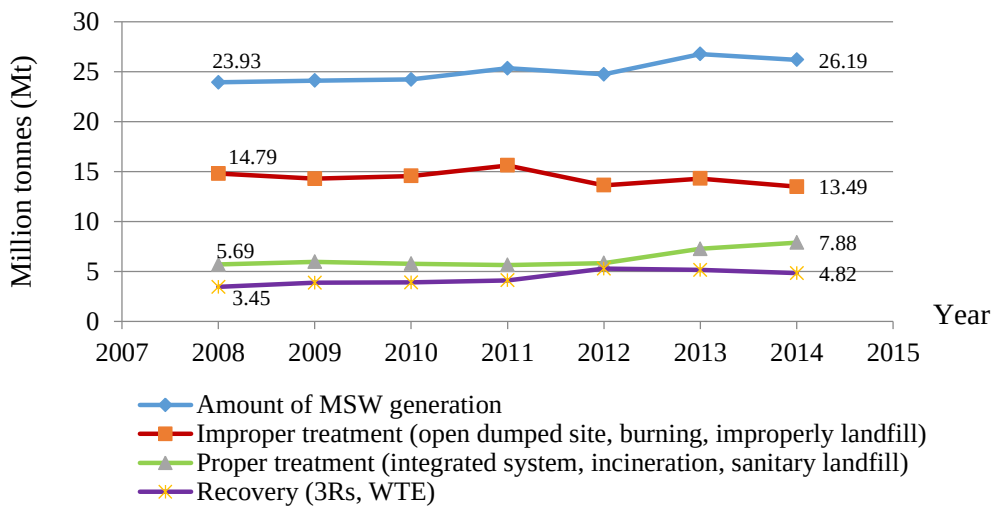


Figure 3.2: The amount of MSW in Thailand
(Source**:** PCD (2001-2014); PCD (2015a))

Regarding the three levels of cities described in the previous section, in 2014, the PCD reported that the MSW generation rate in a city municipality (defined in this study as a 'large city'), town municipality (termed a 'medium city' in this study) and sub-district municipality

(in this study called a 'small city') were approximately 1.89, 1.15 and 1.02 kg/capita/day respectively (PCD, 2015b).

In 2003, PCD investigated MSW composition countrywide, including 121 representative cities, comprising 20 large cities, 57 medium cities and 44 small cities and two transfer stations in Bangkok. The MSW fraction in Thailand does not differ from other Asian countries being composed of a large proportion of food waste and lesser quantities of plastic and paper (AIT, 2004; Shekdar, 2009). On average, the MSW composition in Thailand consists of 63.6% organic or food waste, 16.8% plastic, 8.2% paper, 3.5% glass, 2.1% metal, and 5.8% miscellaneous (PCD, 2004), as shown in **Figure 3.3**. TGO (2014) noted that the composition of MSW using various sources of secondary data surveyed by PCD (2004) and random primary data surveyed by TGO in 2013, concluded that MSW composition in Thailand has not changed during this decade. Their study areas comprised 32 large cities, 178 medium cities, 2,234 small cities, and 5,335 Subdistrict Administrative Organizations (SAO) (TGO, 2014). These fractions can be illustrated for the three levels of cities as presented in **Figure 3.4**. The proportion of food waste in a large city is higher than that of a medium and small city, which are 62.6%, 51.2% and 30.4% respectively. This may reflect the lifestyle of people living in a capital or large city who eat out more often at restaurants. In addition, the number of hotels and service areas for tourists in large cities also generate large amounts of food waste, while relatively fewer restaurants located in rural areas or small cities generate a lower proportion of food waste. Recyclable wastes (e.g., packing materials, glass and metals) generated in a large city has potential for being sorted by people occupied in the informal sector who are more often found in a large city. The high proportion of wood, dust and some inert particles, collected in a small city reflects an urban environment with lots of trees and vegetation, and incomplete infrastructure such as unpaved streets.

From an ultimate analysis, MSW comprises 48.9% carbon, 5.5% hydrogen, 32.5% oxygen, 0.8% nitrogen, 0.3% phosphorus, and 0.02% sulphur (PCD, 2004). Furthermore, moisture content, volatile solid, and ash content are 45.1%, 87.6%, and 19.8% respectively. The net calorific value of Thai MSW is 4 MJ/kg (AIT, 2004) which is similar to other developing countries, e.g., the net calorific value range of Chinese and Bangladesh MSW is 3–6.7 MJ/kg (Cheng and Hu, 2010) and 2–3 MJ/kg (Hossain et al., 2014) respectively. However, this is less than half of that found in developed countries, which is in the range of 8.4 to 17 MJ/kg (Cheng and Hu, 2010).

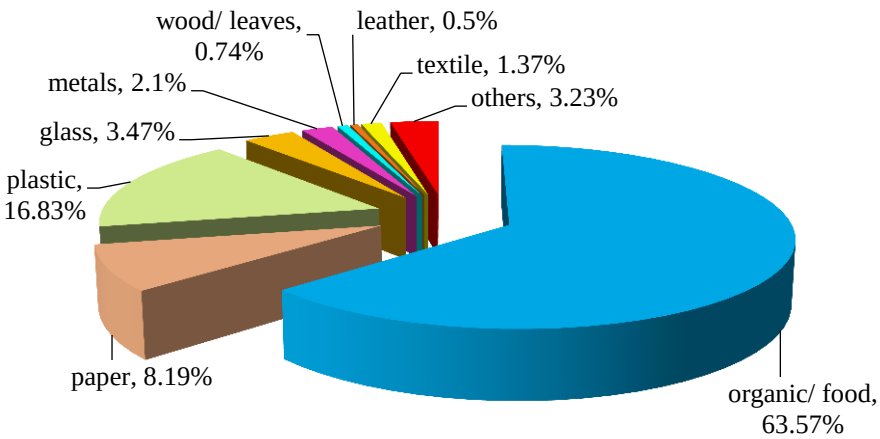


Figure 3.3: Overall composition of MSW in Thailand
(Source: PCD (2004))

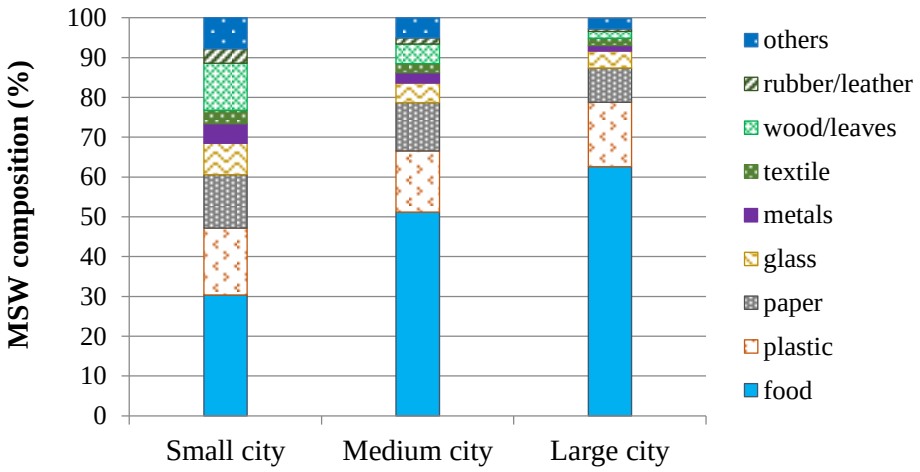


Figure 3.4: Average percentage of MSW composition from various cities (Source: TGO (2014))

3.5.3 MSW management in Thailand

The MSWM strategy of Thailand focuses on bulk collection and mass disposal (Chiemchaisri et al., 2007). Out of 26.2 Mt of MSW generated, 14.8 Mt (56.5%) was collected through household waste containers, waste collection trucks and workers. Waste collection services have been improved in Bangkok and large municipalities, however in smaller towns such services are not fully provided. Approximately 15% of the total MSW generated in Thailand was produced in Bangkok in 2014 (PCD, 2015b). This amount was almost entirely collected and thus there are little or no waste from the Bangkok area. In contrast, only 37% of waste is collected in municipality areas and 6% of waste is collected outside municipality areas (Kaosol, 2009).

3.5.2.1 MSW management systems in Thailand

In last decade, approximately 65% of total MSW generated in Thailand was deposited into improper disposal sites, or open dumps (Chiemchaisri et al., 2007). The government's *10th National Economic and Social Development Plan (NESDB, 2007-2011)* and *11th National Economic and Social Development Plan (NESDB, 2012-2016)* targeted proper disposal for 40% and 50% of waste generated respectively (Vanapruk, 2012); this is further discussed in **section 3.5.2.3**. In 2014, the proportion of MSW disposed of at open dumping sites decreased to 51.5% (13.5 Mt, out of 26.2 Mt) of MSW generated, due to the implementation of Thailand's MSW strategy (PCD, 2015a, 2015b).

According to PCD reports (PCD, 2015a, 2015b), improper disposal sites including open dumping, open burning, and incinerators operating without any air pollution control, totalled 1,970 sites countrywide. Nevertheless, the number of proper treatment plants increased from 93 landfills and three incineration sites in 2002 to 459 landfills, seven incineration plants without energy recovery, two incineration plants with energy recovery, two plants with Mechanical Biological Treatment (MBT) and 12 integrated systems (including waste processing, combined with sorting facilities and biological treatment such as composting or anaerobic digestion) in 2014 (PCD, 2001-2014, 2015b). Out of 26.2 Mt of MSW generated in

2014, only 30% (7.9 Mt) was properly disposed of at 480 sites, including sanitary landfills (7.05 Mt of MSW), composting (0.05 Mt), incineration (0.39 Mt) and other processes (0.35 Mt from mechanical treatment (MT) and mechanical biological treatment (MBT)), whereas 18.3% (4.8 Mt) was recovered.

In the context of Thailand, the most suitable MSW treatment system is a composting system, as a high proportion of organic or food waste (approximately 60%) is found in the MSW stream (AIT, 2004). However, it should be noted that Thai people discard mixed waste into garbage bins. Therefore, it is difficult to separate organic waste completely by using MBT for producing high quality compost. Incineration can be used to treat mixed waste, but it may increase operational costs and release pollutants, such as dioxin and other substances, due to its high moisture content and resulting low system temperature.

As mentioned above, the concept of an Integrated Solid Waste Management System (ISWM) has a key role for resource use through the application and selection of waste management strategies and technologies appropriate to waste characteristics (Shapkota et al., 2006). It comprises the use of various practices to handle MSW effectively by using many techniques such as source reduction, recycling, energy recovery, and waste disposal (e.g., composting, combustion, and landfilling). Waste minimization before disposal not only reduces consumption of raw materials and saves energy during processing, but also reduces the cost of MSW management and minimizes environmental impacts.

3.5.2.2 Waste recovery and utilization

Due to the current lack of sorting at source, the total of potential recoverable MSW fractions in Thailand is estimated to be 83.4% by 2025; these can be divided into 58.2% compostable and 25.2% recyclable wastes (Shapkota et al., 2006). **Table 3.1** shows the target and achievement of MSW plans. It shows that the amount of MSW is increasing, while the recovery rate is decreasing. However, the government has been promoting recycling as a major sustainable waste management activity and this has progressed significantly. Recycling includes many activities such as separation, collection, sorting or pretreatment, and conversion into useful products. The informal sector also plays a role in resource recovery. The “Salengs” use tricycles and collect recyclable materials from households, and a private company, Wongpanit Company Ltd., is the biggest recyclable wastes trader and service center with a number of branches nationwide, as well as in nearby countries (Shapkota et al., 2006). In addition, waste recycling activities at schools, communities, and sorting facilities also play an important role in promoting recycling (Singhirunnusorn et al., 2012; Suttibak and Nitivattananon, 2008).

To manage MSW effectively and to reduce the amount of MSW landfilled, the existing use of MSW generated in Thailand can be classified into three portions, namely recycling, composting and biogas, and energy recovery or WTE. In 2014, out of a total of 26.2 Mt of MSW generated, only 4.8 Mt was recovered, consisting of 3.63 Mt from recycling, 1.07 Mt used for composting and biogas; and 0.10 Mt for energy generation (PCD, 2015a). Recently, waste recovery processes have become more attractive for MSW treatment due to the associated benefits gained from recycling and energy production.

3.5.2.3 Policies related to MSW management

Thai environmental management has been driven by the *Enhancement and Conservation of National Environmental Quality Act B.E. 2535 (1992)*. With regard to the act's requirements, Thailand established a guideline for the country's environmental administration, namely *the Policy and Prospective Plan for Enhancement and Conservation of National Environmental Quality B.E. 2540-2559* (1997-2016) (ECNEQ). This policy has been introduced as the nation's long-term plan and the *Environmental Quality Management Plan* (EQM) is the nation's medium-term plan. These approaches were influenced in particular by the Agenda 21 framework and are being implemented. In 2016, ECNEQ was assessed and the latest plan formulated as *the (draft) Policy and Prospective Plan for Enhancement and Conservation of National Environmental Quality B.E. 2560-2579* (2017-2036) (ECNEQ). To ensure that sustainable development is implemented, the Ministry of Natural, Resources and Environment (MoNRE), the authority responsible according to the ECNEQ policy, formulated the national plan that covers a five year period (ONEP, 2012, 2015).

A MSWM plan targeting 30% recovery (for materials and energy) and 40% proper disposal of waste, and controlling waste generation up to 1.0 kg/day/capita were introduced by the government in *the 10th National Economic and Social Development Plan (NESDB, 2007-2011)*, but these targets have not been achieved (Vanapruk, 2012). The targets were replaced by *the 11th National Economic and Social Development Plan (NESDB, 2012-2016)*, which specifies 30% recoviery and 50% proper disposal (PCD, 2014d), as shown in **Table 3.1**. Based on the ISWM discussed in **section 3.5.2.1**, the latter plan was introduced to accelerate materials recovery (PCD, 2014a, 2014b, 2014c).

After fires broke out at several dump sites in Thailand, as mentioned in **section 3.1**, the management of MSW has become of national importance. The Thai government announced a roadmap for MSWM from 2014 and supports WTE implementation to overcome the lack of landfill space and environmental impacts from landfilling (PCD, 2014c). Recently, incineration technology with energy recovery has become more attractive for treating and reducing the large amounts of MSW generated, particularly in Bangkok and Phuket province, as further discussed in **section 3.7**.

Table 3.1: Targets of MSW management plan, 2012-2016

Targets/ achievement	2012	2013	2014	2015	2016
MSW disposal rate (target)	42%	44%	46%	48%	50%
MSW disposal rate (achieved)	24%	27%	-	-	-
Recovery rate (target)	27%	28%	29%	30%	30%
Recovery rate (achieved)	21%	19%	18%	-	-

(Source: PCD (2014d))

In terms of energy policy, the implementation of WTE in Thailand has been supported and enhanced by many organizations such as the Ministry of Natural Resources and Environment (MoNRE), Ministry of Energy, The Electricity Generating Authority (EGAT), Metropolitan Electricity Authority (MEA), Provincial Electricity Authority (PEA), Thailand Greenhouse Gas Management Organization (TGO) and Thailand's Board of Investment (BOI). The MoNRE is directly responsible for MSWM and provides the funding needed for local authorities to implement WTE projects by subsidizing 90% of capital costs and offers a low interest loan (ONEP, 2011, 2013).

The Ministry of Energy announced *the Alternative Energy Development Plan (AEDP)*, *Renewable Energy Development Plan (REDP)*, *Energy Conservation Plan*, and *Power Development Plan (PDP)* (Chotichananthawewong and Thongplew, 2012; Tongsopit and Greacen, 2013) with a renewable energy (RE) target contributing at least 25% of final energy consumption by 2021 (Tongsopit and Greacen, 2013). It is expected that 400 MW of electricity and 200 ktoe of heat will be generated from MSW by 2021 (DEDE, 2014). A financial incentive or Feed-in-Tariff (FiT) program, called the "Adder" program, was implemented in 2007. The different rates of Adder depend on technology type, contracted capacity, installed capacity, and project location; for instance, Adder for electricity generation from landfill gas (LFG) and anaerobic digestion (AD), and MSW-based thermal processes, are USD 0.075[†] and 0.105 per kWh respectively (Tongsopit and Greacen, 2013). However, weak regulatory support and lack of public discourse on the acceptable level of pass-through costs to buyers has been a problem in Thailand's FiT program (Tongsopit and Greacen, 2013). To tackle this problem, the FiT scheme was updated in 2013 (EPPO, 2015). The potential of MSW-based electricity generation is estimated to be 437 MW, but only 42.7 MW of electricity has been generated as of 2012 (DEDE, 2013; Sutabutr, 2012). The 11th NESDB Plan attempts to restructure the country's consumption behavior and production to prepare for a transition towards a Low Carbon Society (LCS) and environmentally sustainable economy (NESDB, 2012 cited from International Partnership on Mitigation and MRV, 2014). According to the LCS roadmap of Thailand, the share of renewable energy (RE) will increase from 360 ktoe in 2005 to 10,901 ktoe in 2050, of which the use of MSW as renewable energy is estimated to be 351 ktoe (Limmeechokchai et al., 2013). In this context, MSWM in Thailand offers a crucial link between the NESDB and AEDP (International Partnership on Mitigation and MRV, 2014).

One of LCS's objectives is efficient waste management, comprising waste minimization as a demand side option, and increasing waste recycling including WTE processes and disposal as the supply side option (World Bank and NESDB, 2011). For the supply side option, there are ten MSW-to-energy plants which were approved as Clean Development Mechanism (CDM) projects as reported by TGO and reviewed by Intharathirat and Abdul Salam (2016). The estimated annual GHG emission reduction potential from these plants is equal to 1.1 Mt CO_2eq and electricity generation is 35.8 MW (Intharathirat and Abdul Salam, 2016). The key challenges affecting the implementation of CDM projects in Thailand are the lack of understanding of potential CDM projects, high investment costs for implementation, stringency and very long period of approval and organizational capacity. Furthermore, CDM is quite a new area for investment for the banking sectors. Due to uncertainty of income and CDM additional requirements, many banks and the financial sector in Thailand have approved few loans for CDM projects (Pharino and Jaranasaksakul, 2009). Furthermore, BOI also promotes investment on WTE under two categories: i) production of alcohol or fuel from agricultural products, garbage, or wastes; and ii) electricity and steam generation (Kanasawat, 2012). BOI provides exemption on import duties for machinery and exempts tax on 100% of the ceiling investment for 8 years, excluding working capital and cost of land, as well as 50% tax exemption from the ninth to thirteenth year (Kanasawat, 2012).

3.6 **MSWM and WTE systems in selected Asian countries*:* A comparison**

In order to develop a deep understanding of the state of development of MSWM in Thailand, it is necessary to assess and compare MSWM and WTE implemented in other counties. Eight

[†] 1 USD = 33 Baht

Asian countries, including both developed and developing countries, were selected based on available data. In this study, 23 studies were reviewed and information gathered related to MSWM and WTE implementations as discussed below.

Table 3.2 presents and compares MSW characteristics and related challenges and opportunities in eight selected Asian countries. Out of these countries, only the three developed countries (Japan, Singapore and South Korea), have been aggressively improving their MSW systems. These three countries recycled about 60% of waste generated and have established WTE plants and converted 20 to 38% of total waste generated to energy (Chung, 2012; Seo, 2013; Themelis and Mussche, 2013). The outcome is that Japan and Singapore landfill only 2 to 3% of waste generated (Chung, 2012; Themelis and Mussche, 2013). In contrast, landfilling is the major option adopted in developing countries that are affected by many factors, such as rapidly increasing waste quantity, inadequate resources (i.e., funds and experts), inappropriate technology (technologies developed in developed countries are not suitable for developing countries due to the variation of waste characteristics), the lack of citizen participation and strong policies (Shekdar, 2009).

3.7 **Results and discussion**

Based on the methodological step used and MSW management systems reviewed and discussed (**section 3.3** to **3.5**), the possible options identified in this study are described here. Fifty respondents, including 46 entrepreneurs and operators from various MSWM systems and WTE plants, and four governmental officers (from MONRE, PEA, DEDE) were called by telephone and personally interviewed, whereas some were interviewed in person. The identification of these options depends on existing and successful practices inside and outside Thailand, suitability to Thailand's conditions, economics and environmental impacts. Due to the lack of waste separation at source and the difficulty in achieving the planned recycling target, this study therefore focuses on pretreatment and end-pipe treatment systems as described in **section 3.4**.

Although the WTE treatment system is represented in the hierarchy of sustainable MSWM systems, it is less preferable than 3Rs (reduce, reuse and recycle). MSWM systems have been widely assessed in term of mixed systems by various studies, as described in **section 3.2**. These studies simultaneously considered both WTE and other systems such as recycling, incineration, composting and landfill in one case study (Abba et al., 2013), whereas some studies considered only WTE systems (IC, GF, RDF and AD) (Suthapanich, 2014). Therefore, this study considers MSWM systems grouped into two categories: general MSW management and WTE treatment systems, so as to develop a deeper understanding of stakeholder preferences regarding waste-to-energy and other schemes.

Also based on general MSW management and WTE systems, as categorized in **step 3** of **section 3.3**, results of such systems are discussed here**.** In this study, the identification of MSWM systems include mechanical biological treatment (MBT), mechanical treatment (MT), recycling (Re), composting (CP) and landfill (LF), while WTE treatment systems generating electricity and heat consist of LFG, AD, IC, GF and RDF, as defined in **Figure 3.5** and detailed below**.**

A list of organizations permitted for selling electricity into the grid and the status of such permissions are presented in a review article by Intharathirat and Abdul Salam (2016) while a summarization of power produced from these plants is further described in **Figure 3.6**.

Table 3.2: MSW characteristics, challenges and opportunities in Asian countries

Country	MSW generated (10^6 tonnes)		Annual change (%)	Composition (%)							WTE practice[a]	Legislation/ challenges/ opportunities	Sources
				Combustible				Non-combustible					
	2005	2030		Organic	Paper	Plastic	Textile/ leather	Glass	Metal	Other			
Japan[c]	51	49	-0.16[d]	26	46	9	-	7	8	12	40 Mt (2004), 1673 MW (2009)	• Strict government rules and very limited land. • Transportation of collected MSW from one municipality to another is not allowed. • WTE has been implemented since 1970s. • Recycling was legally mandated in 1990s. • Recycling-focused society[b] has been implemented since 2000. • 62% of MSW generated was thermally treated, 36% was recycled and composted and only 2% was landfilled.	(Shekdar, 2009; Tabata, 2013; Themelis, 2006; Themelis and Mussche, 2013)
Singapore[c]	1.73	2.1	0.78[d]	44.4	28.3	11.8		4.1	4.8	6.6	2.6 Mt (2011), 198 MW (2007)	• Incineration technology has been built since 1979. • The target of "Sustainable Singapore Blueprint" is to increase recycling rate to 65% by 2020 and 70% by 2030. • 59% of total MSW generation was recycled, 38% was incinerated as WTE, and only 3% was landfilled.	(Chung, 2012; Mccrea et al.; Shekdar, 2009)
South Korea[c]	17	18	0.23[d]	25	26	7	29	4	9		3.1 Mt (2010), 4.5 TWh (2007)	• Enforcement of the use of disposal bags for households in 1995 and separate collection of food waste in 2005. • Food waste decreased from 36.1% to 13% and lower heating value (LHV) increased from 8.16 MJ/kg to 11.92 MJ/kg in 2002 and 2011, respectively. • "Waste to Energy Strategy Plan" aims to increase energy recovery from current level of 32% to 100% by 2020. • Target of increasing RE for 10% of the national by 2030. • 61% of total waste generation was recycled or composted, 20% was incinerated and 19% was landfilled.	(Cheng and Hu, 2010; Ryu and Shin, 2012; Seo, 2013; Shekdar, 2009; Themelis and Mussche, 2013; Zhang et al., 2010; Zheng et al., 2014)
China	190	480	3.78[d]	35.8	3.7	3.8		2	0.3	47.5	40.2 Mt[e], 2,200 MW (2013)	• WTE has been implemented since 1990s. • Adder: USD 0.04 per kWh for co-firing power plant. • China has developed its own in-house technology (CFB[f]) especially adapted for their MSW since 1990s. • Recycling and source separation have been launched since 2000 but there is still almost no MSW recycling in China. • 17% of MSW is used in WTE facilities while the majority of waste is still being landfilled.	(Cheng and Hu, 2010; Shekdar, 2009; Themelis and Mussche, 2013; Zhang et al., 2010; Zheng et al., 2014)

Table 3.2: MSW characteristics, challenges and opportunities in Asian countries (Cont.)

Country	MSW generated (10^6 tonnes)		Annual change (%)	Composition (%)							WTE practice[a]	Legislations/ challenges/ opportunities	Sources
				Combustible				Non-combustible					
	2005	2030		Organic	Paper	Plastic	Textile/ leather	Glass	Metal	Other			
India	57.86	225.15	5.61[d]	42	6	4	4	2	2	40	24 MW (2011)	• More than 90% of MSW generated is disposed of in landfills. • Lack of waste segregation at source, low efficiency of collection, inefficient recycling and private participation in MSWM. • A number of WTE plants have all met with failure due to lack of financial support, logistical planning and a strong policy framework for WTE process.	(Kalyani and Pandey, 2014; Shekdar, 2009)
Indonesia	31.31	114.15	5.33[d]	74	10	8	2	2	2	2	2 MW (2010)	• The government is starting to place emphasis on the importance of clean, new, and renewable energy applications. • There are no specific guidelines or regulations concerning compliance of MSWM. • There is no specific target of WTE from RE[g].	(Aprilia et al., 2010; Shekdar, 2009)
Malaysia	6.97	9.82[h]	3.00	40	15	15	3	4	3	20	-	• Lack of policy to promote 3Rs and low public participation. • Recycling is the only mechanism promoted to reduce solid waste before landfilling, however, the recycling rate is too low at below 5% of total waste generation. • Recycling targets in specific sectors by year 2020 are 14% of total waste generation from municipality, commercial and industrial sectors, and 30% from the construction sector.	(Abas and Wee, 2014; Noor et al., 2013; Shekdar, 2009)
Thailand[j]	14.32	20.42	1.40	64	8	17	2	4	2	3	42.7 MW (2012)	• Health and environmental impacts, explosive risk and scarcity of landfilling. • Two MSWM targets: 30% recovery (15% achieved) and 50% of waste properly treated by 2016. • RE target of 25% by 2030 including energy from MSW is 400 MW of electricity and 200 ktoe of heat. This approach is subsidized per kWh USD 0.075 for biochemical and USD 0.105 for thermal processes. • 19.1% of MSW generated was recycled and composted. Only 0.4% of waste was used for WTE, 27% was disposed of properly, and 53.5% was disposed of improperly. • The Roadmap of MSWM focuses on waste recovery, particularly WTE technologies has been announced in 2014.	(AIT, 2004; Intharathirat et al., 2015; PCD, 2004, 2014a, 2014c; Sutabutr, 2012)

[a] Amount of MSW used (in year) as fuel for WTE (in year) approaches, [b] Society separates combustible and non-combustible materials

Remarks: [c] As the service is provided to the total population, population is considered for the entire country, [d] adapted from Shekdar (2009), [e] 40.2 Mt is estimated by the author from 110,000 t/d of waste incinerated, [f] Circulating Fluidized Bed technology, [g] RE is defined as Renewable Energy, [h] This value is estimated by year 2020, [j] MSW collected

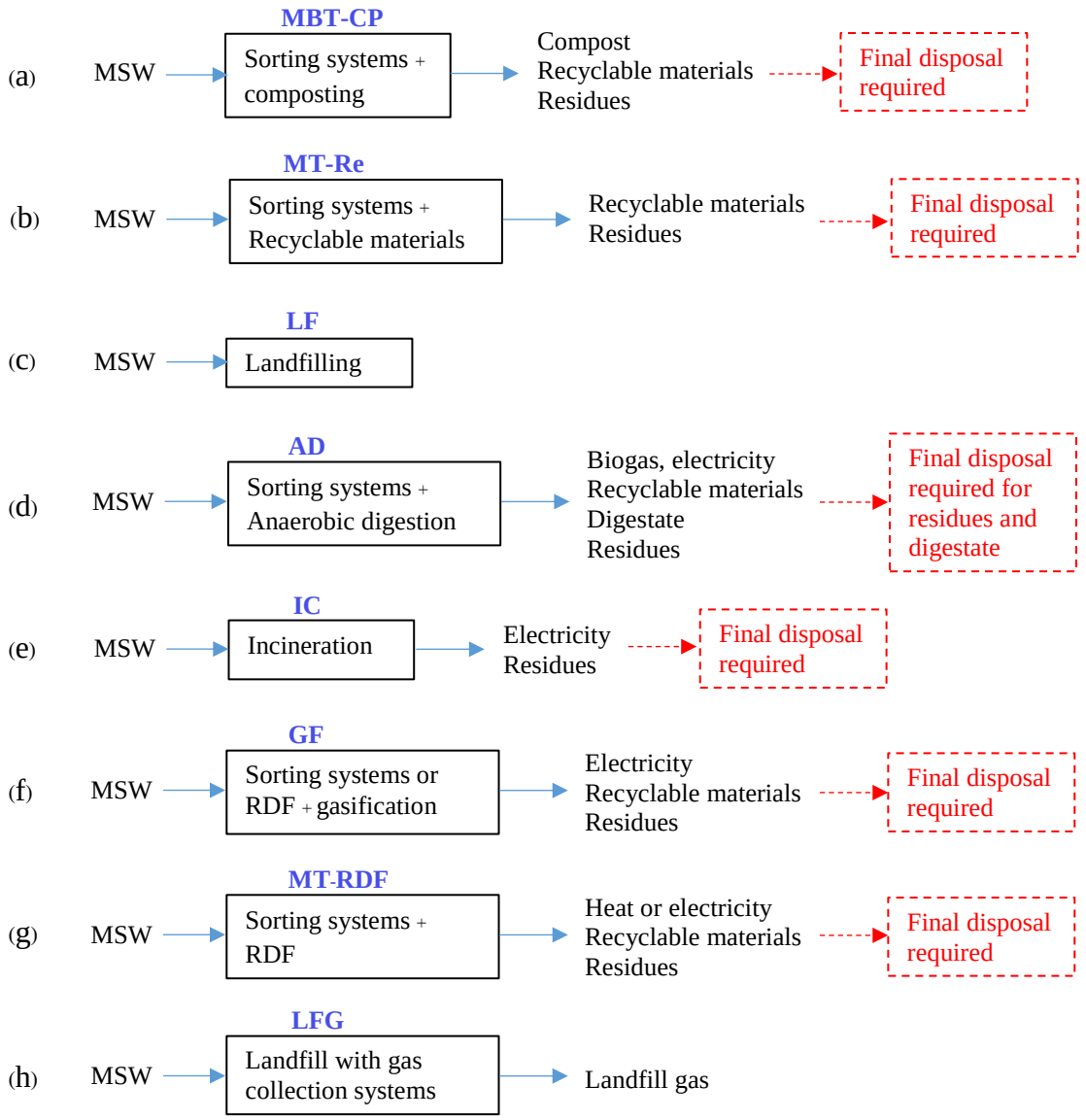


Figure 3.5: General MSW management and WTE systems: (a) MBT-CP; (b) MT-Re; (c) LF; (d) AD; (e) IC; (f) GF; (g) MBT-RDF; (h) LFG

3.7.1 MSW management system options

This section identifies three options for waste management systems, namely mechanical biological treatment combined with composting (MBT-CP); mechanical treatment (MT) for sorting recyclable wastes combined with recycling (MT-Re); and Landfill (LF), as shown in **Figure 3.5** (panels a to c respectively) and described below.

1) Mechanical biological treatment combined with composting (MBT-CP)

The mechanical biological treatment (MBT) system is a type of waste processing facility that combines a sorting system with biological treatment, including composting (CP) and/or anaerobic digestion (AD). The MBT system is designed to process mixed household waste as well as commercial and institutional wastes and is defined as a recycling system. MBT-CP

does not only have a high position on the hierarchy of sustainable solid waste management, but also has collective potential to divert MSW from landfill (Annepu, 2012). MBT and CP systems which have been operated by the private sector were identified specifically due to their success for treating organic waste in Bangkok.

The Bangkok Metropolitan Administration (BMA) estimated that the proportion of organic waste generated in Bangkok is in the range of 49 to 61% which has a potential to be converted to compost (BMA, 2009). However, out of 8,834 tonnes of MSW generated daily in Bangkok, approximately 12% was converted to compost (BMA, 2009). This compost is utilized in green areas within Bangkok and reduces the budget for soil fertilizer. The MBT system is also used to separate organic wastes, which are then fed into the CP system to produce compost in Nakhon Ratchasima and Rayong municipalities; however, mixed waste fed into these facilities can cause machinery to malfunction.

According to Storey et al. (2015), management of MSW in secondary cities and small towns is implemented successfully in Sri Lanka and Viet Nam because the fractions of MSW in these cities consist of high organic waste (50-80%) and recyclable materials (10-20%). They found that waste-to-resource initiatives (composting, anaerobic digestion and recycling) are viable options, although it depends on many factors such as sorting at source, effective participation of communities, predictable sources and steady revenue. In this study, therefore, the MBT-CP (aerobic composting, static pile process) system is considered as an option that is low-tech, low-cost, decentralized and community based for managing MSW in medium and small cities, as defined in **Figure 3.5** (a). In addition, Masood et al. (2014) noted that before increasing compost production, it is very important to create a strong market for the sales of compost. For instance, the percentage of organic waste in the waste stream of Lahore is high and there is already a composting facility in place. The maximum capacity of the composting plant should be utilized as a first step to diverting more waste from being landfilled. Currently, the plant receives mixed waste and processes only 650 t/d out of the 1,000 t/d received. Waste used in the composting plant is mixed waste from households, which substantially reduces the quality of the organic component of waste. Collection of source-separated organic waste directly from restaurants, and fruit and vegetable markets, could significantly improve compost quality.

2) Mechanical treatment combined with recycling (MT-Re)

Mechanical treatment (MT) is a primary process of solid waste management or is usually an automated mechanical stage for sorting. This either removes recyclable materials from a mixed waste stream (such as paper, plastics, glass and metals) or processes them. It typically involves factory style conveyors, manual sorting, eddy current separators, industrial magnets, shredders, trommels, and other tailor made systems. The MT has a number of similarities to a materials recovery facility (MRF). Some systems integrate a wet MRF to separate by density and floatation, and recover and wash recyclable elements of the waste in a form that can be sent for recycling.

In Thailand, there is a recycling waste business that buys recycling waste sorted at source from local communities. The waste separation plant is constructed according to the needs of recycling businesses. Some MBT systems, such as in Nakhon Ratchasima and Rayong, were designed alternatively to process mixed solid waste to produce RDF which can then be used as fuel in cement kilns or thermal power plants for generating electricity. However, it is not financially attractive to transport RDF for 150 kilometers from Nakhon Ratchasima to

Saraburi province. MBT in these cases producing RDF will be replaced by MT-RDF, as is discussed further in **section 3.6.2.3**. This study therefore proposes MT-Re as the second option for evaluating the most suitable waste management system for medium and small cities (as illustrated in **Figure 3.5** (b)).

3) Landfill (LF)

Landfill is a site where MSW is disposed of by burial and is the oldest form of solid waste treatment system in both developed and developing countries, including Thailand. In developed countries, pollution control facilities such as leachate collection and treatment and gas collection, may be strict to protect public health, and is called a sanitary landfill. Conversely, landfill is commonly used to dispose of solid waste in developing countries in response to cost efficiency, simplicity and the requirement of less manpower. Poorly managed landfill has potential for causing many problems such as contamination of groundwater or soil, dust, odor, and reducing local property values. Also landfill without a gas collection system generates methane from decaying organic waste and is reported as the highest potential source of greenhouse gases from human activities. In properly managed landfills, gas is collected and utilized, which may be simple flaring to landfill gas utilization (LFG) as discussed later.

In 2014, PCD (2015b) reported that there were 459 proper landfills categorized into two main groups: sanitary and engineered landfills (78 sites), and appropriate landfill of control dump (381 sites). Landfill (LF), as defined in this section, excludes improper disposal methods such as open dumping, controlled dumping and opened burning that are commonly used at a total of 1,923 sites in Thailand.

3.7.2 WTE system options

Based on the necessity to review existing WTE implementation, as discussed in **section 3.3**, details including pros and cons of each WTE technology, experiences and challenges, are described in this section. Before assessing WTE options in this study, their advantages and disadvantages, financial requirements, and energy production potential are presented below. A brief of selected WTE systems are then described. The assessment of existing WTE treatment systems was simultaneously presented to provide an overall picture of Thailand's situation on WTE implementation.

3.7.2.1 Waste-to-energy implementation

The choice of conversion process generally depends on feedstock types, its characteristics, desired form of energy, end use requirement, pollution control standards, economic performance, and specific factors of the project. In warm climate countries, most WTE technologies generate electrical power only, while RDF is used as fuel for both electricity production and heating, e.g, co-firing with coal in cement kiln industries. The financial and energy production potential of various technologies are compared in **Table 3.3** and **Figure 3.6** (Nithikul, 2007; PCD, 2008, 2012a). In **Figure 3.6**, average costs and energy generation values are used and it is assumed that one tonne of RDF can generate 300 kWh of electricity. This shows that incineration technology requires higher investment and operational maintenance (O&M) costs than other technologies, while it gives less power production per tonne of MSW than that of gasification technology. Among these technologies, LFG generates the lowest power with high investment and operating costs. The advantages and

disadvantages of each WTE technology are presented in **Table 3.4** (Arena, 2012; Bosmans et al., 2012; Cheng and Hu, 2010; Kalyani and Pandey, 2014; Suthapanich, 2014).

Table 3.3: Financial and energy production potential of WTE technologies

No.	Technologies	Optimum Size (t/d)	Appropriate heating value of MSW (MJ/kg)	Capital cost (Thousand USD/t)	O&M cost (USD/t)	Power generation potentials
1	Landfill gas	>100	No limit	28.48–37.88	7.79-28.24	More than 1.38 kWh electricity/tonne of waste (based on 20 years landfill lifespan)
2	Anaerobic digestion	>100	No limit (organic fraction >90%)	37.88–54.55	3.88-21.33	80–120 kWh electricity/ tonne of waste
3	Stoker incineration	75-500	≥7.0	45.45–196.97	24.24-60.61	150–200 kWh electricity/ tonne of waste
4	Fluidized bed incineration	>100	≥8.4	N/A	N/A	-
5	Pyrolysis	1–30	≥8.4	212.12–1060.61	N/A	-
6	Gasification	>15	≥7.0	60.61-148.48	19.33-30.42	170–190 kWh electricity/ tonne of waste
7	Refuse Derived Fuel (RDF)	>50	No limit	22.42–53.03	7.52-19.06	One tonne of MSW produced 0.43 tonnes of RDF; one tonne of RDF converted power more than 300 kWh

Remarks: N/A-not available
(Sources: Nithikul (2007); (PCD, 2008, 2012a))

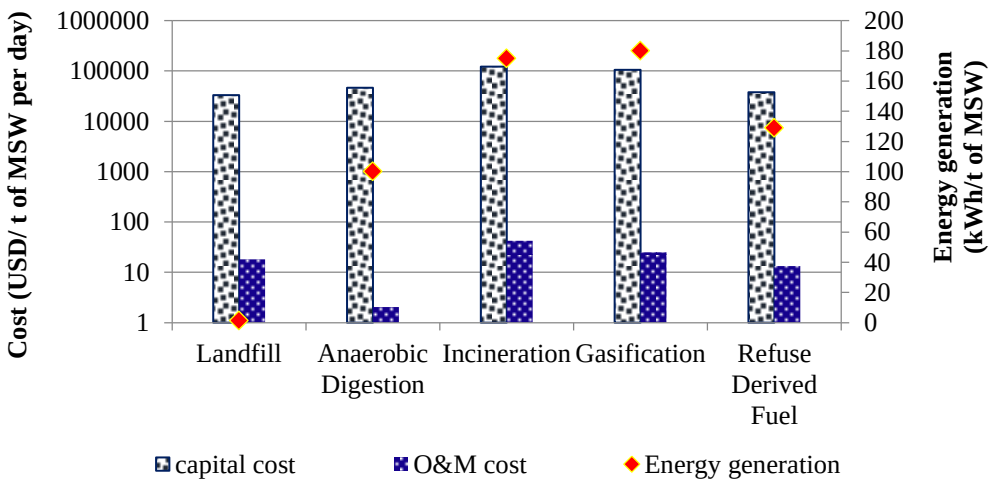


Figure 3.6: Financial and energy production of WTE technologies
(Sources: Nithikul (2007); (PCD, 2008, 2012a))

Table 3.4: Advantages and disadvantages of WTE technologies

Technologies	Advantages	Disadvantages
Landfill gas	Relatively low cost and easy to implement. Gas produced can be utilized for power generation or direct thermal application. Skilled personnel not required. Natural resources are returned to the soil and recycled. Can convert marshy land to useful areas.	May result in secondary pollution problems, including groundwater pollution, air pollution, and soil contamination. Yields only 30–40% of total gas generated. Large land area required. Cost of pretreatment to upgrade the gas to pipeline quality and leachate treatment may be significant. Spontaneous explosion due to methane gas build up. Due to public acceptance and space limitation, landfills are often far away from the places where waste is generated, necessitating long distance transport of waste and significant transportation costs.
Anaerobic digestion	Energy recovery with production of high grade soil conditioner. No power requirement for sieving and turning of waste pile. Enclosed system enables trapping gas produced and controlling GHG emissions. Free from bad odor, rodent and fly menace, visible pollution and social resistance. Compact design needs less land. Net positive environmental gains. Can be done on a small scale.	Unsuitable for wastes containing less organic matter. Requires waste segregation for improving digestion efficiency.
Incineration	Provides substantial reduction (by 90%) in the total volume of waste requiring disposal in landfill. Requires minimal preprocessing of waste The bottom ash from incineration is biologically clean and stable and can be used in road building and the construction industry. A very stable process, and virtually all wastes can be burned and the burning process can be adequately controlled. Heat from combustion can be used as an energy source for generation of steam or electricity. Incineration facilities can be located near residential areas, thereby reducing cost of transporting MSW to location of waste disposal. More optimal land use and more efficient integration of resources than landfilling.	Least suited for aqueous, high moisture content, low calorific value and chlorinated waste. Skilled personnel required. Toxic metal concentration in ash particulate emissions, SO_x, NO_x, chlorinated compounds, ranging from HCl to dioxins. More raw materials have to be used to replace those that have been incinerated, and it does not save energy in the long run as resources are not recycled. High capital and O&M costs. May discourage recycling and waste reduction. Overall efficiency for small power stations is low.

Table 3.4: Advantages and disadvantages of WTE technologies (Cont.)

Technology	Advantages	Disadvantages
Incineration	Units with high throughput and continuous feed can be set up Relatively noiseless and odorless Small footprint is required Hygienic	
Pyrolysis	Production of fuel gas/ oil, which can be used for various purposes Control of pollution superior compared to incineration	Net energy recovery may suffer in waste with excessive moisture High viscosity of pyrolysis oil may be problematic for its burning and transportation
Gasification	Syngas generated by gasification is easy to handle, meter, control and burn Smaller gas volume than that of incineration, so air pollution control equipment is smaller than that of incineration Can be designed for a small-medium scale	Syngas is toxic and potentially explosive, its presence requires a reliable control equipment Feedstock material must be finely granulated, pretreatment is necessary for MSW The required syngas conditioning and cleaning is today costly
	Improvement to quality of solid residues, and substantially reduces dioxins, furans and NO_x Syngas can be used in highly efficient internal-fire-cycles Syngas can be used to generate high-quality fuels or chemicals Possibility to recover material and energy content of the products	Plants tend to be more complex and difficult to operate and maintain since feedstock is converted in two steps (gasification and combustion) The overall efficiency is close to a combustion plant due to the consumption and losses of gasification and syngas clean-up
Refuse Derived Fuel	Clean technology Can apply with incineration (especially in cement kiln), pyrolysis and gasification Small disposal facility, which can be located near to the source of waste generation Small space area is needed Fuel can be stored for a long time	Need final disposal Smaller market for use worldwide

(Sources: (Arena, 2012; Bosmans et al., 2012; Cheng and Hu, 2010; Kalyani and Pandey, 2014; Suthapanich, 2014))

3.7.2.2 A brief of selected WTE system characteristics

In this study, options for WTE treatment systems were identified based on their implementation in Thailand and consideration of various criteria, as defined in **section 3.4**. Information on these options is provided here with regard to six or seven topics: technologies; energy production potential; advantages and disadvantages; policies promoting WTE implementation; experiences; challenges; and costs in Thailand and other countries.

This section provides a brief discussion about characteristics of selected WTE systems such as AD, IC, GF, RDF and LFG, as defined in **Figure 3.5** (d), (e), (f), (g) and (h) respectively. These systems are proposed as appropriate alternatives of waste management systems in

evaluating the most suitable option for medium and small cities (as further discussed in **Chapter 5)**.

1) Anaerobic digestion (AD)

Biogas produced from anaerobic digestion (AD) consists of 50-70% methane, 30-50% carbon dioxide, and traces of other gases such as hydrogen and hydrogen sulfide (Aggarangsi et al., 2013; Chaiprasert, 2011; Khalid et al., 2011). Biogas has a heating value of approximately 15–25 MJ/m^3 (Aggarangsi et al., 2013) which is lower than that of LPG (45 MJ/m^3) and CNG (36 MJ/m^3) (Abbasi et al., 2012). The methane yield of AD ranges from 250 to 350 m^3/tonne of waste depending on reactor types, temperature, hydraulic retention time, pH (5.5-8.5), organic loading rate, particle size, internal pressure and composition of input organic wastes (e.g., volatile solids, total solid, ammonia), and especially the carbon/nitrogen (C/N) ratio which is typically in the range of 10–35 (Divya et al., 2015; Nguyen et al., 2014).

In an AD plant, one tonne of organic fraction can be converted to 100–150 kWh of electricity (Braber, 1995). The amount of CO_2 emitted from this process is about 0.2 kg CO_2 per kWh (Murphy and McKeogh, 2004). Compared to other technologies, AD is a fully enclosed system and all biogas can be collected, which helps to reduce environmental impacts and GHG emissions (Baldasano and Soriano, 2000; Chaiprasert, 2011). One tonne of organic fraction waste in the AD system produces two to four times more methane than landfill does in six to seven years. In addition, municipal, industrial, and agricultural wastes can be co-digested successfully and efficiently. Particularly, co-digestion of MSW and industrial sludge with a ratio of one to two yields higher amounts of methane gas, compared to MSW alone (Khalid et al., 2011). Also the quantity of biogas produced from cow dung is higher than that from paper waste, while the quality of biogas from paper waste is higher than cow dung. Thus, co-digestion of paper waste with cow dung is preferred compared to individual use (Ofoefule et al., 2010).

In 2012, in Thailand, there were 540 anaerobic digestion systems installed by local authorities and schools which could use 7,884 tonnes of food waste per year and produce 492,750 m^3 of biogas (Sharp and Sang-Arun, 2012). Almost all biogas is used for heating, such as for cooking or warming piglets in swine farms, though only a few anaerobic digestion systems can be operated continuously because of their complexity and insufficient biogas supply for heating (Sharp and Sang-Arun, 2012). In the context of biogas generated from MSW and produced electricity, there are four plants which are under operation: i) Thai VSPP company; ii) Rakbanrao company; iii) Thung Song Renewable Energy power plant company; and iv) Nakhon Ratchasima municipality, as detailed in Intharathirat and Abdul Salam (2016). Four plants stopped their operation due to the unavailability of sufficient feedstock. The total potential for electricity generation is about 2.5 MW based on existing and ongoing construction of plants; through the use of 595 tonnes of MSW per day as feedstock. Unsorted MSW causes inefficiency in plants resulting in low biogas production. In 2014, the capacity of AD plants and electricity generation were approximately in the range of 5 to 350 t/d and 0.034 to 1.0 MW respectively. In terms of environmental and social performances, AD is more effective and gives better benefits than that of landfilling and thermal processes (Sharp and Sang-Arun, 2012).

Two AD plants that belong to Rayong and Chonburi municipalities halted operations because of the insufficient amount of organic waste required by these systems. An AD system can treat MSW with high efficiency if the organic fraction is separated. However, a key challenge

of the AD process for conversion of wastes to energy in developing countries, including Thailand, is the purification of MSW to biodegradable organic wastes as feedstock (PCD, 2012a; Sharp and Sang-Arun, 2012; Singh et al., 2011).

As shown in **Table 3.3** and **Figure 3.6**, in Thailand the cost of generating electricity from MSW using AD is approximately USD 0.02 per kWh which is less than that in India with USD 0.05 per kWh (Yadav et al., 2011). The capital and O&M costs related to the Rayong municipality plant are approximately USD 84,848 per tonne and USD 18.3 per tonne respectively (PCD, 2012a), which are very high compared to grid-supplied electricity of only 0.6 MW. It should be noted that this includes the capital costs of the integrated solid waste management system, landfilling, and the separation system which is an important part for sorting organic wastes from mixed MSW.

2) Incineration (IC)

Incineration is a conventional combustion technology including mass burn or moving grate, rotary kilns and fluidized bed incineration (Bosmans et al., 2012). It can significantly reduce the amount of waste by 75% by weight and 90 % by volume, increase the life span of sanitary landfill, occupy less land and requires minimal pretreatment (Stantec, 2011; Zheng et al., 2014). However, it produces high amounts of flue gas which requires a large air pollution control system. Also it generally generates electricity with lower efficiency of up to 26% in a steam turbine generator system than that of a combined cycle turbine system that has an efficiency of about 54% (Bosmans et al., 2012). While dioxins used to be a serious environmental concern associated with MSW incineration (Vogg et al., 1987), the advanced design of incineration and emission control systems driven by stringent regulations in developed countries means that incinerators can now operate with emission of virtually no dioxins (Cheng and Hu, 2010). As shown in the results, MSW incineration technology requires the highest capital and O&M costs compared to other technologies presented in **Table 3.3** and **Figure 3.6**.

According to Intharathirat and Abdul Salam (2016), approximately 16,000 t/d of MSW will be properly disposed of by 15 incineration plants associated with 268 MW of electricity generation in Thailand. Among these, two MSW incineration plants are under operation and generating 34 MW of electricity. Four plants under construction and eight plants at the planning stage will generate 84.1 MW and 147.4 MW of electricity respectively (DEDE, 2013; ERC, 2014; PEA, 2013). Moving grate stoker and circulating fluidized bed (CFB) incinerators with the capacity of 240–500 t/d and 500–2700 t/d respectively, are mostly used in Thailand. Similar technologies are mostly being used in China. Although the fluidized bed incineration technology of co-firing MSW with coal in China is promising, the capacities of such incinerators are limited to the range of 100–500 t/d (Cheng and Hu, 2010) till now. The net electrical efficiency and capital cost of incineration plants in European countries are around 15% and USD 700–1300 per tonne MSW (Murphy and McKeogh, 2004).

In 2010 a private company invested in two units of incinerators totaling 700 t/d generating 14 MW of electricity in Phuket (Phuket Municipality, 2013). The Moving Grate Stoker incinerator is used for this plant, and received[‡] MSW can be fed into the incinerator after separating bulky particles. However, the received MSW still contains high moisture due to a

[‡] As received is defined as a heterogeneous feedstock containing materials with widely varying sizes, shapes, and composition

large amount of food waste. A 1,000 t/d storage pit has been divided into three zones for arranging and reducing moisture content of MSW from 57.61 to 46.56%, which increases the lower heating value from 5.0 to 5.9 MJ/kg (Phuket Municipality, 2013).

After fires that broke out at several dump sites in Thailand (as mentioned earlier), incineration technology has become more attractive for treating and reducing the large amount of MSW generated. The TPI Polene company has invested in the largest refuse derived fuel (RDF) plant to replace coal consumption in cement kiln processes, and has a potential to generate 180 MW of electricity. This company started operation of a 20 MW MSW incineration plant since early 2014 using a circulating fluidized bed technology. The capacity of the plant is 500 t/d of RDF.

3) Gasification (GF)

Gasification involves an incomplete oxidation of organic compounds and converts combustible waste to syngas or producer gas at temperatures in the range of 500 to 1800°C. Syngas comprises carbon monoxide, hydrogen, methane, carbon dioxide, water, nitrogen, argon, solid carbon and contaminated substances such as tar, particulate, chloride, alkali metals, and sulphide (Arena, 2012; Fabry et al., 2013). It contains chemical components that have a calorific value depending on the oxidizing agent used and burnable gases rather than the energetic value of flue gas from incineration (Arena, 2012; Bosmans et al., 2012). The amount of air pollutants, particularly dioxins and furans, emitted from gasification is typically reported to be less than incineration (Arena, 2012; Gesell et al., 2008). Furthermore, the types of air pollution control devices may be similar, but are less expensive and smaller in size than incineration. This shows higher efficiency and energy recovery along with lower investment costs than for incineration (Gesell et al., 2008) (as shown in **Figure 3.6**). Therefore, gasification technology has greater potential to treat MSW in the future because of easy handling and burning of syngas, efficient conversion, lower air pollution, as well as the capability to scale-down the technology. The conversion efficiency of gasification is in the range of 30–40% for a single cycle steam power plant and can be up to 60% for a combined cycle gas turbine (CCGT) power plant (Fabry et al., 2013).

There are three main types of MSW gasification technologies that are commercially available and commonly used for energy recovery and associated with sustainable waste treatment. These can be classified based on the type of reactor: downdraft; updraft; and fluidized bed, which consists of bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) (Arena, 2012; Bosmans et al., 2012; Fabry et al., 2013). Around 100 successful gasification plants using MSW are in operation worldwide, which are mostly in Japan but also in Europe and Korea (Arena, 2012; Bosmans et al., 2012; Gesell et al., 2008; Stantec, 2011). Many commercial scale gasification technologies have been improved and developed in Japan and China (Castaldi and Themelis, 2010; Fabry et al., 2013). Japan is the world leader in plasma and high temperature gasification, primarily due to regulations that require vitrification of ash prior to final disposal. China is leading in the development of CFB, downdraft and updraft gasification technologies which will likely be the next generation of WTE thermal conversion systems installed (Castaldi and Themelis, 2010).

In Thailand, there are two gasification plants in operation, located in Phijit and Songkla. These plants use CFB and two-stage gasification (updraft and ash melting) technologies and totally treat 259 t/d RDF or 602 t/d of MSW and generate 7.2 MW of electricity. Due to the mixed MSW delivered, these plants use RDF as the proper feedstock. A private company has

signed a concession contract with the Had Yai municipality for 25 years and invested approximately USD 19.7 million for the Songkla plant. However, the operating and maintenance costs of these MSW gasifiers are not available. One BFB gasification plant has stopped operation because of the heterogeneous characteristics of waste, inefficiency of the conversion system, economic infeasibility and limitation of available commercial plants (DEDE, 2013; ERC, 2014; PEA, 2013).

Currently, nine gasification and one pyrolysis plant have potential operation with the generation of 28.04 MW of electricity recovered from MSW associated with approximately 1,983 t/d of waste treated properly. Thailand has no regulation to prohibit transportation of MSW from one municipality to another as in Japan. As a result, most WTE plants in Japan are relatively small compared to those in the US (Themelis and Mussche, 2013). This causes Japan to be a largest user of MSW gasification in the world, which are relatively new compared to the well-known grate combustion technologies and they are generally more expensive than grate combustion and CFB (Themelis and Mussche, 2013).

Major challenges of gasification technology are technical and economic problems, mainly related to the highly heterogeneous feedstock of MSW and the relatively number of plants worldwide which have been operating continuously under commercial conditions. However, investment and O&M costs per unit of electricity produced are lower than that of incineration. Improvement of commercial advanced gasification technologies with lower costs for syngas cleaning and higher electric energy conversion efficiencies is needed (Arena, 2012).

The capital cost for thermal energy and electricity generation per kW is in the range of USD 180–270 and USD 540–810 respectively (IISc, 2000-2004). The operational cost is approximately USD 0.05–0.07 per kWh (NRI, 2012; Wu et al., 2002), while the parasitic load and CO_2 emissions are about 20% of power generation and 114 g CO_2/kWh respectively (Niessen et al., 1996).

4) Mechanical treatment combined with refuse derived fuel (MT-RDF)

MSW is a more complex feedstock for thermal treatment processes associated with energy recovery. The use of ‘as received MSW’ in the WTE plants can lead to operational problems and low quality products. More advanced technologies of thermochemical processes require a high calorific value feedstock to obtain higher efficiency, easier handling, storage, and transportation. Therefore waste derived fuels are often used as a feedstock in WTE treatment plants (Bosmans et al., 2012; Gendebien et al., 2003). There are three main types of waste derived fuels such as Refuse Derived Fuel (RDF), Solid Recovered Fuel (SRF), and Automotive Shredder Residue (ASR) (Bosmans et al., 2012) which can be directly obtained from ‘fresh’ MSW and excavated from landfilled wastes. RDF is classified into seven types based on MSW pre-sorted as per the American Standards for Testing of Materials (ASTM) E-75 (Nithikul, 2007). For fresh MSW, RDF is normally produced from mechanical biological treatment (MBT) that gives two main outputs: RDF presenting a high calorific value due to its increased content of paper and plastics and stabilized organic waste (Di Lonardo et al., 2012). The manufacturing process of RDF typically consists of screening, shredding, size reduction, classification, separation, drying, densification and storage (Tippayawong and Vichadee, 2009), which needs to be imported for developing countries. The calorific value of RDF should be higher than 15 MJ/kg and moisture content should also be lower than 25% (Caputo and Pelagagge, 2002; Di Lonardo et al., 2012; Nithikul et al., 2011; Prechthai et al.,

2006). The most critical factors of selecting alternative fuels in cement kilns by co-firing RDF with coal are moisture content (about 10–15%) and calorific value (should be more than 16.7 MJ/kg) (Aimmanee, 2012; Kara, 2012). On the other hand, Prechthai et al. (Prechthai et al., 2006) reported that excavated MSW has potential to produce RDF given its high calorific value, and therefore reduce the volume of waste disposed of in landfill and increase landfill lifetime. The calorific value of excavated MSW from a dumping site (e.g., 29.5 MJ/kg) is higher than that of RDF from fresh MSW (e.g., 19.4 MJ/kg). However moisture content and heavy metal contamination in excavated MSW exceeds the standard of RDF. As a result, a trammel screen can effectively be used to separate the soil fraction (55%) from other waste components.

In Thailand, there are three existing incinerators and gasifiers power plants that use RDF as fuel. Similarly in Italy, out of the total 53 WTE plants, 17 of these use RDF as feedstock (Gendebien et al., 2003). RDF has high potential as an alternative fuel in industries when co-fired, e.g. in cement kilns and power boilers (Gendebien et al., 2003; Nithikul et al., 2011; Stantec, 2011; Tippayawong and Vichadee, 2009). Cement kilns can use RDF as co-fired fuel without any modification to the process due to their operation at very high temperatures of about 1,450°C (Gendebien et al., 2003; Nithikul et al., 2011). Other industries were not designed for using RDF because it contains 41% of plastics and requires specific burners as well as more air pollution control equipment to treat dioxins, furans and acid fumes (Nithikul et al., 2011). Since the cement industry consumes a large amount of energy, representing over 30% of its total production cost, the industry has high potential to make use of RDF (Kara, 2012; Lamas et al., 2013). Up to 15% of total energy in the cement industry could be substituted by RDF without much effect on clinker quality and gas emissions (Kara, 2012).

In Thailand, three cement companies have invested in sorting plants for RDF production: TPI Polene Company (TPI), Siam City Cement Public Company (SCCC), and Siam Cement Group Company (SCG) (Aimmanee, 2012; DEDE, 2013; Nithikul et al., 2011; PCD, 2012a; Rattanaruedeerom, 2012; Sriworanart, 2012). All three companies co-fire RDF in cement kilns, but TPI also generate electricity. Suitable RDF for cement kilns is characterized by at least 18.8 MJ/kg of calorific value, lower than 30% moisture content, as well as less than 1% chloride and sulphur. The separating systems of all companies were imported, comprising six units: pretreatment and receiving hall (size <300 mm), separation, size reduction (<90 mm), sorting, size reduction (<30 mm), and storage unit (Rattanaruedeerom, 2012). RDF and MSW from a number of local authorities including small, medium and large cities in ten provinces (Saraburi, Ayutthaya, Phathumthani, Nakhonnayok, Nakhon Ratchasima, Ratchburi, Burirum, Surin, Supanburi and Singburi) are delivered to cement kilns for co-firing and producing RDF respectively. In the first phase, TPI co-fire RDF with coal and produces 61.96 ktoe of heat and also generate 20 MW of electricity. This can reduce the use of coal by 5% and SCG can save 5 % of coal by using RDF. In addition, TPI is planning to invest in RDF plants to generate 60 MW and 100 MW of electricity in the 2nd and 3rd phase respectively (Rattanaruedeerom, 2012).

RDF technology clearly plays an important role in treating and reducing a large amount of MSW. However, key challenges in using RDF in cement kilns are the variation of input MSW characteristics, high transportation costs, need for sophisticated sorting technology and large storage. Furthermore, policy making, such as setting RDF standards, revised air quality emission standards and integrated waste management approaches at decentralized or centralized level are required to address the potential utilization of RDF (Nithikul et al., 2011).

5) Landfill gas (LFG)

LFG is a type of gas emitted from the fermentation of organic wastes in underground landfills. It contains 45–65% methane, 25–35% carbon dioxide and 10–20% trace elements such as nitrogen and oxygen. The calorific value of LFG is about 17 MJ/m^3 which is half that of natural gas (37.5-43 MJ/m^3) and pure cn (35.8 MJ/Nm^3) (Hamad et al., 2014; Noor et al., 2013; Zheng et al., 2014). Typically, the yield of LFG is in the range of 100–170 m^3/tonne of MSW depending on MSW characteristics, moisture content within landfills, the age and operation of landfill, and types of collection system (Bolan et al., 2013; Chen et al., 2010; Conestoga-Rovers & Associates, 2010; El-Fadel et al., 2012; Surroop and Mohee, 2011).

Two types of LFG collection system typically used are active and passive systems. An active collection system includes a prime mover that creates a vacuum at a landfill. A passive system relies on concentration or pressure gradients to function (Bolan et al., 2013; Dudek et al., 2010; Surroop and Mohee, 2011). A gas extraction well is the main part of these collection systems for achieving a steady state flow. The three wells used in practice are vertical, horizontal, and combined vertical-horizontal systems (Bolan et al., 2013; Chen et al., 2010; Conestoga-Rovers & Associates, 2010; Surroop and Mohee, 2011; SWICS, 2007).

The potential for electrical energy recovery from LFG is around 215 kWh/tonne of MSW (Latsios et al., 2009) or around 5.0 MJ/m^2 of the land used (Stöglehner, 2003), while emissions from producing electricity from LFG are estimated in the range of 1–1.2 kg of CO_2/kWh (Shin et al., 2005).

In 2002, there were 955 LFG plants around the world, most of which were distributed in the US and European countries (Chen et al., 2010). There were 26 LFG projects in China with approximately 56.8 MW of power production in 2008. In Thailand, there are ten LFG plants producing 23 MW of electricity from 54.75 Mt of MSW which is exported to the grid (DEDE, 2013; ERC, 2014; PEA, 2013). These plants are located at four landfill sites: Kamphaengsaen, Nakornphathom; Phanomsalakarm, Chachoengsao; Bang Plee, Samutprakarn; and Hod, Chiangmai, as shown in **Figure 3.8** (DEDE, 2013; ERC, 2014; PEA, 2013). MSW collected from the Bangkok Metropolitan Authority (BMA) is deposited at Kamphaengsaen, Phanomsalakarm and Bang Plee, while Hod receives MSW collected from Chiangmai municipality and other municipalities located near to the site. LFG collection systems cannot collect all gases and function at low efficiency (Pharino and Jaranasaksakul, 2009) capturing around 50–75% of LFG produced (Yedla and Parikh, 2002) with a yield of 110 m^3/tonne of MSW (Wang-Yao et al., 2004). Both vertical and horizontal pipes are used to collect LFG by using the active gas collection system. With a vertical layout of collection pipes, leachates sometimes flow into collecting pipelines which can block biogas flow and lessen the amount of gas collected (Pharino and Jaranasaksakul, 2009). Out of ten LFG plants, horizontal and combined systems are used in six plants because of the high water level in landfills (UNFCCC, 2013). According to Wang-Yao (Wang-Yao et al., 2004) horizontal extraction wells are more suitable for Thai landfills compared to vertical ones because of flooding. However, with fast degradable organic materials and non-uniform settlement of solid wastes, bending and damage to pipes may cause gas leakage as well as water blockage of gas extraction systems (Pharino and Jaranasaksakul, 2009). As a result, the vertical collection system is used in many LFG plants in Thailand, which is similar to China (Chen et al., 2010). Collected LFG flows into vertical wells with the active collection system comprising the header, cyclone, blower, cooling, and filters to clean the gas, and then the balloon and flexible storage lagoon to stabilize the amount of gases. Gases are transferred

from the balloon to the cooling system to reduce moisture content and temperature, and then flow into the gas engine (Thanombun, 2013).

Key factors that cause difficulty in estimating LFG generation are the types of waste or amount of degradable organic fractions and the decay rate of different organic wastes. These should be considered as factors for the uncertainty of prediction (Chen et al., 2010). The investment cost for LFG CDM projects is higher than that without CDM by USD 2–6 million. For instance, the investment cost of the Charoensompong company plant (in Panomsarakarm) is approximately USD 10.8–11.8 million for 1 MW of electricity, which is higher than that without a CDM project (USD 7.3–10.9 million), IRR at 13–23% and will break even in 4 years. At Kampaengsan, the investment cost (1 MW) is approximately USD 7.5–8.1 million which is less than that with a CDM project (about USD 13.0–13.9 million), internal rate of return (IRR) at 27–38% and will break even in 3 years (Pharino and Jaranasaksakul, 2009). However, due to the current declining price of CERs (Certified Emission Reduction), one LFG plant in Thailand halted operation in May 2013 due to capital loss from flaring methane gas only for the CDM project without any revenues gained from electricity production.

There has been no LFG project planned in Thailand since 2014 due to four influencing factors: i) citizen opposition that emerged after fires broke out at several landfill sites; ii) the huge amount of landfill space required for economic feasibility; iii) low electricity generation achieved, as presented in **Figure 3.7**; and iv) high investment and O&M costs as shown in **Figure 3.6**.

In developing countries, LFG plants are typically expensive with a capital cost of around USD 15,000 per kW (Kumar, 2000) and estimated operating cost and cost of electricity generation in the range of USD 61–115 per kW/year and USD 0.08–0.15 per kWh respectively (Bove and Lunghi, 2006).

As described above, the total potential of energy production from existing WTE plants and those under construction and planned is estimated to be 319 MW of electricity and 78 ktoe of heat, as calculated from this study and shown in **Figure 3.7** and **Figure 3.8** (DEDE, 2013; ERC, 2014; TGO, 2012).

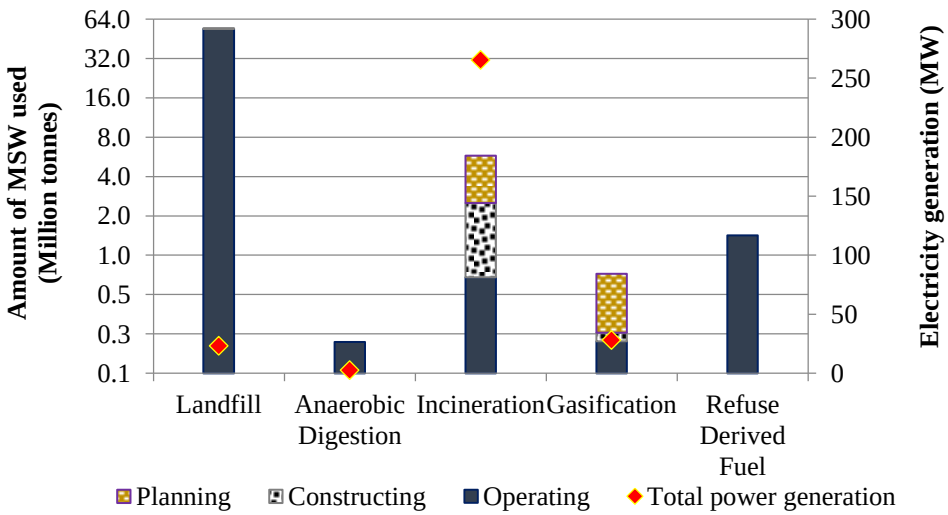


Figure 3.7: Total potential electricity generation from WTE facilities in Thailand

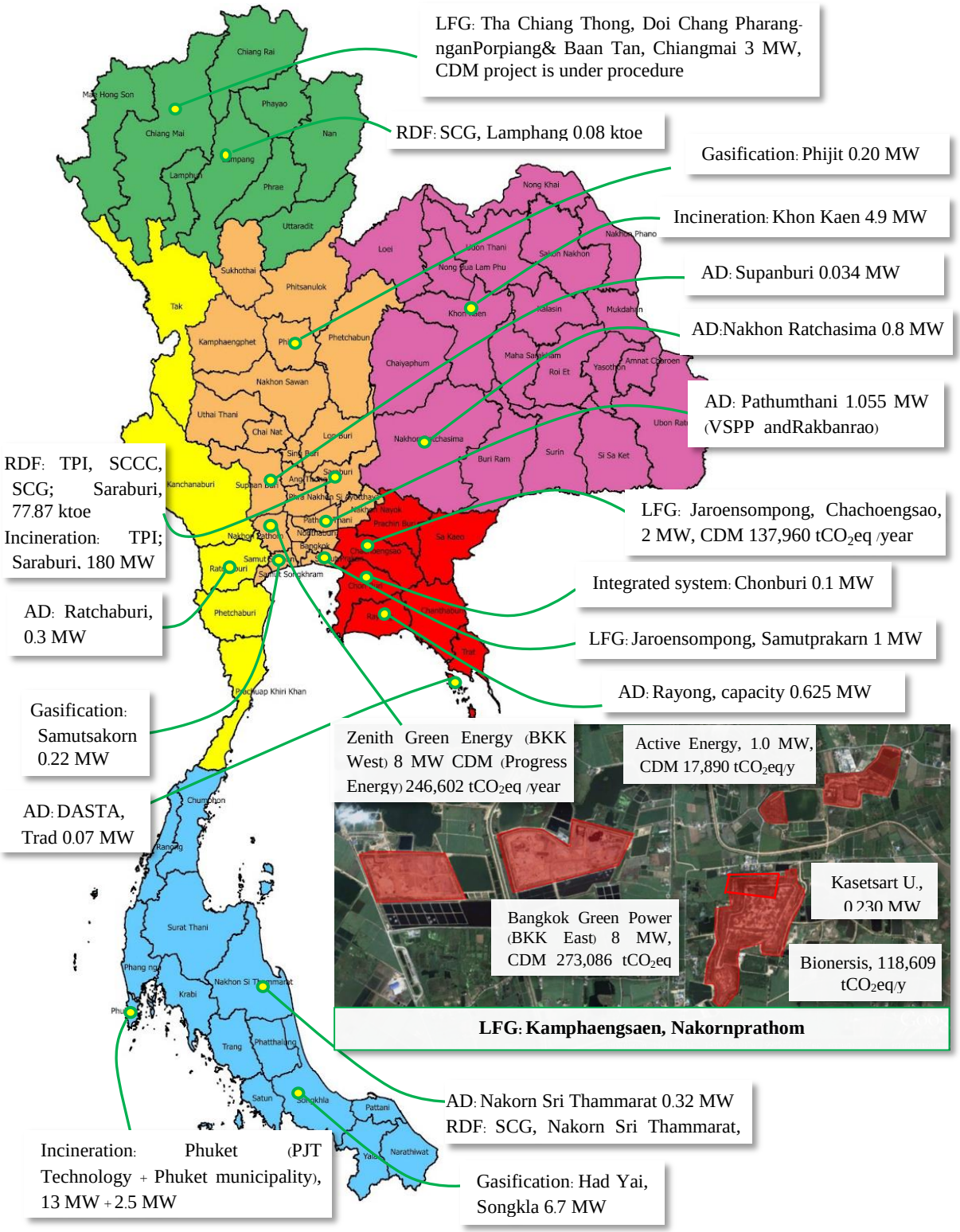


Figure 3.8: Existing and WTE plants under construction in Thailand (Source: (DEDE, 2013; ERC, 2014; TGO, 2012))

3.8 **Summary**

The background of MSW characteristics and its management in Thailand were discussed in this chapter. The reviews and assessment of the overall commercial MSW management and WTE systems in Thailand were identified and discussed based on available literature, interviews and site visits. The identification of MSW management systems consist of MBT-CP, MT-Re and LF. Based on positive experiences in Sri Lanka and Viet Nam, the MBT-CP system was proposed as a possible option for medium and small cities in this study, while there are others operational waste management systems in Thailand.

The existing WTE systems comprise AD, IC, GF, RDF and LFG. These WTE systems can be used to treat 2.54 Mt of MSW per year (9.5% of the total 26.8 Mt generated in 2013) and generates 66 MW of electricity and 78.26 ktoe of heat. It is estimated that about 8.17 Mt of MSW (30.5%) will be treated that will generate 319 MW of electricity and 78.26 ktoe of heat.

The AD system seems suitable for converting the high proportion of food waste generated. However, only 595 t/d of MSW is treated in AD plants that generate 2.5 MW of electricity. MSW sorted at source plays a key role for AD implementation to increase economic feasibility and efficiency of the plant.

IC is increasingly implemented to treat MSW and recover energy. Currently 1,863 t/d of MSW is used to generate 34 MW of electricity and it is expected that at the completion of the planned 15 plants a total of 16,152 t/d of MSW will be used to generate 268 MW. This technology becomes attractive for large cities due to the high subsidy provided by the government (i.e., USD 0.105 per kWh). Scaling down to suit smaller municipalities, high capital and O&M costs, and the lack of available technology are the main challenges of using this technology in developing countries.

The total RDF used and the heat produced through co-firing in cement kilns, excluding electricity generation, is approximately 0.36 Mt per year and 78.26 ktoe respectively. Total MSW treated in RDF plants is approximately 1.4 Mt per year or 3,893 t/d. Key challenges of using RDF in cement kilns are the variation of input MSW characteristics, high transportation costs, the need for sophisticated sorting technology, and large storage.

In 2014, there were ten LFG plants with landfill capacity of 54.75 Mt MSW and these generated 23 MW of electricity in Thailand. However, there has been no LFG project planned in Thailand since 2014 due to uncertainties of LFG produced in the landfills, high investment and operating costs, with low energy generated and particularly the large area of land required, as well as opposition from citizens.

Information discussed in this chapter will be used and proposed as possible options for evaluating the most suitable MSW management system in Thailand. The methodology of evaluating MSW management for medium and small cities is detailed and discussed in **Chapter 5**.

Chapter 4

Forecasting MSW Quantity Using Grey Models[§]

This chapter presents the current MSW quantity and the methodology for future forecasting of MSW quantity including consideration of associated influencing factors. Current and future MSW quantity with respect to representative factors from residential and commercial sectors in Thailand are also described.

Forecasting of MSW is introduced in **Section 4.1**. An overview of MSW forecasting models used in previous studies is provided in **Section 4.2**. **Section 4.3** describes a systematic methodology for formulating alternative models, identifying factors affecting MSW quantity, verifying models, and forecasting MSW quantity. **Section 4.4** presents the results and discussion containing the identification and quantification of influencing factors, and the development and verification of models. The summary is given in **Section 4.4.2**.

4.1 **Introduction**

To plan, manage and use municipal solid waste (MSW) in a sustainable way, an accurate forecasting of MSW generation and composition plays a key role (Batinic et al., 2011; Beigl et al., 2008; Cherian and Jacob, 2012; Kumar et al., 2011). However, due to a lack of sufficient reliable historical data of MSW characteristics, particularly in developing countries, it is difficult to develop accurate forecasting models (Rimaityte et al., 2011). Theoretically, more reliable data used in statistics-based forecasting gives greater accuracy. Failure of accurate forecasting and assessment may lead to several problems in environment and waste management systems, such as increased environmental impacts and over or underestimated capacity of MSW treatment facilities, as well as irrelevant policies. In the context of MSW management, it is necessary to understand how influencing factors (e.g., socio-economic and demographic factors) may affect MSW generation. A proper waste management system needs more detailed data on waste generation and composition (Beigl et al., 2008), as well as a clear-cut relationship between these data and influencing factors, such as socio-economic, demographic and geographic, which are poorly understood (Buenrostro et al., 2001). For instance, social factors concerning migration and population growth play a key role in influencing the accuracy of forecast MSW generation and the proper capacity of facilities (Pires et al., 2011b). A forecasting method offering low cost with high accuracy has always been a management goal (Hsu, 2009). Consequently, policy makers have constantly been looking for innovation and solutions to address this difficulty (Kumar et al., 2011), which is far from reaching general modelling standards (Beigl et al., 2008).

Given insufficient data in developing countries, the use of traditional or statistics-based models, such as regression analysis and time series analysis to forecast MSW generation may provide inaccurate results and incorrect validations. For instance, some regression analysis models using small data sets (less than 30 data values) give high coefficient of determination or R^2, values of nearly 1.0. However, this may not indicate a perfect fit for models because the thumb rules of regression analysis, namely normality of error distribution, linearity of the relationship between dependent and independent variables, multicollinearity and

[§] Part of the work described in this chapter has been published as follows: 'Forecasting of municipal solid waste quantity in a developing country using multivariate grey models', Intharathirat, R., Abdul Salam, P., Kumar, S., & Untong, A. (2015). *Waste Management*, *39*, 3-14.

homoscedasticity, were not checked before analysis. To address this problem, alternative forecasting models including traditional and innovative models were investigated and performances compared to select the best fit model. The selected model was then used to forecast the amount of MSW as illustrated in **Figure 2.2**. An overview of MSW forecasting models is presented in the next section to depict the principles and development of traditional and innovative models.

4.2 **An Overview of MSW Forecasting models**

Forecasting models are extensively used in many fields based on various theorectical approaches comprising linear and non-linear, white and grey, and statistical and mathematical bases. For MSW forecasting, statistics-based models can be widely used in developed countries because of the availability of sufficiently reliable data, while on the other hand, many studies have attempted to carry out accurate modelling to forecast MSW generation in developing countries based on limited data (Intharathirat et al., 2015; Yu et al., 2014; Yuan et al., 2012; Zhang, 2013). To better understand forecasting models, a review of existing models, highlighting their limitations, strengths and influencing factors used in each study, are discussed in the following sections.

4.2.1 A review of existing tools for MSW Forecasting

The choice of MSW forecasting method depends on considering four criteria: quantity and quality of available data (MSW generation and socio-economic factors); type of information (e.g., random or continuous data); relationship of various variables associated with MSW generation; and expected changes in MSW management (Rimaityte et al., 2011). Beigl et al. (2008) reviewed 45 methods used for forecasting MSW quantities, which were categorized into seven groups, namely correlation analysis, group comparison, single regression analysis, multiple regression analysis, time-series analysis, input-output analysis, and system dynamics.

Table 4.1 depicts a review of existing models which are widely used for forecasting MSW characteristics, focusing on regression analysis (RA), time series analysis (TSA), Artificial Neural Network (ANN), and an innovative Grey model (GM) used to forecast MSW generation with incomplete historical data. To serve as a very helpful methodology for forecasting MSW generation at different regional scales, the number of data used and regions studied, types of data (time series, cross-sectional, and panel data), level of data collected (country, city or household), and influencing factors studied from 50 studies are described in **Table 4.1** and discussed below.

1) Regression analysis (RA)

As per the 45 methods reviewed by Beigl et al. (2008), regression analysis is widely used to forecast MSW generation due to its mature theory and simple algorithms. Regression analysis is based on the configuration of semi-empirical mathematical models, requiring detailed historical data, but it is also impossible to consider all factors affecting waste generation (Noori et al., 2009b). However, regression analysis neither can learn from new data nor can adapt to new situations, and its precision is poor when inaccurate data are used

Table 4.1: MSW forecasting models and the hypothesis of influencing factors

Models	Methods used	No. of data	No. of regions	Type of data	Period forecasted	Level of data collection	Influencing factors considered: GDP	Income	Expense	Employment	Urbanization	Family size	Age	Population	Education	Waste generated rate	Other factors	Remarks	References
	Thailand																		
Regression	MRA	9	1	Y-TS	S	CO▼			+●(1)					+●(2)					Vanapruk (2012)
Regression	MRA	10	1	Y-TS	L	CI▼	+●1							+●					Mongkoldhumrongkul & Tharark (2012)
Regression	SRA	60	1	M-TS	L	CI▼	+●1									+●			Luanratana (2003)
Regression	SRA	12	1	Y-TS	L	CO▼													DEDE (2009)
Regression	MRA	96	1	M-TS	-	CI▼	●(1)	●(1)				●(2)		●(2)			no. of households(2), CPI(1)	Standardized coefficient compared	Sukholthaman & Chanvarasuth (2013)
Time series	TSA	16	1	Y-TS	L	CO▼	+●							+●		+●		Extrapolation	TGO (2010)
	Other countries																		
Statistics data analysis	CA	110	1CI/ 4*	CD	-	HH∇		+●(4)		+●(3)		+●(1)	○		+●(5)		(+) no. of rooms(2), marital status		Sankoh et al. (2012)
Statistics data analysis	PCA, CTA	21	1	Y-TS	-	CO▼	○	○	○		○						area of urban construction, area of paved roads, area of urban garden, no.of large cities, energy consumption	Among 3 groups, economic and urbanization are the most important.	Liu and Wu (2010)
Statistics data analysis	ANOVA	125	1CI	CD	-	HH▼		●				●			●				Ojeda-Benitez et al. (2008)
Regression	CA, MRA	100	1CI	CD	-	HH▼		+●(3)				-●(2)		+●2(1)					Thanh et al. (2010)
Regression	CA, MRA	400	6CO	CD	-	HH▼		-●		+○		+○			-●		no. of rooms		Monavari et al. (2011)
Regression	MRA	7 each	5CO	Y-TS	L	CO∇,▼	●				●			●	●3				Khajuria (2010)
Regression	MRA	243	1CI	CD	-	HH▼		+●(1)		○		+●(2)	○		○		no. of working dates, area of facilities, working hours per day	Studying on non-and-residential waste	Buenrostro et al. (2001)
Regression	MRA	542	1ST	CD	-	CI▲				○		-●(2)	○	○4,5			(-) heat(1),(-) tax(3), over night stay, percentage of building/area		Lebersorger & Beigl (2011)
Regression	MRA	422	1CI	CD	-	HH▼		+●		+●		-●					Tax, no.of vehicles in household		Bandara et al. (2007)
Regression	MRA	550	1CI	CD	-	HH▼		+●(2)				-●(1)			○		(-) tipping fee per household(3)		Aburhress (2013)
Regression	MRA	100	1CI	CD	-	HH▼		○				+●(1)	○		○		(-) dining out(2), home cooking rate, marital status, religion, sex, race, house category, ownership status, unit types, home cooking	Data collection at household level, conclusion at city level	Mohd.Yosof et al. (2002)
Regression	SRA	14, 34	2CO	Y-TS	-	CO▲	●		●					●				The EU and the US.	Daskalopoulos et al. (1998)
Regression	MRA	10	1	Y-TS	L	CI▼			+●(2)		+●(1)								Yuan et al. (2012)
Regression	MRA	NA	1	NA	NA	CO▼	●				●								Wang & Nie (2001)
Regression	MRA, CA, PCA, OLS	86	55CI, 32CO	PD, Y-TS	-	CI, CO▲	+●(4)					-●(1)	+●7(3)				Unemployment rate, (-) infant mortality rate(5), over night stay, (+) life expectancy at birth(2)	three prosperities were studied	Beigl et al. (2004)

Table 4.1: MSW forecasting models and the hypothesis of influencing factors (Cont.)

Models	Methods used	No. of data	No. of regions	Type of data	Period forecasted	Level of data collection	Influencing factors considered											Remarks	References
							GDP	Income	Expense	Employment	Urbanization	Family size	Age	Population	Education	Waste generated rate	Other factors		
Regression	FGLS	156	30 ^{CO}	PD	-	HH▲			+●$^{(3)}$		+●$^{(2)}$			+●$^{2(4)}$			(-) percentage of children$^{(1)}$		Johnstone and Labonne (2004)
	SVM, PLS-SVM	144	1	PD, W-TS	-	CI▼		●											Abbasi et al. (2013)
	SVM, WT-SVM	>240	2	W-TS	-	CI▼		●											Abbasi et al. (2014)
Time series & combined model	TSA	1-12 each	15 ^{CO}	PD	L	CO▲	●		●			●		●			no. of households, Gross value added	Individual forecasting of the EU countries.	Skovgaard et al. (2005)
	MRA,TSA (ARIMA, SES)	87, 384	1	PD, W-TS	L	CI▲	○			●		●	●				infant martality rate, life expectancy, % of labour force		Rimaityte et al. (2011)
	TSA (ARIMA), FA	29	1	Y-TS	L	CI▲	●$^{(2)}$							●$^{(3)}$			(-) no. of housing estates participated$^{(1)}$		Chung (2010)
	TA (SARIMA), GM (1, 1)	120, 10	1	M-TS	S, L	CI▼													Xu et al. (2013)
Grey models	GFM (1,1)	10	1	Y-TS	-	CI▼													Xiang & Daoliang (2007)
	GM (1,1), GFM (1,1)	14	1	Y-TS	S	CI▼													Chen & Chang (2000)
	GM (1,1)	10	1	Y-TS	L	CI▼													Guo (2009)
	GM (1,1),GFM, GRA, GRNN	13	1	Y-TS	S	CI▼	●$^{(3)}$	●$^{(2)}$						●$^{(1)}$					Srivastava & Nema (2006)
	GRA, GM (1,1), GIM (1), GPPM (1), GLPM (1)	13	1	Y-TS	L	CI▼	●$^{(4)}$	●$^{(7)}$						●$^{(6)}$			consumption of gas$^{(1)}$, water$^{(2)}$, and consumption of electricity$^{(3)}$, total retail sales $^{(5)}$		Liu & Yu (2007)
	MRA, GM	14	1	Y-TS	S	CI▼											No detail of factors of MRA and GM		Ying et al. (2011)
	GRA,GM(1,5)	10	1	Y-TS	L	CI▼	●$^{(4)}$		●$^{(2)}$		●$^{12(1)}$						sales of consumer goods$^{(3)}$		Wang et al. (2012)
	GM (1,5)	9	1	Y-TS	S	CI▼	●$^{(4)}$		●$^{(3)}$					●$^{(1)}$			retail sales$^{(2)}$		Zhang (2013)
Kuznets curve	EKC	275	25 ^{CO}	PD, Y-TS	-	CO▲	○		○		○	○	○	+●$^{2(1)}$			policies, (-) share of manufacturing$^{(2)}$	EU25 countries case	Mazzanti&Zobori (2008)
	MRA, EKC	11 each	6^{CI}	Y-TS	-	CI▼		●$^{(6)}$		-●$^{6(2)}$			-●$^{(3)}$	●$^{2(5)}$	●$^{(4)}$		(+) policy$^{(1)}$		Chen (2010)
Artificial Neural Network	OLS, ANN	120	1	M-TS	L	CI▼		+●$^{(3)}$						+●$^{(1)}$			(+) maximum temperature$^{(2)}$		Ali Abdoli et al. (2012)
	MRA, ANN	342	1	Y-TS	-	CO▲		-●$^{8(3)}$			+●$^{(4)}$			+●$^{(1)}$	+●$^{(5)}$		(+) no.of libraries$^{(2)}$		Ordonez-Ponce et al. (2004)
	ANN, PCA-MRA	158	1	W-TS	S	CI▼										●	no. of trucks		Noori et al. (2009a)

Table 4.1: MSW forecasting models and the hypothesis of influencing factors (Cont.)

Models	Methods used	No. of data	No. of regions	Type of data	Period forecasted	Level of data collection	Influencing factors considered											Remarks	References
							GDP	Income	Expense	Employment	Urbanization	Family size	Age	Population	Education	Waste generated rate	Other factors		
Artificial Neural Network	ANN	144	1	W-TS	S	CI▼										●	no. of trucks		Jalili Ghazi Zade & Noori (2008)
	ANN	54	1 CO	CD, W-TS	L	CI▼		●		●			●		●		Housing condition		Batinic et al. (2011)
	ANN	40	1	Y-TS	L	CI▼	●				●			●		●			Kumar et al. (2011)
	ANN	144	1	W-TS	-	CI▼										●	no. of trucks		Shahabi et al. (2012)
	ANN	384	1	W-TS	-	CI▼													Roy et al. (2013)
	ANN	98	1 ST	CD	L	CI▼								●		●	total received as tax, latitude, longitude		Patel & Meka (2013)
	WT-ANFIS, WT-ANN	240	1	W-TS	-	CI▼													Noori et al, (2009b)
Econometric	OLS, LES, MNL, SESY	25	1 ST	Y-TS	L	CI▼	●		●	○		○	○	○			unemployment, policies, saving rate, no.of households, ratio of family , Gini coefficient, Engel ratio		Weng (2009)
	SEM, OLS	NA	5 ST	Y-TS	-	CI▼											Urban road linghing(1), community health center visits(2), accommodation enterprises(3), passenger traffic volume(4), investment enterprises profit rate(5)	All factors affected to MSW positively	Yu et al. (2014)

Remarks: ○ denotes as insignificant factor, ● denotes as significant factor (as concluded in the literature reviewed).
(1), (2), …, (n) denotes the order of significant factors from the most important variables to the least one.
CI City region, CO Country region, ST State region, * Constituency region,
ANFIS - Adaptive Neuro-Fuzzy Inference System; ANN - Artificial Neural Network; ANOVA – Analysis of Variance; ARIMA - Autoregressive Integrated Moving Average; CA - Correlation analysis; CTA - Cluster Analysis; EKC - Environmental Kuznets Curve Hypothesis; FA – Factor analysis; FGLS – Feasible General Least Square; GFM – Grey fuzzy dynamic model; GIM - Grey index model; GLPM - Grey logarithm power model; GM - Grey model; GPPM - Grey parabola power model; GRA – Grey relational analysis; GRNN – General regression neural network; LES – Linear Expenditure System; MRA - Multiple regression analysis; MNL – Multinomial Logit; OLS - Ordinary Least Square; PCA - Principal Component Analysis; PLS–SVM – Hybrid Partial Least Square and Support Vector Machine; SARIMA - Seasonal Autoregressive Integrated Moving Average; SEM – Spatial error model; WT-SVM - Hybrid Wavelet Transform-Support Vector Machine; SES – Seasonal exponential smoothing; SESY – Simultaneous Equation System; SRA – Single regression analysis; SVM - Support Vector Machine; TSA - Time-series analysis.
PD - Panel data, the term of data refers to multi-dimensional data frequently involving measurements over time; CD – Cross-sectional data, data collected by observing many subjects at the same point of time or without regard to differences in time; W-TS - Weekly time-series; M-TS - Monthly time-series; Y-TS - Yearly time-series.
S - Short term period (≤ 5 years); L - Long term period (> 5 years).
CO – Country level; CI – City level; HH – Household level; ▽ low income country; ▼ middle income country; ▲ high income country; NA – Not available.
[1] Gross Provincial Production or GPP; [2] population density; [3] illiteracy rate; [4] population and population density; [5] percentage of population in each ranked age and percentage of immigrants; [6] unemployment rate; [7] percentage of population aged 15 to 59 years; [8] indigents; [9] consumption of gas, [10] consumption of water, [11] consumption of electricity; [12] no. of urban non-agriculture population

(Ordonez-Ponce et al., 2004; Thanh et al., 2010). Regression analysis also does not consider all factors affecting waste generation (Noori et al., 2009b).

2) Time series analysis (TSA)

Past studies have shown better results using time series analysis, which appear to be the most appropriate forecasting method considering seasonal impacts (Chung, 2010; Rimaityte et al., 2011). However, this requires a large number of data to provide accurate forecasting for a short-term period (Beigl et al., 2008; Xu et al., 2013). From a waste management perspective, time-series analysis leads to lack of power of generalization and intellectual values, while factor analysis can explain the changes of MSW characteristics associated with influencing variables (Beigl et al., 2008; Chung, 2010).

3) Artificial Neural Network (ANN)

Recently, Artificial Neural Network (ANN) has been shown to provide more accurate results compared to regression analysis and traditional time series analysis because of ANN's ability to learn and construct a complex nonlinear system through a set of input/output examples (Ali Abdoli et al., 2012; Batinic et al., 2011; Jalili Ghazi Zade and Noori, 2008; Kumar et al., 2011; Noori et al., 2009a; Ordonez-Ponce et al., 2004; Patel and Meka, 2013; Roy et al., 2013; Shahabi et al., 2012). However, it needs a large number of historical data and has some disadvantages, such as over-fitting training, difficulty in the determination of network architecture, local minimum, and its poor generalizing performance remains unsolved and the ANN approach has limited application in practice (Abbasi et al., 2014).

4) Grey models (GM)

Grey system theory, which consists of grey relational analysis (GRA), grey generating space, grey forecasting, grey decision making, grey control, grey mathematics and grey theory was initially pioneered by Deng (1989) in 1982. For grey forecasting, GM (1, 1), an univariate model, is the most widely used in MSW forecasting and other applications, with highest accuracy (Chen and Chang, 2000; Guo, 2009; Liu and Yu, 2007; Srivastava and Nema, 2006; Untong, 2012; Xiang and Daoliang, 2007; Xu et al., 2013; Ying et al., 2011). In addition, GM (1, 1)-α, i.e., applying GM (1, 1) with adaptive levels of α, has also been used in a tourism field (Huang, 2012).

Nevertheless, forecasting of MSW generation by univariate modelling is not satisfactory because solid waste is heterogeneous and can be affected by numerous factors (Ali Abdoli et al., 2012; Chen, 2010). Therefore, GM (1, n), a multivariate model, has been implemented for MSW forecasting (Wang et al., 2012; Zhang, 2013). GRA was used to investigate the relationship between MSW generation and other factors affecting the amount of waste (Liu and Yu, 2007; Wang et al., 2012). In addition, grey model with a convolution integral GMC (1, n) was proposed by Tien (2005) to improve GM (1, n), but it has been applied in only a few studies such as forecasting internet access (Wu and Chen, 2005) and the indirect measurement of tensile strength (Menikpura et al., 2012).

The relationship between MSW generation and influencing factors has therefore been theoretically explored and implemented in practice as illustrated in **Table 4.1** and summarized in **Table 4.2**. **Table 4.2** shows key findings from literature reviewed in terms of model characteristics, such as minimum data used, ability of the models for using or considering influencing factors and ranking of factors affecting MSW generation. Forecasting periods (short-term and long-term), advantages and limitations of the models are also described.

To create an accurate forecasting model, the literature reviewed highlights not only the role of selecting models, but also the selection of suitable factors affecting MSW generation (see **Table 4.1**). Considering the factors used among all models, a statistics-based model (especially regression analysis) provides the factors used, significant and insignificant factors, and the order of significant factors in different perspectives and/or studied scales. It can be concluded that ten factors, such as population and population density, Gross Domestic Product (GDP), income, family size, consumption expenditure, urbanization, proportion employment, age, education, and waste generation rate, were frequently used with mostly significant effects to MSW generation (black circle symbol in **Table 4.1**). Also, plus and minus symbols provided in **Table 4.1** illustrate, respectively, positive and negative effects of the factors to MSW generated. Hence, the selection of appropriate factors in selected models can serve as very helpful instruction for decision makers to develop measures and policies for waste management. Therefore, it is necessary to classify and select influencing factors in a systematic way, comprising a thorough literature review and an intensive discussion.

Table 4.2: Summary of characteristics of existing forecasting models.

Models	No. of data[a]	Factors used[b]	Ranking of factors	Period[c]	Other criteria
RA	≥ 30	Yes	Yes	Long term	RA cannot learn from new data and adapt to a new situation. Precision is poor when using inaccurate data. All factors cannot be included in the model.
TSA	≥ 15	Yes	No	Short term	TSA requires a large number of data. Lack of power of generalization and intellectual values. A few factors can be included.
ANN	40-384	Yes	No	Long term	More accuracy than RA and TSA. A large number of data are needed. Over-fitting training. Difficulty in the determination of network architecture. Poor generalizing performance. Limitation of the application.
GM	≥ 4	Yes	Yes	Long term	GM can be developed by using limited data. Simplicity for development. Higher accuracy than TSA and ANN. All factors can be included in the model. Limitations of the application. Outliers of data are not suitable for GM.

Remark: [a] No. of minimum data needed
[b] Factors can be used/included/studied/investigated in the models
[c] Short-term period is less than 5 years, Long term period is more than 5 years

4.2.2 A review of factors affecting MSW characteristics

Solid waste is heterogeneous and is affected by many factors. Therefore, the use of a univariate model to forecast MSW generation is not satisfactory. Lebersorger & Beigl (2011) and Beigl et al. (2008) reviewed a number of influencing factors. Forecasting of MSW generation by using socio-economic factors reveals the causal relationship between these variables which is more intellectually sound and sophisticated (Chung, 2010). UNU-ISP (2011) showed that solid waste generation in four Asian countries, namely China, India, Sri Lanka and Thailand, is based on economic development, density of population, size of urban habitation and consumption rate of commercial goods. In addition, Intharathirat et al. (2015) derived clear information on the use of influencing factors affecting MSW characteristics based on a review of 50 studies, as presented in **Table 4.1**. These factors are categorized into two groups: socio-economic and demographic as discussed below.

1) Socio-economic factors

According to the literature reviewed in **Table 4.1**, socio-economic factors include income, GDP, expenditure, tax, employment, unemployment, number of overnight stays per habitant of tourists and business travelers, and energy consumption. Among these, income is the most widely and significantly hypothesized factor in MSW forecasting, followed by GDP, expenditure and employment respectively.

In order to investigate the relationship between MSW generation and socio-economic factors at household level, questionnaires were effectively used for data collection (Beigl et al., 2008). Income is widely utilized to forecast MSW quantity at household and city levels. Higher income represents higher potential consumption and more waste generated. However, income is not only a function of daily life consumption, but also a function of investment in edible goods and paying debt. Some literature reported that income affected MSW generation insignificantly (Mohd.Yosof et al., 2002; Skovgaard et al., 2005). Liu and Yu (2007) also found that income was the least (among seven factors) factor affecting waste quantity.

GDP represents the status of a country's economy, while GDP per capita represents the purchasing power per capita. An increase in GDP leads to an increase in waste generation because high prosperity encourages consumer activities and business expansion (Mazars, 2003 cited from Purcell and Magette, 2009). Despite GDP not being a measure of living standard, it has been hypothesized in MSW forecasting at city and country level because it is often measured consistently, frequently, and is widely available (Ahmad, 2012; Kumar et al., 2011; Liu and Wu, 2010; Sjöström and Östblom, 2010). However, Sokka et al. (2007) and Liu and Wu (2010) did not find a clear-cut relationship between GDP and the quantity of waste generated in Finland and China, respectively. It appears that improved policy measures contribute to the reduction of MSW and a decoupling of MSW generation and GDP (Sokka et al., 2007). Liu and Wu (2010) also found that the annual growth rate of GDP, a factor that is often used for analyses, did not match MSW quantity.

Consumption expenditure is observed to be a factor that is less important than GDP, the proportion of the significant hypothesis to insignificant hypothesis is higher than that of GDP.

Several studies also found that consumption expenditure is connected more closely with MSW generation than GDP (Liu and Wu, 2010; Liu and Yu, 2007; Weng, 2009). Therefore, individual consumption expenditure was reasonably and significantly hypothesized as a driving force of MSW generation and composition (Skovgaard et al., 2005; Weng, 2009).

The proportion of employment represents the wage and purchasing power of citizens at city and country levels. The higher the proportion of working population to total citizens in any area, the more MSW is generated due to economic prosperity (Bandara et al., 2007; Batinic et al., 2011; Rimaityte et al., 2011)

2) Demographic factors

Demographic factors include population size, population density, number of households, urbanization, household size, age of people, education and attitude, number of rooms of a residence, infant mortality rate, and life expectancy at birth. Population-related factors (population, population density and number of households) are the most widely and significantly hypothesized for forecasting MSW generation, followed by household size, urbanization, education, and age-related factors respectively. Social characteristics and demographic factors were identified as the most significant factors to explain the variation of MSW generation than economic ones (Chen, 2010). A number of studies have significantly hypothesized population-related factors affecting MSW quantities positively. The number of households or size of population was closely correlated with MSW generation than the level of individual consumption. This means that a higher population generated larger quantities of MSW (Chen, 2010). This has been shown to be the most reliable factor for explaining increased MSW generation (Skovgaard et al., 2005).

Household size or family size has widely been hypothesized at household level. It should be noted that the literature reviewed can be categorized into two groups. Firstly, in studies which surveyed data of influencing factors using questionnaires and investigated MSW characteristics at households, it was shown that household size affected MSW quantities significantly and positively. This means that a single family generated less MSW than a multi-family dwelling (Beigl et al., 2008). Secondly, studies that conducted surveys using questionnaires for data collection of factors at household level but carried out MSW characteristics at municipal level or from statistical data, showed that household size factors affected waste quantity significantly and negatively. This means that as the average household size decreased and where there has been an increase in apartment type dwellings, MSW has increased (Purcell and Magette, 2009).

As industrialization and urbanization has changed people's lifestyles, this phenomenon has resulted in 'mass production, mass consumption, mass waste discard' (Weng, 2009). An increasing proportion of the population in urban areas has significantly and positively affected MSW generation. Also, the total amount of MSW has been affected by the growth of urbanization, rather than by GDP (Rimaityte et al., 2011).

Several studies included age as an influencing factor in different models at various levels. Elderly couples generated lower MSW quantities than that of households with infants and schoolchildren (Beigl et al., 2008). However, much of this research concluded that age affected

quantity of waste insignificantly. In addition, educational or attitudinal factors, which were primarily used in many studies to explain changes in MSW generation at the household level, were not considered significant for MSW modeling at municipality level (Lebersorger and Beigl, 2011).

4.3 **Methodology of the study: forecasting models development**

4.3.1 Formulating alternative forecasting models

Based on the analytical framework for MSW forecasting models discussed in **Chapter 2**, details of the methodology for forecasting MSW quantity is discussed here. The methodological framework shown in **Figure 2.2** was adapted from many studies (Buenrostro et al., 2001; Hsu and Wang, 2009; Lebersorger and Beigl, 2011; Liu and Yu, 2007; Purcell and Magette, 2009; Tien, 2005, 2012; Wu and Chen, 2005) and was incorporated in this study. This methodology could be distinguished as having four main steps for forecasting of MSW quantity: i) identifying and selecting influencing factors; ii) developing alternative models; iii) model validation; and iv) determination of prediction interval (PI), as discussed below.

4.3.2 Identification and selection of influencing factors

This section describes two steps for identifying and selecting influencing factors. Firstly, influencing factors were identified and selected based on a literature review through a theoretical approach. Secondly, these factors were then quantified based on statistical and mathematical approaches.

Step 1: Identification and selection of factors

A large number of studies described that influencing factors used for MSW forecasting models were selected from a literature review. Similarly, this research presents the number of important factors affecting MSW characteristics based on a review of 50 studies considering different levels, households, city and country, as presented in **Table 4.1** and described in **section 4.2.2**.

Step 2: Quantification of influencing factors

Multivariate models incorporate multiple factors affecting MSW characteristics. To develop multivariate grey models, influencing factors are essentially ranked and show the highest grey relational grade (nearby 1.0) as the most important factor affecting MSW quantity. The aim of this step is to quantify factors selected from the previous step. Based on a statistical approach, the Pearson correlation coefficient (r) was firstly tested to ensure that selected factors were related to MSW quantity, and then the mathematics-based grey relational analysis (GRA) was used to rank these factors based on sequences of importance. Pearson correlation coefficient and GRA can be determined as is described as follows.

Pearson Correlation Coefficient (r)

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}} \tag{4.1}$$

where x and y is a variable of MSW quantity, and influencing factor respectively. r gives a value between $+1$ and -1 inclusive, where 1 is total positive correlation, 0 is no correlation, and -1 is total negative correlation.

Grey relational analysis (GRA)

GRA is a method to determine the relationship between the reference series (MSW quantity) and comparative series (influencing factors), and to determine the degree of their correlation. The reference series and comparative series are denoted as $x_0 = \left(x_0(1), x_0(2), x_0(3), ..., x_0(k)\right)$ and $x_i = \left(x_i(1), x_i(2), ..., x_i(k)\right)$, $(i = 1, 2, ..., N)$ respectively. The procedures for modeling GRA are described as follows.

1) Transferring data

Besides the order variation of the original data that may cause error in the grey relational grade, the values of original data need to be normalized for having the same order (Hsu and Wang, 2009). The original data can be normalized by the following equation:

$$y_0 = \frac{x_0(k)}{\frac{1}{m}\sum_{k=1}^{m} x_0(k)},\ y_i = \frac{x_i(k)}{\frac{1}{m}\sum_{k=1}^{m} x_i(k)},\ \ i = 1, 2, ..., N,\ \ k = 1, 2, ..., m. \tag{4.2}$$

2) Determination of grey relational coefficient

The grey relational coefficient is defined as $\gamma(y_0(k), y_i(k))$ between two series and can be calculated by the following equation (Hsu and Wang, 2009; Liu and Yu, 2007):

$$\gamma(y_0(k), y_i(k)) = \frac{\min_i \min_k \left|y_0(k) - y_i(k)\right| + \rho \max_i \max_k \left|y_0(k) - y_i(k)\right|}{\left|y_0(k) - y_i(k)\right| + \rho \max_i \max_k \left|y_0(k) - y_i(k)\right|} \tag{4.3}$$

where, $i = 1, 2, ..., N$, $k = 1, 2, ..., m$, and $\rho \in (0,1)$ generally taken as 0.5, which is the distinguishing coefficient used to diminish the effect of a large absolute error.

3) Determination of grey relational grade

The grey relational grade can be calculated by averaging the grey relational coefficients from the previous step as follows:

$$\gamma(y_0, y_i) = \frac{1}{m}\sum_{k=1}^{m}\gamma(y_0(k), y_i(k)), \quad i = 1, 2, ..., N\ ,\ k = 1, 2, ..., m \tag{4.4}$$

4) Ranking of influencing factors

The rank of factors affecting MSW quantity is obtained by comparing the values of the grey relational grade. If $\gamma(y_0, y_i) > \gamma(y_0, y_j)$, then pattern y_i is more relative with pattern y_0 than pattern y_j. This rank is denoted as $y_i \succ y_j$.

4.3.3 Development of alternative models

In order to select the most accurate model, 15 alternative models comprising five univariate models and ten multivariate models were developed. Five univariate models consisted of two traditional models (Naïve and trend curve analyses), and three innovative models (grey models, GM (1, 1), GM (1, 1)-α=0.1 and GM (1, 1)-α=1.0). These five univariate models were developed and their precision compared with multivariate grey models in a benchmarking exercise. In addition, ten multivariate innovative forecasting models comprised five GM (1, n) models (GM (1, 2), GM (1, 3), GM (1, 4), GM (1, 5), GM (1, 6)) and five GMC (1, n) models (GMC (1, 2), GMC (1, 3), GMC (1, 4), GMC (1, 5), GMC (1, 6)). Thereafter, these 15 alternative models were distinguished into two groups: traditional models and innovative grey models, which can be simply modeled as described below.

4.3.3.1 Traditional forecasting models

1) Naïve method

Naïve and trend curve analysis based on statistical approaches are the traditional time series and single regression models respectively. The Naïve method defines that the value of the period to be forecast equals the value of the previous period for which data are available (Hsu and Wang, 2009):

$$F_k = A_{k-1}\,. \tag{4.5}$$

2) Trend curve analysis

Trend curve analysis is a simple method that can also be used to forecast waste quantity by plotting a graph of time series data of MSW quantity and times k as denoted as (estimated by the author)

$$\tilde{F}_k = 9.3582 \times k^3 - 56272.2433 \times k^2 + 112791308.9809 \times k - 75359185666.6011\,. \tag{4.6}$$

4.3.3.2 Grey models (GM)

Based on the overview of MSW forecasting models as described in **section 4.2.1**, the grey model is normally represented as GM (M, N) dealing with the order of differential equation as denoted M and variables as denoted n. The first index of the GM (1, N) stands for the first order derivative of accumulated generating operation (I-AGO) series of the second index, i.e., N variables. The procedures for modeling GM (M, N) are presented as below (Hsu and Wang, 2009).

Assuming the initial series which is a non-negative series:

$$x_1^{(0)} = \left\{ x_1^{(0)}(1), x_1^{(0)}(2), ..., x_1^{(0)}(k), \right\},$$

$$x_2^{(0)} = \left\{ x_2^{(0)}(1), x_2^{(0)}(2), ..., x_2^{(0)}(k), \right\},$$

$$\vdots$$

$$x_N^{(0)} = \left\{ x_N^{(0)}(1), x_N^{(0)}(2), ..., x_N^{(0)}(k), \right\}, \quad k = 2, 3, ..., m.$$

Based on the above initial series, accumulated generating operation (AGO) is defined as follows:

$$x_1^{(1)} = \left\{ x_1^{(1)}(1), x_1^{(1)}(2), ..., x_1^{(1)}(k), \right\},$$

$$x_2^{(1)} = \left\{ x_2^{(1)}(1), x_2^{(1)}(2), ..., x_2^{(1)}(k), \right\},$$

$$\vdots$$

$$x_N^{(1)} = \left\{ x_N^{(1)}(1), x_N^{(1)}(2), ..., x_N^{(1)}(k), \right\}, \quad k = 2, 3, ..., m,$$

where $x_{\tilde{i}}^{(1)}(k) = \sum_{j=1}^{\tilde{k}} x_{\tilde{i}}^{(0)}(j)$, $\tilde{i} = 2, 3, ..., N$.

1) Modeling GM (1, 1) and GM (1, 1)-α

GM (1, 1) and GM (1, 1)-α models represent the first-order and one-variable grey differential equation model without considering influencing factors (Huang, 2012; Xu et al., 2013). The first order differential equation of GM (1, 1) and GM (1, 1)-α is defined as follows:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b, \tag{4.7}$$

where a is a developing coefficient, and b is a control variable. These parameters can be determined by ordinary least squares method (OLS) (Hsu and Wang, 2009; Huang, 2012; Liu and Yu, 2007; Xu et al., 2013):

$$\begin{bmatrix} a & b \end{bmatrix}^T = (B^T B)^{-1} B^T Y_N \text{, where } B = \begin{pmatrix} -\left[\alpha x_1(1) + (1-\alpha) x_1(2)\right] & 1 \\ -\left[\alpha x_1(2) + (1-\alpha) x_1(3)\right] & 1 \\ \vdots & \vdots \\ -\left[\alpha x_1(m-1) + (1-\alpha) x_1(m)\right] & 1 \end{pmatrix} \text{ and } Y_N = \begin{pmatrix} x_1^{(0)}(2) \\ x_1^{(0)}(3) \\ \vdots \\ x_1^{(0)}(m) \end{pmatrix}, \quad (4.8)$$

where, α is in the range of [0, 1]. When α is close to 0 (zero), it means that the old data is more important to the system. Conversely, if α is close to 1.0, the latest data is very important. If α = 0.5, GM (1, 1)-α will be the GM (1, 1). The forecasting function of GM (1, 1) and GM (1, 1)-α is denoted as below:

$$x_1^{(1)}(k) = \left[x_1^{(0)}(1) - \frac{b}{a} \right] e^{-a(k-1)} + \frac{b}{a} \quad \text{and} \quad x_1^{(0)}(k) = x_1^{(1)}(k) - x_1^{(1)}(k-1) \quad \text{or} \tag{4.9}$$

$$x_1^{(0)}(k) = \left[x_1^{(0)}(1) - \frac{b}{a} \right] (1 - e^{a}) e^{-a(k-1)}, \; k = 2, 3, ..., m. \tag{4.10}$$

2) Modeling GM (1, N)

In order to forecast MSW quantity associated with N-1 number of influencing factors, these factors are input in the discrete equation of GM (1, N) which is denoted as

$$x_1^{(0)}(k) + a z_1^{(1)}(k) = \sum_{i=2}^{n} b_i x_i^{(1)}(k), \tag{4.11}$$

where $k \geq 2$ and z is a back ground value and can be determined as

$$z_1^{(1)}(k) = 0.5 x_1^{(1)}(k) + 0.5 x_1^{(1)}(k-1). \tag{4.12}$$

These parameters can also be estimated by OLS as (Hsu and Wang, 2009):

$$\begin{bmatrix} a & b_2 & \cdots & b_N \end{bmatrix}^T = (D^T D)^{-1} D^T Y_N, \tag{4.13}$$

where, $D = \begin{pmatrix} -z_1^{(1)}(2) & x_2^{(1)}(2) & \cdots & x_N^{(1)}(2) \\ -z_1^{(1)}(3) & x_2^{(1)}(3) & \cdots & x_N^{(1)}(3) \\ \vdots & \vdots & & \vdots \\ -z_1^{(1)}(m) & x_2^{(1)}(m) & \cdots & x_N^{(1)}(m) \end{pmatrix}$ and $Y_N = \begin{pmatrix} x_1^{(0)}(2) \\ x_1^{(0)}(3) \\ \vdots \\ x_1^{(0)}(m) \end{pmatrix}$.

The forecasting equation of GM (1, N) is denoted (Hsu and Wang, 2009; Zhang, 2013) as

$$x_1^{(1)}(\tilde{k}) = \sum_{l=2}^{N} \beta_l x_l^{(1)}(k) - \alpha x_l^{(1)}(\tilde{k}-1), \;\; \tilde{k} = 2,3,...,m, \tag{4.14}$$

where $\alpha = \dfrac{a}{1+0.5a}$, $\beta_l = \dfrac{b_l}{1+0.5a}$, $l = 2,3,...,N$.

3) Modeling GMC (1, N)

Besides the grey model with convolution integral (GMC (1, N)) that has the same discrete equation of GM (1, N), GMC (1, N) has an additional term the developmental coefficient u written as

$$x_1^{(0)}(k) + az_1^{(1)}(k) = \sum_{i=2}^{N} b_i x_i^{(1)}(k) + u, \tag{4.15}$$

where, a is the grey control parameter and b_i are the associated coefficients corresponding to the associated series $x_i^{(0)}$, $i = 2,3,...,N$, respectively. These modelling parameters of GMC (1, N) can also be determined by OLS (Menikpura et al., 2012; Tien, 2005; Wu and Chen, 2005) as

$$\begin{bmatrix} a & b_2 & ... & b_N & u \end{bmatrix}^T = (E^T E)^{-1} E^T Y_N, \tag{4.16}$$

where $E = \begin{pmatrix} -z_1^{(1)}(2) & z_2^{(1)}(2) & \cdots & z_N^{(1)}(2) & 1 \\ -z_1^{(1)}(3) & z_2^{(1)}(3) & \cdots & z_N^{(1)}(3) & 1 \\ \vdots & \vdots & & \vdots & \\ -z_1^{(1)}(m) & z_2^{(1)}(m) & \cdots & z_N^{(1)}(m) & 1 \end{pmatrix}$, $Y_N = \begin{pmatrix} x_1^{(0)}(2) \\ x_1^{(0)}(3) \\ \vdots \\ x_1^{(0)}(m) \end{pmatrix}$,

and

$$f(k) = b_2 x_2^{(1)}(k) + b_3 x_3^{(1)}(k) + ... + b_N x_N^{(1)}(k) + u, \;\; k = 2,3,...,m. \tag{4.17}$$

The estimated value can be obtained from

$$x_1^{(1)}(k) = x_1^{(0)}(1) \times e^{-a(k-1)} + \frac{1}{2} \times e^{-a(k-1)} \times f(1) + \sum_{\tau=2}^{k-1} \left[e^{-a(k-\tau)} \times f(\tau) \right] + \frac{1}{2} \times f(k), \; k = 2,3,...,m, \tag{4.18}$$

$$x_1^{(0)}(k) = x_1^{(1)}(k) - x_1^{(1)}(k-1), \; k = 2,3,...,m, \tag{4.19}$$

where $x_1^{(1)}(k) = e^{-a(k)}$ is the unit impulse response function $h(t)$ of the model $x_1^{(0)}(k) + az_1^{(1)}(k) = \sum_{i=2}^{N} b_i x_i^{(1)}(k) + u$.

4.3.4 Verification of models

To evaluate the performance of alternative models, the mean absolute percentage error (MAPE, %), which is a sensitive measure and suitable for time series data, was carried out in this study and is defined (Hsu and Wang, 2009; Pai et al., 2007; Xu et al., 2013) as

$$MAPE(\%) = \left(\sum_{k=1}^{m} \left| (A_k - \tilde{F}_k)/A_k \right| / m \right) \times 100, \tag{4.20}$$

where A_k denotes actual observations, and $\tilde{F}_k$ denotes the forecast value.

4.3.5 Prediction intervals (PI)

Most literature often forecasts MSW generation as single numbers or point forecasts which gives no guidance as to their likely accuracy. Prediction intervals (PI) presents an important part of the forecasting process intended to indicate the likely uncertainty in point forecasts (Armstrong, 2002). In this study, the forecasting of MSW quantity with PI (95% confidence intervals) was carried out to provide guidance on MSW forecasting for policy makers. If errors are normally distributed, the equation of prediction intervals for a $100(1-\alpha)\%PI$ is defined as

$$100(1-\alpha)\%PI = \tilde{F}_k(h) \pm z_{\alpha/2} \sqrt{Var\left[e_k(h)\right]}, \tag{4.21}$$

where $\tilde{F}_k(h)$ defines as the point forecast of the value at time h, the time steps ahead, $z_{\alpha/2}$ denotes the appropriate (two-tailed) percentage point of a standard normal distribution, and $e_k(h)$ denotes forecast error that is equal to $A_k - \tilde{F}_k(h)$ (Armstrong, 2002) or

$$e_k(h) = A_k - \tilde{F}_k(h). \tag{4.22}$$

4.4 **Results and discussion**

4.4.1 Identification and quantification of influencing factors

4.4.1.1 Identifying influencing factors

As per the scope of the study described in **section 1.4**, no literature studied factors affecting MSW generation from all sectors, namely residential, commercial, institutional and municipal services. Information is only available on factors identified in residential and commercial sectors. Based on the identification and selection of influencing factors described in **section 4.2.2**, and given in **Table 4.1**, the most important factors reported in the literature are categorized in **Figure 4.1**. According to Buenrostro et al., (2001), Lebersorger and Beigl (2011) and Purcell and Magette (2009), these factors are categorized into two groups, namely residential and commercial. Based on the characteristics of the factors, they can also be grouped into two categories of socio-economic and demographic factors. Hence, influencing factors are identified

by considering six criteria, namely frequency of use, the impact of the factor on waste generation, redundancy of factors, applicability to the model, studied area (whether developing country, middle income, and Asian country) and data availability. Among these factors, five representative factors from two groups, namely, two factors of household or residential sector (household consumption expenditure and household size) and three factors from the commercial sector (employment, population density and urbanization), as shown in **Figure 4.1** (the italics underlined), were selected for developing alternative models that are described in **section 4.4.3**.

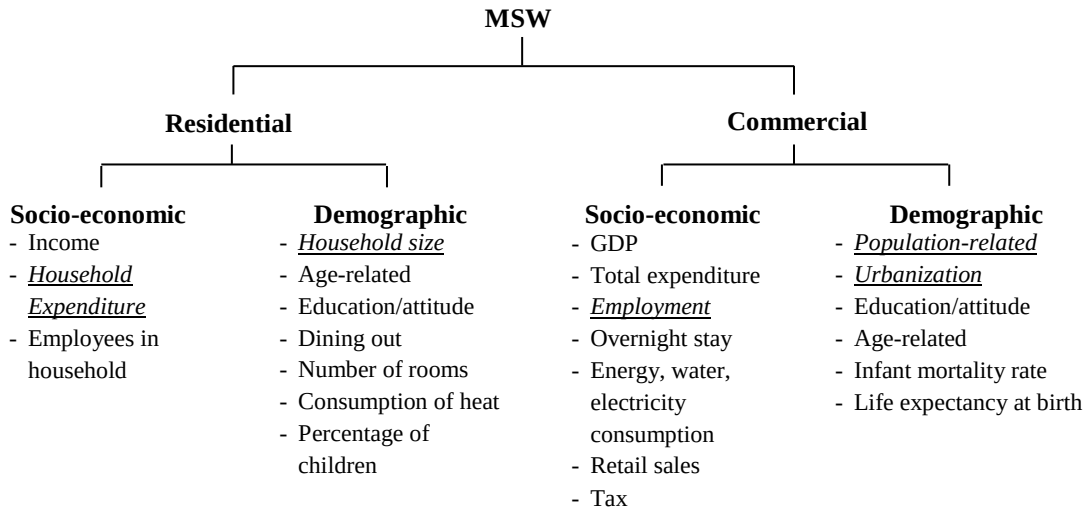


Figure 4.1: List of important factors affecting MSW quantity in residential and commercial sectors

4.4.1.2 Data collection

The background of the case study area is discussed in **Chapter 3**, and other information and assumptions needed for the MSW forecasting model are presented in this section. Information and assumptions used in this study concern the data used and the limitation of their measurement from particular sources. The assumptions of the analyses, namely the number of data used for training and verification in this study are also discussed.

Given the scope and limitations as described in **section 1.4** and the lack of reliable data collected from large, medium and small cities, this study used time series data of MSW quantity reported by the Pollution Control Department (PCD) at the country level for training of alternative models. Also, since waste generation cannot be measured directly in developing countries, the amount of waste reported at country level is normally obtained from municipalities by estimating vehicles' capacity and/or weighting at dump sites. In Thailand, the quantity of MSW, including the amount of residential and commercial waste collected in the civic area, is reported by PCD at country level. PCD uses two approaches for collecting information on MSW. Firstly, MSW data is mainly collected from estimating the volume of vehicles or trucks and is available in most municipalities or cities. Secondly, MSW data were randomly collected from Sub-district

Administrative Organizations (SAO) in rural areas that generate high amounts of MSW but are unable to collect data on MSW effectively. Amounts were estimated countrywide and combined with the first estimate. Over the last decade, a large number of SAO have expanded to become municipalities who were supported vehicles for collecting MSW generated by the national government. As a result, PCD initiated collecting data on the amount of MSW from all municipalities in 2012, while data of MSW generation during 2008-2011 presented in **Chapter 3** were estimated by PCD. To achieve good accuracy, development of the grey model needs at least four years of time series data. Therefore, MSW data collected (hereafter referred to as "MSW quantity") used in this chapter during 2000-2012 were gathered from PCD's annual report of "Thailand State of Pollution" (PCD, 2001-2014, 2011).

Additionally, time series data regarding influencing factors such as population density, consumption expenditure, household size, proportion in employment and urbanization during 2000-2012 were accessed from the National Statistical Office (NSO) (NSO, 2013), the Bureau of Registration Administration (BORA) (BORA, 2014) and the Bureau of Epidemiology (BOE) (BOE, 2014). The descriptions and raw data of these five factors and MSW quantity are presented in **Table 4.3** and **Table 4.4** respectively.

4.4.1.3 Data analyses

Since inflation causes change to the cost of goods and services, the household consumption expenditure as collected from NSO (2013) was adjusted by inflation rate (or Consumer Price Index (CPI) in this study). Data on CPI were collected from the Bank of Thailand (BOT) (2014) as presented in columns (3) to (5) in **Table 4.4**. The adjusted value of consumption expenditure is defined as AdCONEXP in the models presented in **Table 4.3**.

Table 4.3: Definitions and sources of variables.

Variables	Description	Unit	Accessed Sources
MSW quantity	Waste collected by municipality typically comprises household and commercial materials, excluding hazardous and industrial waste.	Tonnes/day	PCD (2001-2014)
Consumption expenditure (AdCONEXP)	Consumption expenditure per household adjusted by Consumer Price Index (CPI) based on the bench marking in year 2011.	Bath/month	NSO (2013) and BOT (2014)
Household size (HHSIZE)	Number of members in a household	Capita	NSO (2013)
Proportion employment (EMPLOY)	Number of employed persons/ total population	None	BORA (2014), NSO (2013) and BOE (2014)
Population density (POPDEN)	Population in Thailand/Area	Capita/km^2	BORA (2014), NSO (2013) and BOE (2014)
Urbanization (URBAN)	Proportion of number of population staying in urban area of municipality to total population	None	BORA (2014), NSO (2013) and BOE (2014)

Table 4.4: Raw data used in the alternative models

Year	MSW quantity (t/d)	Consumption expenditure (THB/m)	CPI (%)	AdCONEXP (Bath/month)	HHSIZE (persons/ household)	EMPLOY	POPDEN (capita/km^2)	URBAN
(1)	(2)	(3)	(4)	(5)	(7)	(8)	(6)	(9)
2000	38170	8558.03	74.5	6375.73	3.80	0.3499	120.59	0.2669
2001	38643	8757.63	75.7	6629.53	3.60	0.5274	121.43	0.2714
2002	39225	9601.00	76.2	7315.96	3.50	0.5260	122.49	0.2754
2003	39240	10168.49	77.6	7890.75	3.42	0.5365	122.93	0.2830
2004	39956	10885.00	79.8	8686.23	3.34	0.5604	120.78	0.2974
2005	39221	11608.24	83.4	9681.27	3.30	0.5649	121.65	0.3047
2006	40012	12701.00	87.3	11087.97	3.26	0.5680	122.45	0.3117
2007	40332	12735.00	89.2	11359.62	3.23	0.5750	122.85	0.3187
2008	41064	14711.70	94.1	13843.71	3.22	0.5840	123.54	0.3251
2009	41410	14244.00	93.3	13289.65	3.18	0.5936	123.80	0.3328
2010	41532	15407.76	96.3	14842.30	3.12	0.5955	124.49	0.3394
2011	43779	15327.50	100	15327.50	3.04	0.6002	124.88	0.3471
2012	43448	16545.88	103.02	17045.57	3.04	0.6043	125.62	0.3543

Since time series data were used in this study, stationary analysis of such data is one of the features to be tested before being used in the statistical analysis to ensure that the series can strongly influence behavior and properties. Data that were trending over time, or non-stationary data, can give misleading parameter estimates of the relationships between variables (Mahadeva and Robinson, 2004). Stationary analysis of such data was determined by using time series oriented econometric analysis. Results show that all series are stationary at different levels as shown in **Table 4.5**. Therefore, stationary analysis of the data must be tested before using the time series in a statistics-based analysis, such as correlation analysis.

Table 4.5: Statistics and mathematical approaches of variables.

Variables	MSW quantity (tonnes/day)	AdCONEXP (THB/month)	HHSIZE (capita)	EMPLOY	POPDEN (capita/m^2)	URBAN
Mean	39,727	9616.042	3.39	0.5386	122.25	0.2987
Median	39,598	9183.750	3.32	0.5626	122.47	0.3011
Maximum	41,410	13843.71	3.80	0.5936	123.80	0.3328
Minimum	38,170	6375.730	3.18	0.3499	120.59	0.2669
Std. Dev.	1,025.468	2690.103	0.197	0.070	1.102	0.024
Skewness	0.216	0.330	0.965	-2.153	-0.186	-0.006
Kurtosis	2.099	1.751	2.869	6.532	1.818	1.577
Jarque-Bera	0.416	0.831	1.560	12.926	0.640	0.844
Probability	0.812	0.660	0.458	0.002	0.726	0.656
Stationary at	1st difference	1st difference	level	level	1st difference	1st difference
Pearson correlatoin	-	0.940**	-0.887**	0.754*	0.761*	0.935**
Sig.	-	0.000	0.001	0.012	0.011	0.000

1 USD = 31 THB.

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

4.4.1.4 Quantifying and ranking influencing factors

1) Correlation analysis

To ensure that five selected influencing factors are related to MSW quantity, Pearson correlation coefficients were determined. Time series data during 2000–2009 were used in the correlation analysis. Results show that these factors correlate with MSW quantity because their coefficients are higher than 0.7 (Streiner and Norman, 1995 cited from Hsu and Wang, 2009). Therefore, this study utilized all selected influencing factors, i.e., household consumption expenditure, household size, employment, population density and urbanization, as presented in **Table 4.4-Table 4.5**, into grey relational analysis (GRA) as described in next section.

2) Grey relational analysis (GRA)

In GRA, the series of MSW quantity and selected factors must firstly be normalized to be in the same order, because inaccurate grey relational grade will be induced by the order variation of the data characterizing the factors (Hsu and Wang, 2009). In this study, the mean value was used to normalize original data because of the normal distribution of the data as illustrated in **Equation 4.2**. Results of normalization of each selected factor are presented in **Table 4.6**.

The grey relational coefficient and relational grade were determined by using **Equation 4.3** and **Equation 4.4**. These coefficients and grades comparing between reference series and comparative series were obtained and presented in **Table 4.6**. The grey relational grade of each factor presented that population density is the largest factor (0.9479), followed by urbanization (0.8310) and proportion in employment (0.8295). Household size is the fourth (0.7996) and household consumption expenditure is the fifth (0.5404). These results can be illustrated as POPDEN > URBAN > EMPLOY > HHSIZE > AdCONEXP. As a result, GRA cannot be used only for carrying out the correlation between influencing factors and MSW collected, but also provides the degree of correlation based on limited information.

Table 4.6: Normalization (Nor.) and grey relational coefficient between x_0 and x_i (co.)

Year	MSW (x_0)	AdCONEXP (x_1)		HHSIZE (x_2)		EMPLOY (x_3)		POPDEN (x_4)		URBAN (x_5)	
	Nor.	Nor.	Co.	Nor.	Co.	Nor.	Co.	Nor.	Co.	Nor.	Co.
2000	0.9608	0.6630	0.4165	1.1226	0.5718	0.6498	0.4058	0.9864	0.9122	0.8935	0.7718
2001	0.9727	0.6894	0.4289	1.0635	0.7099	0.9793	0.9950	0.9933	0.9328	0.9085	0.7807
2002	0.9874	0.7608	0.4856	1.0340	0.8356	0.9767	0.9763	1.0019	0.9586	0.9220	0.7771
2003	0.9877	0.8206	0.5635	1.0103	0.9245	0.9961	0.9867	1.0056	0.9444	0.9475	0.8575
2004	1.0058	0.9033	0.6829	0.9867	0.9393	1.0405	0.8773	0.9880	0.9446	0.9957	0.9790
2005	0.9873	1.0068	0.9373	0.9749	0.9685	1.0488	0.7884	0.9950	0.9895	1.0199	0.8851
2006	1.0072	1.1531	0.5978	0.9631	0.8441	1.0546	0.8328	1.0016	1.0000	1.0434	0.8718
2007	1.0152	1.1813	0.5651	0.9542	0.7900	1.0677	0.8163	1.0049	0.9779	1.0668	0.8192
2008	1.0336	1.4396	0.3425	0.9513	0.7309	1.0843	0.8224	1.0105	0.9224	1.0883	0.8094
2009	1.0424	1.3820	0.3844	0.9394	0.6818	1.1021	0.7938	1.0127	0.8965	1.1142	0.7588
GR grade			0.5404		0.7996		0.8295		0.9479		0.8310

It is no surprise that population density contributes the largest MSW quantity because higher population generates larger quantities of MSW. In spite of population being the most important driving factor, there are other factors that affect MSW quantity. The population in Thailand increased 4.17% from 2000 to 2012, while waste quantity rapidly rose by 13.83%. MSW quantity typically also increases with the improvement of living standards.

In Thailand, urbanization has rapidly increased in the last decade. The number of municipalities which are classified as cities increased from 1131 in 2000 to 2272 in 2012, and urbanization doubled during this period. Therefore, urbanization is the second most important factor contributing to MSW quantity, because as urbanization increases, life style, consumption style and living conditions change, and more MSW is generated. Moreover, the inner disparities of lifestyle and consumer behavior may exist between urban and rural regions (Weng et al., 2011). In urban areas, the actual population in cities is larger than official statistics, as many people live in the city and produce waste but are not registered as citizens (Wang and Nie, 2001). Employment, which represents wage and purchasing power, increased by 79.88% from 22 million persons in 2000 to 39 million persons in 2012. This factor also affects waste quantities, reflecting economic prosperity-related GDP, which rose 3.98% annually from 2000 to 2012 (NESDB, 2014). At country level, MSW was generated not only from consumption from individuals, but also from service industries, such as the large amount of food waste discarded from hotels, super markets, institutes and so on. In this study, it can be concluded that the commercial sector plays a crucial role in MSW quantity.

In the context of the residential sector, household size is the most important factor, followed by household consumption expenditure. This means that demographic factors significantly affect more MSW quantity than that of socio-economic factors. However, in this study, household size slightly affected MSW quantity negatively because household size slowly decreased from 3.80 capita per household in 2000 to 3.04 capita per household in 2012. Individual consumption expenditure was considered as one important factor to producing MSW that is related to changes in lifestyle (Weng et al., 2011; Yuan et al., 2012). However, in most countries, the size of the population or the number of households is closely correlated with MSW quantities than the level of private consumption (Skovgaard et al., 2005). In this study, household consumption expenditure is the least influencing factor because the correlation degree of GRA is required to be greater than 0.6 (Hui et al., 2013). Hence, at country level, representative factors of the residential sector affected less MSW quantity than that of commercial sector.

4.4.2 Developing and verifying alternative models

Details of the analyses and results from the development of 15 alternative models, as mentioned in **section 4.3.3**, are discussed in this section. MSW quantity was forecast by developing alternative models using ten years of data, from 2000 to 2009, also called an ex-ante forecast. These models were validated using three years of time series data, from 2010 to 2012, also called an ex-post forecast. The ex-ante forecast and ex-post forecast were carried out by using **Equation 4.5-4.19**. In this study, the MAPE, which is widely used in many studies (Guo, 2009; Hsu and Wang, 2009; Huang, 2012; Pai et al., 2007; Srivastava and Nema, 2006) is used as a criterion to validate performance. The MAPE of each model was determined by using **Equation 4.20** and compared with other models to select the most accurate model. The performance of the

forecasting models can be categorized into four levels: excellent, good, reasonable, and incorrect, where MAPE is in the range of <10, 10-20, 20-50, and >50% respectively, as listed in **Table 4.7** (Lewis, 1982).

Table 4.7: Range of MAPE.

MAPE (%)	Forecasting performance
<10	Excellent
10-20	Good
20-50	Reasonable
>50	Incorrect

Source: Lewis (1982)

Among the 15 alternative models, the best fit model was selected and used as a representative model to forecast MSW quantity during 2013-2030 by using the ex-post forecast, as discussed further in **section 4.4.3**. This section categorizes these alternative models into two groups: univariate and multivariate models as discussed below.

4.4.2.1 Univariate models

1) Naïve and Trend curve analyses

The Naïve method states that the value of the period to be forecast equals the value of the last period for which data is available (Hsu and Wang, 2009). Results show that the MAPE of a three year forecast of MSW quantity, on average, equals 2.06%, as presented in **Table 4.8**. Trend curve analysis, which is the simplest method, was also developed to forecast the amount of waste over the long-term period in this study. The MAPE of the Trend curve analysis model is 2.98%, which is higher than that of Naïve analysis, however the Naïve analysis can be used to forecast the amount of waste over the short term (less than 5 years) only. Despite the performances of Naïve and trend curve analyses, which provide excellent accuracy, the innovative grey models were developed to address the higher error in the long-term forecasting period, as discussed below.

Table 4.8: Forecasting of MSW quantity using univariate models

Year	Actual data (t/d)	Traditional models				Innovative models					
		Naïve		Trend curve		GM (1,1)		GM (1, 1)-α=0.1		GM (1, 1)-α=1.0	
		Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)
2000	38170										
2001	38643	38170		38173		38653		38530		38807	
2002	39225	38643		38529		38959		38834		39115	
2003	39240	39225		38710		39267		39141		39426	
2004	39956	39240		38846		39578		39450		39740	
2005	39221	39956		39032		39892		39762		40055	
2006	40012	39221		39324		40208		40076		40374	
2007	40332	40012		39741		40526		40392		40694	
2008	41064	40332		40264		40847		40711		41018	
2009	41410	41064		40839		41171		41033		41344	
2010	41532	41410	0.29	41373	0.38	41497	0.09	41357	0.42	41672	0.34
2011	43779	41532	5.13	41737	4.67	41825	4.46	41684	4.79	42003	4.06
2012	43448	43779	0.76	41762	3.88	42156	2.97	42013	3.30	42337	2.56
Avg.			2.06		2.98		2.51		2.84		2.32

2) Grey models

Based on the development of grey models as described in **section 4.3.3.2**, the initial series and the accumulated generating operation (AGO) of MSW quantity were defined as $x_1^{(0)}$ and $x_1^{(1)}$, respectively. The AGO series was determined by the ordinary least squares method (OLS) using **Equation 4.8**. The estimated MSW quantity was then carried out through **Equation 4.9** or **4.10** as presented in **Table 4.8**. Results show that the MAPE of GM (1, 1), GM (1, 1)-α=0.1 and GM (1, 1)-α=1.0 were 2.51, 2.84, and 2.32% respectively. Comparing the traditional models mentioned above and the innovative grey models, results show that the univariate grey models give higher accuracy than that of trend curve analysis. Results show that all univariate models reveal high performance for MSW forecasting with excellent accuracy.

4.4.2.2 Multivariate grey models

In this section, ten multivariate grey models (GM (1, 2) – GM (1, 6) and GMC (1, 2) – GMC (1, 6)), were developed by using the time series of ranked influencing factors that are the outputs from **section 0**. Similar to the univariate grey models, three steps were involved in developing the multivariate grey models. Firstly, assuming an initial series of MSW quantity and influencing factors as $x_1^{(0)}$ and $x_2^{(0)}$ to $x_n^{(0)}$, respectively, the AGO of these series was then applied to both the reference series (MSW quantity) and compared series (influencing factors) as defined by $x_1^{(1)}$ and $x_2^{(1)}$ to $x_n^{(1)}$ respectively. Secondly, unknown variables of the first order differential equation built using the AGO series were determined by the OLS. The differential equations of GM (1, n) and GMC (1, n) models are illustrated in **Equation 4.12-4.13** and **Equation 4.16-4.17**, respectively. Results from the previous step were input to the forecasting equations: **Equation 4.14**, **4.18** and **4.19** of the various grey models.

Among the five grey models (GM (1, 2) – GM (1, 6) developed in this section), GM (1, 4) gave the highest accuracy, which is also higher than trend curve analysis and the univariate grey models as described in **Table 4.9**. According to Tien (2012), GM (1, n) is fairly good but not very accurate. The prediction accuracy of the grey model GM (1, n) is therefore doubtful and can be improved by introducing more messages into the system. Given that the GM (1, 1) conforms to the grey exponential law and is the most widely used in MSW forecasting and other applications, with higher accuracy, GMC (1, n) derives a more accurate trend than GM (1, n). The GMC (1, n) model includes a term of the grey control parameter u, like GM (1, 1) besides the same terms of the GM (1, n) model. Thus, the GMC (1, n) can degenerate to be GM (1, 1) for the special case $n = 1$ and becomes the linear differential equation (Tien, 2005). Among multivariate grey models presented in **Table 4.9** and **Table 4.10**, the errors of grey models with convolution integral, namely GMC (1, 2) – GMC (1, 6), are much less than that of GM (1, n) models, i.e., GM (1, 2) – GM (1, 6). This study found that the grey model with convolution integral, GMC (1, n), provides the most accuracy for MSW forecasting in the context of Thailand.

Table 4.11 shows the performance of all alternative models that reveal high performance for MSW forecasting with excellent accuracy. Comparing the two main types of models, it can be observed that the multivariate models not only provide higher performance or more accuracy

than that of univariate models, but also present the factors affecting waste quantities. For long-term forecasting of MSW, the innovative grey models mentioned above show their precision higher than traditional ones. Also, it is necessary to select the most accurate model to prevent under or overestimation of MSW forecast (Dyson and Chang, 2005). As per the results, GMC (1, 5) gave the best representation of MSW quantity forecast with a least error of 1.16% MAPE. It demonstrates that GMC (1, 5) is a robust forecasting model of MSW quantity from 2013 to 2030 in this study. Considering the ranked influencing factors used in this model, it illustrates that the decrease of household size, the increase of population density, proportion employment and urbanization result in an increase of MSW quantity in Thailand. These factors are categorized as three representative factors and one representative factor affecting waste generated from commercial and residential sectors respectively. This is expected to inform policy makers regarding waste quantity patterns, beyond focusing on the commercial sector. Influencing factors of the commercial sector affect MSW quantity rather than residential sectors. However, segregated information/data of waste generated from residential and commercial sectors are needed to confirm key findings from this study.

Besides the outlier of MSW quantity in 2011, because of extensive flooding countrywide, the MAPE in 2011 and other values from training data from using both of GM (1, n) and GMC (1, n) indicate high error. To avoid data outliers, training data during 2000–2009 were used for validation in this study. It can be concluded that continuous data is required for using the grey model. According to Liu and Yu (2007), a single or a few outliers are acceptable; this is one advantage of the grey model over that of statistical regression analysis. If frequent outliers occur, the grey model is not an appropriate choice. However, the results of this study indicate that an outlier can be included in GM (1, n), but cannot be accepted for GMC (1, n). Therefore, time series data are required to support and improve the reliability of grey models. In order to develop an accurate model associated with influencing factors, not only the selection of suitable factors, but also the accurate forecasts of these factors play important roles in MSW forecasting.

Table 4.9: Forecasting of MSW quantity by using GM (1, n) models

Year	Actual data (t/d)	GM (1,2)		GM (1,3)		GM (1,4)		GM (1,5)		GM (1,6)	
		Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)
2000	38170										
2001	38643	37585		38713		38683		38715		38599	
2002	39225	38891		39171		39196		39286		39361	
2003	39240	39798		39385		39461		39253		39294	
2004	39956	40044		39460		39446		39434		39546	
2005	39221	39894		39252		39222		39369		39345	
2006	40012	40657		40182		40145		40170		40155	
2007	40332	40818		40631		40627		40645		40280	
2008	41064	40890		41122		41141		41143		41273	
2009	41410	40371		41176		41231		41277		41222	
2010	41532	39741	4.31	41251	0.68	41418	0.28	41328	0.49	41081	1.09
2011	43779	40757	6.90	41805	4.51	41951	4.18	41499	5.21	40862	6.66
2012	43448	41064	5.49	42205	2.86	42417	2.37	42145	3.00	41744	3.92
Avg.			5.57		2.68		2.28		2.90		3.89

Table 4.10: Forecasting of MSW quantity by using GMC (1, n) models

Year	Actual data (t/d)	GMC (1,2)		GMC (1,3)		GMC (1,4)		GMC (1,5)		GMC (1,6)	
		Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)	Estimated (t/d)	MAPE (%)
2000	38170										
2001	38643	38695		38832		38417		38387		32408	
2002	39225	38838		38988		38749		38628		35427	
2003	39240	38962		39180		39219		39172		36777	
2004	39956	39166		39434		39397		39386		37124	
2005	39221	39454		39746		39468		39429		37150	
2006	40012	39747		40093		39829		39794		37536	
2007	40332	40062		40472		40343		40310		37854	
2008	41064	40406		40877		40850		40808		38451	
2009	41410	40791		41310		41314		41261		38973	
2010	41532	41224	0.74	41769	0.57	41877	0.83	41834	0.73	39218	5.57
2011	43779	41712	4.72	42253	3.49	42616	2.66	42625	2.64	39586	9.58
2012	43448	42263	2.73	42762	1.58	43474	0.06	43503	0.13	39941	8.07
Avg.			2.73		1.88		1.18		1.16		7.74

Table 4.11: Performance comparison of alternative models.

	Models	MAPE (%)	Accuracy*
Univariate	*Traditional models*		
	Naïve	2.06	Excellent
	Trend curve analysis	2.98	Excellent
	Grey models		Excellent
	GM (1, 1)	2.51	Excellent
	GM (1, 1)-$\alpha_{=0.1}$	2.84	Excellent
	GM (1, 1)-$\alpha_{=1.0}$	2.32	Excellent
Multivariate	GM (1, 2)	5.57	Excellent
	GM (1, 3)	2.68	Excellent
	GM (1, 4)	2.28	Excellent
	GM (1, 5)	2.90	Excellent
	GM (1, 6)	3.89	Excellent
	GMC (1, 2)	2.73	Excellent
	GMC (1, 3)	1.88	Excellent
	GMC (1, 4)	1.18	Excellent
	GMC (1, 5)	**1.16**	**Excellent**
	GMC (1, 6)	7.74	Excellent

Remark: * the accuracy was defined by Lewis (1982) as presented in Table 4.7

4.4.3 Forecasting of MSW quantity in Thailand

4.4.3.1 Influencing factors forecast

To forecast MSW quantity by using GMC (1, 5), it is necessary to estimate annual values of each influencing factor from 2013 to 2030. These influencing factors, described in **section 4.4.2.2,** were forecast by using GM (1, 1) due to its mature implementation, conformance to the grey exponential law, and being the most widely used in MSW forecasting. The ex-post forecasts

were carried out by using twelve time series data sets (see **Table 4.4**) during 2000-2011, and used as inputs for training models, and one data set from 2012 was used for validation. Results show the excellent accuracy of the forecasts for influencing factors: 0.69%, 1.20%, 1.80% and 1.06% MAPE for population density, urbanization, proportion of employment and household size respectively (as shown in **Table 4.12)**. Population density is projected to increase from 125.07 capita per km^2 in 2013 to 130.64 capita per km^2 in 2030. Urbanization and proportion in employment would increase from 0.3676 and 0.6238 in 2013 to 0.5617 and 0.7901 in 2030 respectively, while household size would decrease from 2.96 persons per household in 2013 to 2.30 persons per household in 2030. These annual estimated values of each factor are used as inputs to GMC (1, 5) to forecast MSW quantity from 2013 to 2030, as discussed later.

Table 4.12: Influencing factors forecast during 2013-2030

Year	POPDEN			URBAN			EMPLOY			HHSIZE		
	Actual	Estimated	MAPE	Actual	Estimated	MAPE	Actual	Estimated	MAPE	Actual	Estimated	MAPE
2000	120.59	120.59		0.2669	0.2669		0.3499	0.5280		3.80	3.80	
2001	121.43	121.27	0.13	0.2714	0.2725	0.42	0.5274	0.5353	0.10	3.60	3.54	1.62
2002	122.49	121.59	0.74	0.2754	0.2794	1.46	0.5260	0.5428	1.77	3.50	3.49	0.30
2003	122.93	121.90	0.84	0.2830	0.2865	1.22	0.5365	0.5504	1.18	3.42	3.44	0.52
2004	120.78	122.21	1.19	0.2974	0.2937	1.25	0.5604	0.5581	1.78	3.34	3.39	1.41
2005	121.65	122.53	0.72	0.3047	0.3011	1.16	0.5649	0.5659	1.19	3.30	3.34	1.13
2006	122.45	122.84	0.32	0.3117	0.3087	0.95	0.5680	0.5739	0.36	3.26	3.29	0.86
2007	122.85	123.16	0.25	0.3187	0.3165	0.68	0.5750	0.5819	0.20	3.23	3.24	0.30
2008	123.54	123.47	0.05	0.3251	0.3245	0.18	0.5840	0.5900	0.35	3.22	3.19	0.87
2009	123.80	123.79	0.01	0.3328	0.3327	0.04	0.5936	0.5983	0.59	3.18	3.14	1.11
2010	124.49	124.11	0.31	0.3394	0.3411	0.50	0.5955	0.6067	0.48	3.12	3.10	0.69
2011	124.88	124.43	0.36	0.3471	0.3497	0.76	0.6002	0.6152	1.08	3.04	3.05	0.42
2012	125.62	124.75	0.69%	0.3543	0.3586	1.20%	0.6043	0.6238	1.80%	3.04	3.01	1.06%
2013		125.07			0.3676			0.6325			2.96	
2014		125.39			0.3769			0.6414			2.92	
2015		125.71			0.3864			0.6503			2.88	
2016		126.03			0.3962			0.6595			2.83	
2017		126.36			0.4062			0.6687			2.79	
2018		126.68			0.4164			0.6780			2.75	
2019		127.01			0.4269			0.6875			2.71	
2020		127.33			0.4377			0.6972			2.67	
2021		127.66			0.4488			0.7069			2.63	
2022		127.99			0.4601			0.7168			2.59	
2023		128.32			0.4717			0.7268			2.55	
2024		128.65			0.4836			0.7370			2.52	
2025		128.98			0.4958			0.7473			2.48	
2026		129.31			0.5083			0.7578			2.44	
2027		129.64			0.5212			0.7684			2.41	
2028		129.98			0.5343			0.7792			2.37	
2029		130.31			0.5478			0.7901			2.34	
2030		130.64			0.5617			0.5280			2.30	

4.4.3.2 MSW quantity forecast

Based on the most accurate model and forecast of influencing factors described in **sections 4.4.2** and **4.4.3.1** respectively, the analyses and results of MSW quantity forecast are described here. In this section, the most accurate model, GMC (1, 5), was utilized to forecast MSW quantity with

PI (95% confidence intervals) during 2013-2030 associated with four influencing factors. As shown in **Figure 4.2**, the GMC (1, 5) model provides good fitness of MSW data collected, correlating closely with actual data and the forecast curve trends in the extrapolated forecasting phase. In this study, MSW quantity increases with the average annual growth rate of 1.40%. The uncertainty of the MSW forecast was carried out by using the prediction interval (PI) technique. Results show that the PI of MSW quantity rate per day is expected to increase from 43,435–44,994 tonnes in 2013 to 47,735–49,293 tonnes in 2020, and to 55,177–56,735 tonnes in 2030 (as presented in **Table 4.13)**. These forecasts are similar to those obtained by TGO (2010), who used GDP and population as influencing factors in extrapolation and found that MSW increased at 1.08% annually from 43,751 tonnes per day (t/d) in 2013, to 47,112 t/d in 2020 and to 52,560 t/d in 2030. The Department of Alternative Energy Development and Efficiency (DEDE) (2009) forecast the MSW quantity rate by using single linear regression analysis, and concluded that it would be 42,667 t/d in 2013 and 45,146 t/d in 2020 with a 0.80% annual average growth rate. The MSW forecast in this study is slightly higher than that of TGO (2010). In addition, it can be concluded that DEDE (2009) underestimated MSW collected (40,896–42,313 t/d) when compared with actual data (41,064–43,448 t/d) during 2008–2012.

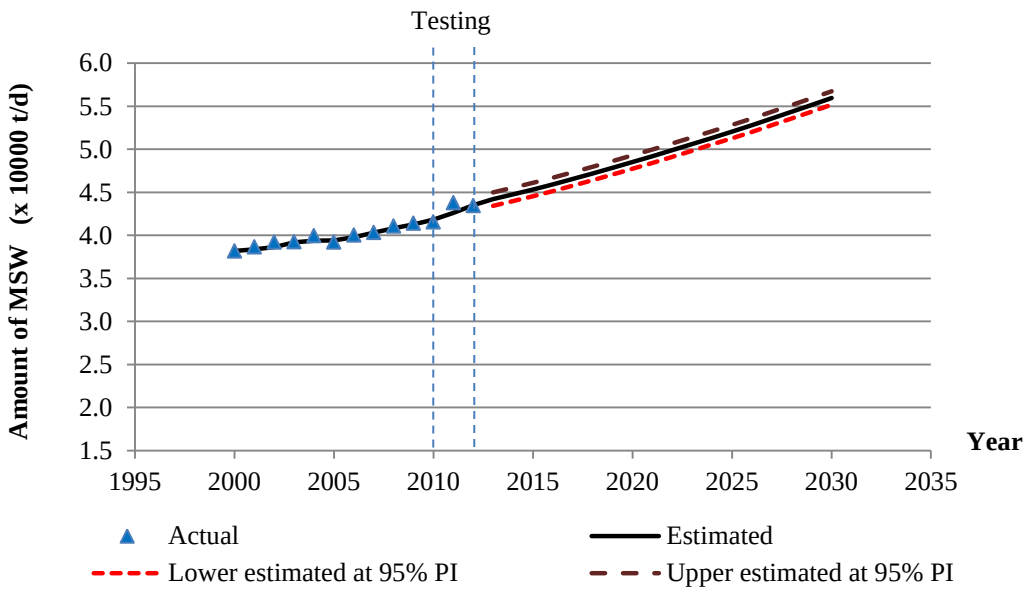


Figure 4.2: Forecasting of MSW collected using the GMC (1, 5) model during 2013-2030 with 95% PI.

Table 4.13: Forecast interval of MSW collected rate (tonnes per day).

Year	2013	2015	2020	2025	2030
GMC (1, 5)	44,214	45,336	48,514	52,061	55,956
Lower estimated at 95%PI	43,435	44,556	47,735	51,281	55,177
Upper estimated at 95%PI	44,994	46,115	49,293	52,840	56,735

Regarding the MSW quantity forecast from the GMC (1, 5) model, it comprises three representative factors and one representative factor affecting waste quantity from commercial and residential sectors respectively. This is expected to provide policy makers with an understanding of waste quantity patterns. The influencing factors of the commercial sector affect the amount of MSW collected rather than the residential sector. A study by Manomaivibool (2012) showed that hotels in Chiang Saen And Chiang Khong district, Chiang Rai, generated solid waste of about 3.15 kg/capita/day which was higher than that from guest houses with 2.3 kg/capita/day. This shows that commercial activities produce more waste, as hotels offer more services and more food is produced. The main sources of commercial sector waste include hotels, supermarkets, restaurants, hospitals, institutes and public areas. They not only generate more waste, but also make for easier implementation of waste management programs than the residential sector. In order to achieve the government's targets, as described in **Chapter 3**, specific strategies of 3R, WTE, and regulation for commercial and residential sectors are required: enhancement of the 3R strategy for key sources of waste, such as hotels, supermarkets, restaurants and institutes; implementation of sufficient economy for decreasing human activities; and management of population density and urbanization should be strongly focused and implemented. However, segregated information/data on waste generated from residential and commercial sectors will be needed.

4.5 **Summary**

This chapter presents the implementation of the analytical framework for MSW quantity forecasting in the context of limited data in developing countries and by using grey system theory, GRA and grey forecasting models in Thailand as a case study. This methodological process helps to formulate the appropriate set of factors affecting MSW quantity. The selection of such factors was carried out based on theoretical and mathematical approaches. Alternative models were developed based on the traditional and innovative models and validated with high accuracy.

To forecast MSW collected and associated with influencing factors based on limited data available, 15 alternative models including two traditional models, three univariate grey models and ten multivariate grey models were simulated in this study. For multivariate models, the influencing factors of residential and commercial sectors affecting waste collected were identified, classified and quantified using correlation analysis and GRA. The most accurate model was used to forecast waste collected over the long term in Thailand with the uncertainty forecast and prediction interval technique.

Among these models, the grey model with convolution integral GMC (1, 5) is the best representative model for forecasting MSW collected, with the lowest error of 1.16% MAPE. This model indicates that the amount of MSW collected would increase by 1.40% per year, which is in the range from 43,435–44,994 t/d in 2013 to 47,735–49,293 t/d in 2020, and to 55,177–56,735 t/d in 2030. The increase of MSW collected may be affected by representative factors of the commercial sector (i.e., population density, urbanization and proportion in employment) rather than that of the residential sector (i.e., household size). It was also observed that demographic factors are more important than socio-economic factors. In the long term, these results can help decision makers to develop measures and policies for waste management: the implementation

and development of new targets for 3R and WTE strategies in commercial and residential sectors; strong enhancement of the 3R strategy for hotels, supermarkets, restaurants and institutes; focusing on the sufficient economic philosophy to reduce consumption; and control the increase of population density and urbanization. However, future research on estimating MSW quantities in spatial distributions in the residential and commercial sectors is needed.

Based on the scope and limitations of this study as discussed in **Chapter 1**, the future MSW quantity and its annually increasing rate at country level are assumed to be constant and equal between medium and small-sized cities. This increasing rate will be proposed as an input of the various factors considered in the analytical hierarchy process (AHP) method to select the most suitable MSW management system for medium and small cities in Thailand, which will be described in **Chapter 5**.

Chapter 5

Evaluation of MSW management systems for medium and small cities

This Chapter describes the evaluation of MSW management systems comprising general MSW treatment and waste-to-energy treatment systems for medium and small cities in Thailand by using the Analytical Hierarchy Process (AHP) method. The aim of this chapter is to evaluate the most suitable solid waste management system for both types of cities and to investigate stakeholder group preferences on criteria, sub-criteria and alternative MSW management systems related to sub-criteria. Before describing in detail, the rationale and aims of this chapter are introduced in **sections 5.1** and **5.2** respectively, and section **5.3** reviews overall decision making tools and the methodology of the AHP method used for evaluating MSW management systems. Consequently, the sensitivity analysis approach for verifying the model is described in **section 5.4**. The implementation of the decision making process is then addressed in **section 5.5**. Results and discussion of the evaluation of MSW systems are presented in **section 5.6**. Limitations and problems faced in this study, and recommendations related to MSWM policies are discussed in **section 5.7**, followed by a summary in **section 5.8**.

5.1 **Introduction**

Management of municipal solid waste (MSW) has become a critical issue during previous decades because of the rapidly increasing amount of waste generated and the complexity of the waste stream. To address this issue with respect to sustainable MSW management, treatment facilities should be designed after careful planning in the selection of technologies based on social, economic and environment benefits that would be best suited for a particular city (Menikpura et al., 2013). The process of planning and decision making policies can be complex and uncertain, and must take into account environmental impacts, financial aspects, social implications and technical aspects of each specific option of MSW treatment and disposal (Arena and Gregorio, 2014) and the involvement of stakeholders. Decision makers have to look for a decision support framework that can guide in defining alternatives, relevant criteria, and find suitable solutions. In the process of evaluating MSWM, multiple stakeholders, namely government, experts, industries, municipalities and/or general public are involved (Soltani et al., 2015). This is evident for MSW streams that need a particular treatment and positive community acceptance and consensus among stakeholder groups (Achillas et al., 2013). Under this issue, the identification of criteria plays an important role for performance evaluation of MSW systems. Also stakeholder involvement in the MSWM process has normally been operationalised in a social assessment process for addressing impacts and recommending streategies to minimese negative impacts of policy proposals. This process normally involves accurate and inaccurate or missing information, expert evaluation, and changing public opinion. Also, it is necessary to recognise the variety of affected stakeholders and their conflicting objectives (Harrison and Qureshi, 2000). The main challenge is to develop decision support tools by considering cooperative interactions between stakeholders who can affect or be affected by MSWM systems (Karmperis et al., 2013).

Since any large city has certain characteristics (as mentioned in **section 1.2**) that differ from medium and small cities, it is important to evaluate the most suitable MSWM system for medium

and small cities. In Thailand, the government has budgeted considerably for large cities on facilities (e.g., underground and elevated train systems in Bangkok) and high technology MSWM systems (e.g., initiated an incineration system in Phuket and integrated MSWM system in Rayong) (Intharathirat and Abdul Salam, 2016). The lower funding priority and lack of skilled workers in rural areas and small cities creates greater potential for environmental impacts from MSWM and insufficient development of basic infrastructure. The ineffective plan of MSWM in small cities leads to improper management of MSW, and MSWM becomes a critical issue when small cities expand. As the evaluation of appropriate MSWM systems is still limited to large cities due to the availability of data and critical issues faced, the decisions made in medium and small cities, prior to them growing into large cities, should be carried out.

Based on the background of the study areas described in **section 3.5**, this study defines municipalities into three groups: city municipality (hereinafter called large city), town municipality (hereinafter called medium city), and sub-district municipality (hereinafter called small city).

To gain more understanding on how to evaluate sustainable MSW management systems and conducting the stakeholders' preferences for medium and small cities as discussed in **Chapter 1**, this study, intends to incorporate stakeholders preferences and analyze their opinions on waste management and policies-making. Also, to tackle issues associated with sustainability as described above, the AHP is developed by considering multi-criteria and involvement of multiple stakeholders, with the overall methodology is discussed in **section 2.1**.

5.2 **An overview of supporting tools in decision making**

In order to implement suitable MSW management, decision makers often set and plan a strategy of local and regional goals. The proper MSW management system plays a role in achieving sustainable development goals such as the protection of environment and human health, economic development, and fulfillment of regulatory and social requisites (Soltani et al., 2015). The multi-criteria decision analysis (MCDA) method is a popular framework employed for evaluating suitable MSWM strategies due to its advantages, such as helping multiple stakeholders evaluate conflicting criteria, communicating different opinions, ranking of options, and making applicable decisions (Soltani et al., 2015). To achieve the aims of this study, an overview of decision making comprising a review of existing tools and relevant criteria used for evaluating MSW management systems in previous studies are discussed in the following sections.

5.2.1 A review of existing tools for evaluating MSW management systems

Several studies reviewed multi-criteria decision making models used for evaluating MSWM (Achillas et al., 2013; Karmperis et al., 2013; Morrissey and Browne, 2004; Soltani et al., 2015). In this study, **Table 5.1** illustrates a review of decision making methods and criteria from 25 studies based on whether focusing at the country level or at different city sizes (large, medium and small). Almost all methods were used to evaluate appropriate MSWM systems for large cities, whereas a few focused on medium and small cities. The number of stakeholders, criteria and sub-criteria, and MSWM options are also presented in **Table 5.1**. From the literature review,

the frameworks of decision support models can be categorized into three groups: cost benefit analysis (CBA), life cycle assessment (LCA), and multi-criteria decision analysis (MCDA) or multi-criteria decision making (MCDM) (Karmperis et al., 2013; Morrissey and Browne, 2004; Soltani et al., 2015). The CBA is used to evaluate options based on monetary value, while LCA mainly evaluates potential environmental impacts from the options selected. The MCDA methods can be used to evaluate MSWM integrated with conflicting criteria and therefore provides more robust decisions than the above two methods (Morrissey and Browne, 2004). In addition, MCDA approaches have been developed for evaluating MSWM issues that have high potential impacts to environment and human health, and involve viewpoints and more criteria.

Application of the CBA framework presents two critical issues concerning the selection of social discount rates and the level of analyses. The discount rate may violate the rights of future generations. The level of CBA analysis is normally limited to a particular area and the project releases global impacts (e.g., climate change), then the environmental benefits are considered in relation to only one area, the externalities in other areas may not be taken into account (Karmperis et al., 2013). The most critical issue for developing LCA models concerns assumptions made by analysts. Since different assumptions are used by different analysts in a given LCA model for the same product, these assumptions may provide significant impacts on the results given by each analyst. Other issues are the reliability of LCA model results when limited data are available, and its time-consuming nature (Karmperis et al., 2013). The most critical issue in the MCDM framework is the selection of specific criteria (Achillas et al., 2013; Karmperis et al., 2013). Among these frameworks, MCDM have widely been applied for addressing the inherent complexity of MSWM because it is flexible, which can be used by an individual decision maker and easily expanded into a group (Karmperis et al., 2013).

Various MCDA methods have been used in MSWM focusing mainly on the two primary issues of optimal location of MSW treatment facilities and MSWM strategy (Achillas et al., 2013). Among these methods, AHP and its family, Analytical Network Process (ANP) and fuzzy AHP, are identified as the most dominant method. Also, AHP is the most prevalent method for combining with other approaches (Soltani et al., 2015). The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is defined as an emerging approach, while Elimination Et Choix Traduisant la Realité (ELECTRE) is defined as the most consistent method. In addition, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is used to rank alternatives in several studies. The combination of AHP and GIS (Graphical Information System) is also the most popular method used in MSWM, particularly in studies of site selection (Soltani et al., 2015).

For multiple stakeholders involved in MSWM studies, AHP is commonly used to incorporate multiple stakeholders, while PROMETHEE and ELECTRE are used in a few studies with participatory stakeholders because ELECTRE does not discuss tradeoffs among criteria (Soltani et al., 2015). Several studies highlight that AHP is not only suitable for complex decision problems and combination of qualitative and quantitative data, but also for multi-criteria making

Table 5.1: Evaluation tools and criteria used in various decision making methods for solid waste management

Details/Main criteria						Technical												Environmental									Economic								Social					
Model	Studied level	No. of stakeholders	No. of alternatives	No. of sub-criteria	Inputs	Energy content	Net output	Maturity	Complexity	Know-how/ experience	Land requirement	Pre-treatment	Technical implication	Availability in local	Suitable for characteristics	Performance records	Scaling /expansions	Other criteria	GHG emission	Regulations	Volume reduction / diversion from landfill	Environmental impacts	Energy consumed	Recycling rate	Fossil fuel substitution	Resource consumption	Other criteria	Capital cost	O&M cost	Revenue/benefit	Fuel costs	Energy produced	Available co-financing	Marketing potential	RE contribution	Job creation	Public acceptance	Odor impacts	Health risk & safety	Other criteria	References
Thailand																																									
MFA, SAT/AHP	CI▼ (M)	14	4	24	√									√	√	√	√	√	√			√	√			√		√	√	√			√			√	√		√	√	Suthapanich (2014)
LCA, IPCC [a]	CI▼ (S)	-	6	-															√																						Menikpura et al. (2013)
DDS, CBA, MCDA [b]	CO▼	NA	12	21					√						√			√	√		√									√							√		√	√	PCD (2012a)
MDT	CI▼ (L)	-	6	-	√																																				Hanko (2007)
MCDM [b]	CO▼	-	17	-							√																	√													PCD (2014a)
Other countries																																									
AHP	CI▼ (L)	NA	4	8-14	√														√		√	√	√	√			√	√	√	√	√					√	√			√	Milutinović et al. (2014)
AHP	CI▼ (L)	10	7	12						√								√				√						√	√					√			√	√	√	√	Samah et al. (2010)
AHP	CI▼ (L)	3	4	8	√																	√					√														Abba et al. (2013)
AHP	CI▼ (L)	35	-	44														√				√						√								√					Parekh et al. (2014)
AHP	CI▼ (L)	21	4	12					√					√				√	√		√	√								√						√			√	√	Garfi et al. (2009)
TAS, AHP	CI▼ (M)	192	3	12	√																	√						√		√				√		√	√			√	Taboada-Gonzalez et al. (2014)
AHP-BOCR[c]	CO▼ CO$^{\Delta}$	6	5	14				√			√				√			√			√	√					√	√		√									√	√	Yap and Nixon (2015)
AHP, LCA	CI$^{\Delta}$ (L)	3[d]	3	4	√														√								√		√										√		Contreras et al. (2008)
Fuzzy-AHP, TOPSIS	CI$^{\Delta}$ (L)	7	18	14															√		√		√				√	√	√	√								√		√	Pires et al. (2011a)
SAW, AHP	CO$^{\Delta}$	1	4	5					√												√							√				√					√				Begum et al. (2012)

Table 5.1: Evaluation tools and criteria used in various decision making methods for solid waste management (Cont.)

Details/Main criteria						Technical													Environmental									Economic								Social					
Model	Studied level	No. of stakeholders	No. of alternatives	No. of sub-criteria	Inputs	Energy content	Net output	Maturity	Complexity	Know-how/ experience	Land requirement	Pre-treatment	Technical implication	Availability in local	Suitable for characteristics	Performance records	Scaling /expansions	Other criteria	GHG emission	Regulations	Volume reduction / diversion from landfill	Environmental impacts	Energy consumed	Recycling rate	Fossil fuel substitution	Resource consumption	Other criteria	Capital cost	O&M cost	Revenue/benefit	Fuel costs	Energy produced	Available co-financing	Marketing potential	RE contribution	Job creation	Public acceptance	Odor impacts	Health risk & safety	Other criteria	References
LCA, ME, AHP	CI$^{\Delta}$ (M)	4	3	9	√														√								√	√	√							√		√			Antonopoulos et al. (2014)
ANP, AHP	CO$^{\blacktriangledown}$	5	5	11		√	√					√						√	√		√							√	√											√	Nixon et al. (2013)
ANP	CI$^{\blacktriangledown}$ (L)	12	3	13					√	√			√							√								√	√								√		√	√	Khan and Faisal (2008)
Fuzzy-AHP, CAM	CI$^{\blacktriangledown}$ (L)	4	5	11				√			√											√				√	√	√		√				√			√			√	Hung et al. (2007)
AHP, ELECTRE II, PROMETHEE II, TOPSIS GIS, MCDA	CI$^{\Delta}$ (L)	4	6	13				√						√				√	√		√	√				√	√	√	√						√	√					Martowibowo and Riyanto (2011)
	CI$^{\Delta}$ (L)	8	5	15				√										√	√			√					√	√							√	√			√		Longden et al. (2007)
MCA	CO$^{\Delta}$	NA	3	5	√						√														√				√		√					√					Kondili et al. (2012)
LCA	-	-	5	10															10 environmental criteria used in LCA approach [e]																							Arafat et al. (2015)
SWOT	CO$^{\Delta}$	39	13	18	√														√	√						√			√		√									√	Zaman (2013)
MCA	CI$^{\Delta}$ (L)	NA	5	10																	√			√								√					√			√	Generowicz (2011)

Remarks: AHP-Analytic Hierarchy Process; ANP-Analytic Network Process; BOCR - Benefits Opportunities Costs and Risks; CAM-Consensus Analysis Model; CBA-Cost Benefit analysis; DSS- Decision Support System; ELECTRE II- Elimination and Choice Expressing Reality; GIS- Geographical Information System; IPCC – Intergovernmental Panel on Climate Change; LCA-Life Cycle Analysis; MCA-Multi-criteria Analysis; MCDA-Multi-criteria Decision Analysis; MCDM-Multi-criteria Decision Making; DMT-Decision making tool; ME-Mass and Energy balance; MFA-Material Flow Analysis; PROMETHEE II- Preference Ranking Organization Method for Enrichment Evaluations; SAT-Sustainability Assessment of Technologies; SAW-Simple Additive Weight; SWOT- Strength, Weakness, Opportunity and Threats; TAS-Technology Assessment; TOPSIS-Technique for Order Preference by Similarity to Ideal Solution.

Input (√) means MSW characteristics; input (√) means MSW quantity and its forecasts; NA-Not available

$^{\Delta}$ developed country, $^{\blacktriangledown}$developing country, (L) – Large city, (M) – Medium city, (S) – Small city

[a] used IPCC formula to calculate GHG emissions reduction to select the suitable waste management which has a high potential to reduce GHG emissions; [b] not specific, the guideline report of the government, [c] Main criteria consists of Benefit (B), Opportunity (O), Cost (C) and Risk (R), however; sub-criteria were decomposed into technical, environmental, economic and social components in this study; [d] groups of stakeholders (48 residents, 2 NGOs, 1 local government); [e] LCA-based criteria including abiotic resource depletion, GHG emission, eutrophication, human toxicity, photo-oxidant formation and acidification

and incorporation of multi-stakeholders involving both tangible and intangible data (Kangas, 1994; Saaty, 1980). MCDA enables discussion of tradeoffs between criteria rather than between stakeholders (Hung et al., 2007) and AHP is the most applied MCDA method to studies applying multi-criteria decision making analysis (MCDM) in MSWM; the incorporation of relevant waste management stakeholders becomes a key role in the decision making process. It is apparent that problems with multiple stakeholders will likely acquire more attention in the near future (Soltani et al., 2015). This study therefore attempts to develop AHP for evaluating MSW management systems for medium and small cities associated with the incorporation of stakeholder preferences.

5.2.2 Coverage of criteria used related to MSW management

Based on the critical issues, the selection of criteria to be employed in the decision making model, in evaluating MSWM (Achillas et al., 2013; Karmperis et al., 2013) are discussed in **section 5.2.1**, the optimal criteria identified are discussed here. According to Achillas et al. (2013), the selection of criteria heavily depends upon the issue of study (whether optimal strategy or location is questioned). They reviewed the use of criteria related to MSWM strategic issues from 1994 to 2010 and concluded that environmental impacts and the cost of alternatives are dominant criteria while social (i.e., public health and safety, social acceptance and employment) and technical (i.e., applicability, feasibility and reliability) criteria were not considered. Many studies suggest that, for sustainable waste management, three main criteria of environment, economy and society should be identified (Milutinović et al., 2014; Morrissey and Browne, 2004; Woolridge et al., 2005). Apart from the three pillars of sustainability, additional concerns such as technological, regulatory, operational and functional criteria should also be considered in the evaluation process (Soltani, Hewage, Reza, & Sadiq, 2015). In addition, technical criteria should be emphasized for evaluating optimal options considering sustainable waste management (Achillas et al., 2013).

To understand multi-criteria and multi-disciplinary approaches required to be taken into account in evaluating MSWM options, this study reviewed various criteria considered in different decision making models. **Table 5.1** depicts the criteria considered in 25 studies from 2007 to 2015, which can be categorized into four main criteria: technical, environmental, economic and social. Several sub-criteria were considered regarding these four main criteria. Regarding technical considerations, technical maturity is most frequently addressed in evaluating MSWM systems, followed by complexity or simplicity, local equipment, know-how, and land demand. GHG emission or its reduction were the most widely considered environmental aspects, followed by volume of waste reduction or diversion from landfill, human impacts, low waste water quantity, resource consumption, environmental impacts, and recycling rate. With regard to economic considerations, capital and O&M costs are most widely used in the decision making approach, followed by energy produced, revenues/benefits, budget control, and energy recovery. Public acceptance is the most considered social aspect, followed by job creation, health risk, and economic efficiency. In addition, criteria related to sustainable MSW management as suggested above (i.e., environmental, economic, social and technological) were also identified and used in the AHP model as discussed further. As shown in **Table 5.1**, the frequency of use of the main criteria and sub-criteria at each level of study (i.e., country, large city, medium and small cities) are identified in **Table B-1**.

5.3 **Methodology of the study: Analytic Hierarchy Process (AHP)**

AHP was initially pioneered by Satty in the 1970s and is an area of research in multi-criteria decision making (MCDM) (Saaty, 1980). The AHP method was developed as a simple and powerful decision making tool for assisting decision makers in evaluating sustainable MSM management that involves multi-criteria and assists ordinary people in making complex decisions (Contreras et al., 2008; Milutinović et al., 2014). AHP is based on an aggregation process and a hierarchical structure. The complex problem is disaggregated into a group of factors. The hierarchy can be designed into several levels of factors, including criteria and alternatives. Through the hierarchical structure, a pair of factors is then compared to determine the priorities by using the numerical ratio scale. For several levels of the hierarchical structure, different evaluation scales are determined to prioritize alternatives with respect to each criterion and weights of criteria. In this hierarchy, all weights can be calculated through pair-wise comparisons regarding a one (1) to nine (9) scale for quantifying verbal expressions. These verbal expressions illustrate the strength of important alternatives or criteria among others (Contreras et al., 2008).

The ratio scale is used to measure preference of stakeholders, allowing the AHP method to be employed for decision making by considering both quantitative and qualitative aspects (Saaty, 2006). Application of the AHP approach is widely used for decisions that require consideration of stakeholder preferences as the major concern. Several meetings of stakeholders are taken into account for acquiring group consensus, otherwise individual judgment is enabled by using the AHP method. An individual stakeholder is firstly needed to make his or her own decision. A group decision is consolidated by using Geometric Mean Method (GMM) as described below. According to Saaty (1980), for a single stakeholder or decision maker, the application of the AHP involves four steps as described below.

Step 1: Discomposing the problem into a hierarchical structure.

This step is important in defining the decision problem that needs to be solved by using a hierarchy model comprising three main levels, such as a goal or problem, attribute of main and sub-criteria and alternative decisions. The top level represents a goal related to a problem. The attribute and alternatives are then presented as inter-related elements as shown in **Figure 5.1**. The decision elements shown in the hierarchical structure are utilized as a basis for developing the questionnaire and formulating questions (Contreras et al., 2008). In this study, the problem concerned is how to obtain the degree of importance of the items, criteria and alternatives relevant for managing MSW in a sustainable way. Thus, the objective is to specify the weighting for each item.

Step 2: Prepare a pair-wise comparison matrix

The aim of this step is to determine the weight of each attribute and alternative. During this step, it is necessary to know how much the attribute and alternative are greater than others and to determine which ones are most preferred. A pair of alternatives at the third level (see **Figure 5.1**) is compared with respect to the attribute to which they relate at the second level. Similarly, if the attribute is categorized into main and sub-categories, a pair of sub-categories is compared in

respect to main categories. The number of comparisons equal $\frac{n(n-1)}{2}$ per matrix; where n is a number of main criteria or sub-criteria or alternatives. In this step, a 9-point weighting scale as presented in **Table 5.2** is suggested for ranking subjective opinions, and utilized to generate input data. A set of pair-wise comparisons construct the individual comparison matrix A as expressed in **Equation (5.1).**

$$A = [a_{ij}]_{n\times n} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \tag{5.1}$$

where a_{ij} is relative importance between indicator i and indicator j.

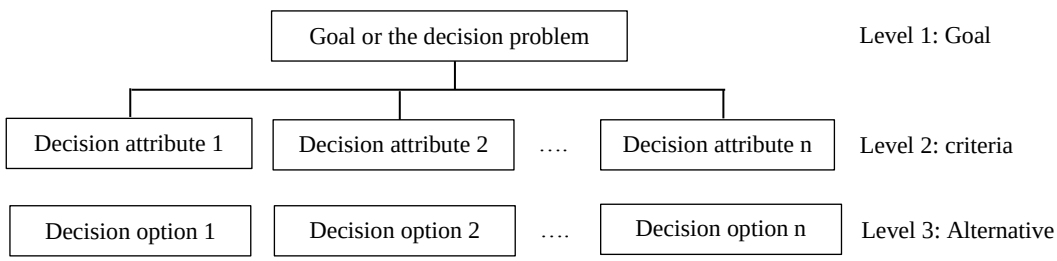


Figure 5.1: A hierarchical structure for stakeholder participation.
Source: Adapted from Contreras et al. (2008)

Table 5.2: Pair-wise comparison scale

Numerical value	Definition
1	Equal importance of both elements
3	Moderate importance of one element over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

(Source: Saaty (1980))

Step 3: Examining the consistency of a comparison matrix to eliminate the null responses.

This step follows the main axiom underlying the theoretical validation of the comparison matrix (Contreras et al., 2008). If judgments on the matrix A are found consistent, the relative weights can be carried out by using **Equation (5.2)**. As the AHP method for multi-criteria decision making is quite subjective, inconsistency can be expected. After all pair-wise comparisons have been made, the consistency index (CI) for a $n\times n$ comparison matrix can be calculated by the maximum eigenvalue or $\lambda_{\max}$ as illustrated in **Equation (5.3).** In this step, $\lambda_{\max}$ is the

summation of products between each weighting and the sum of columns of the matrix. To obtain the judgment consistency ratio (CR), the CI value from previous step and the random index (RI) proposed by Saaty (1980) are used as variables in **Equation (5.4)**. However, it is suggested that the corresponding consistency ratio (CR) of a comparison matrix should not exceed 0.10 or a 10% (Saaty, 1980). If CR is more than 0.10, the judgment matrix shows inconsistency. To obtain the consistency matrix, pair-wise comparisons should be reviewed according to a situation (Al-Harbi, 2001; Contreras et al., 2008).

(1) Calculating the relative weights,

$$Aw = \lambda_{\max} w, \tag{5.2}$$

where λ is the non-zero eigenvalue of the consistent matrix A.

(2) Calculating the consistency index (CI),

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)}. \tag{5.3}$$

(3) Calculating the consistency ratio (CR),

$$CR = \frac{CI}{RI}, \tag{5.4}$$

where RI is the random index value depending on the size of a comparison matrix as presented in **Table 5.3**.

Table 5.3: Random index (RI) in AHP

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

(Source: Saaty (1980))

Step 4: Estimation and rating of the global weight (GW)

This step determines the final priority of the alternatives based on local priorities and weight of the criteria. The global weight (GW) can be calculated by a matrix that summarizes the weight of criteria (w_j) multiplied by a matrix of local priority (l_{ij}) as illustrated in **Equation (5.5)**. The weights of criteria and local priorities can be calculated by using three sub-steps: firstly by summarizing the elements of column j (**Equation (5.6)**); secondly, normalizing each element by dividing its column sum as presented in **Equation (5.7)**; and thirdly, all values of row j are averaged to derive those of such priorities (p_i) (**Equation (5.8)**) (Ishizaka and Labib, 2011). The most relevant alternative is then determined and suggested by comparing global weights.

$$GW_i = \sum_j w_j . l_{ij} \tag{5.5}$$

$$\text{Sum of column } j = \sum_{i=1}^{n} a_{ij}, \forall_{i,j} \tag{5.6}$$

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \forall_{i,j} \tag{5.7}$$

$$p_i = \frac{\sum_{i=1}^{n} a'_{ij}}{n} \tag{5.8}$$

In case of several stakeholders, the group preference needs aggregating. To aggregate group preferences, the geometric mean method (GMM) and a weighted arithmetic mean method (WAMM) are employed in the AHP approach. In the GMM, individual evaluations are utilized as elements in the pair-wise comparison matrices. Prioritizing and rating of final weights are then carried out by using **Equation (5.9)** through the same processes as mentioned above. In WAMM, priorities are calculated and then aggregation achieved by using **Equation (5.10)**. In case that the stakeholder group acts as an individual, either WAMM or GMM can be used for the resulting priorities (Contreras et al., 2008). This ensures that both methods do not violate the Pareto principle. Therefore, this study utilized GMM to produce group comparison matrices, as shown below:

$$W_i = \frac{\sqrt[n]{\prod_{j=1}^{n} a_{ij}}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{j=1}^{n} a_{ij}}}, i = 1, 2, ..., n. \tag{5.9}$$

$$W_i = \sum_{k=1}^{m} \alpha_k w_i^k, i = 1, 2, ..., n \text{, and } k = 1, 2, ..., m, \tag{5.10}$$

where n denotes as criteria, m denotes as decision makers, α_k, for $k = 1, 2, ..., m$ with $\alpha > 0$ and $\sum_{k=1}^{m} \alpha_k = 1$.

As mentioned above, AHP is selected as a tool for assigning weights of a MSW management system which depends on several factors such as the availability of resources and time, the number of factors required for decision making, and the degree of consensus expected to be obtained from the stakeholders.

Based on stakeholder preferences considered in this study, the GW can be carried out by aggregating weights assigned by each group of stakeholders to each criteria. In this case, the geometric mean method is used to aggregate weights assigned by stakeholders. After assigning

weights and consensus method discussed, the next step is to verify the robustness of the AHP model by using sensitivity analysis (SA).

5.4 **Sensitivity analysis (SA)**

The ranking of different MSW management systems may provide different variations depending on weights assigned by stakeholder groups and weights of the criteria. Weights of the alternatives that are sensitive to change the ranked alternatives, may change based on the circumstances (Contreras et al., 2008). Therefore, the last step of the decision making process is the sensitivity analysis that is achieved by slightly modifying input data to observe impacts on the results. If priorities do not change, it can be said that the model is robust, otherwise it is considered sensitive (Ishizaka and Labib, 2011).

Sensitivity analysis (SA) is an important process in AHP that is used to determine the effects of changes on input values and global weights on model results. The SA may provide the robustness of a decision making model (Ananda and Herath, 2003; Leonelli, 2012; Triantaphyllou, 1997). In the AHP, SA can be investigated on three levels: weight, local priority and comparison (Ishizaka and Labib, 2011). The methods used for SA on AHP problems can be categorized into three groups: mathematical models, probabilistic simulations and numerical incremental analysis (Chen and Kocaoglu, 2008). Among these methods, the numerical incremental analysis was mostly used in previous studies, where AHP is taken into account for tackling decision problems (Chen and Kocaoglu, 2008; Leonelli, 2012). This method involves the relative weight values changed associated with the new solution calculated. This is also called One-at-a-time (OAT) and works by incrementally changing the weight of one criteria at a time associated with calculating new solutions and graphically showing how global weight/ranking of alternatives changed. In this study, SuperDecisions® (Creative Decision Foundation, USA) software is used to investigate stabilities of outcomes with respect to each type of control criteria: environmental, economic, social and technical priorities.

5.5 **Implementing AHP for MSW management**

5.5.1 Identification of alternatives, criteria and stakeholders

5.5.1.1 Identifying optimal alternatives

Identification and selection of alternatives or scenarios of MSW management is normally based on waste composition (Milutinović et al., 2014) and/or based on the status of three relevant components, including existing systems which are accessible in the literature, changes of the status-quo, and possible consequences (Ananda and Herath, 2003).

Based on the review of existing, ongoing and planned general MSW treatment and WTE treatment systems discussed in **Chapter 3**, eight alternative MSWM systems which comprise three general MSW management systems and five WTE treatment systems (see **section 3.7**) are considered in this chapter. The general MSW treatment systems consist of mechanical biological treatment (MBT) integrated with composting (MBT-CP), mechanical treatment system (MT) for sorting recyclable materials (MT-Re), and landfill (LF). On the other hand, WTE treatment

systems include anaerobic digestion (AD), incineration (IC), gasification (GF), refuse derived fuel (RDF) produced from MT (MT-RDF), and LFG as described in **Table 5.4**. This study does not consider issues related to generation, collection and transportation of MSW.

Table 5.4: Description of alternative MSW management systems

Items	Options	Description
MSWM systems	MBT-CP	Small sorting and composting systems, by products are compost, recyclable materials and residues, and needs a final disposal system.
	MT-Re	Small sorting system, the main product is recyclable materials, more residues than MBT-CP (e.g., organic and other wastes etc.) that need a final disposal system.
	LF	Engineering landfill or sanitary landfill without energy recovery, and without a sorting system, called a business-as-usual (BAU) disposal system in most medium and small cities.
WTE systems	AD	Sorting system and anaerobic digestion, sometimes called MBT-AD system, by-products comprise biogas (generate heat or electricity), recyclable materials, two main types of residues (digestate from a biodegradable feedstock and residual wastes from the processes). Final disposal systems for both residue and digestate are required.
	IC	A thermal treatment process, typically is a moving grate type of incinerator, by-products consist of electricity and residues from bulky wastes and ash, and a final disposal system is needed.
	GF	Sorting system and gasifier, by-products are electricity, recyclable materials and residual wastes, and a final disposal system is needed.
	MR-RDF	Sorting system, the major product is Refuse Derived Fuel (RDF) and other products are heat or electricity (because it is normally used as fuel in cement kilns to generate heat or in IC or GF systems for electricity generation), recyclable materials and residues. A final disposal system is also needed
	LFG	A sanitary landfill with energy recovery, landfill gas is the main product from the system

5.5.1.2 Identifying sustainability criteria

Criteria were identified based on the literature review and objectives of the study. However, application of the AHP in the field of solid waste management is very limited (Contreras et al., 2008). In this study, 25 studies were reviewed to identify criteria and stakeholders for evaluating MSW management systems for medium and small cities as presented in **Table 5.1** and classified in **Table B-1**. Unfortunately, as shown in **Table B-1**, there are only a few studies addressing medium and small cities. Criteria used in medium and small cities could not be identified. Therefore, this study selected important criteria used in all the literature reviewed and considered these same criteria in both medium and small cities.

The selection of criteria was made according to their ability to translate into a comprehensive meaningful assessment of sustainable MSWM and on their frequency of use. This study reviewed the number of criteria and sub-criteria used from 25 studies. As discussed in **section 5.2.2**, the main criteria were identified into four groups (technical, environmental, economic and social), while sub-criteria were identified regarding the following factors proposed by Intharathirat et al. (2015) and Klundert (2000):

- Relevance regarding to the sustainable development concept and Agenda 21
- Validity or capability to measure and indicate

- Reliability or capability to achieve objectives
- Easy to understand for non-expert stakeholders
- Clear overview
- Sensitivity over time as well as to future change
- Availability of time and data sequences
- Ability to retrieve data
- International compatibility
- Adaptable to the other contexts, in particular developing countries
- Frequency of use
- Importance given by stakeholders in previous studies
- Redundancy of criteria
- Applicability of the model

The final identification of criteria was based on sustainable solid waste management which must consider environmental, economic and social criteria (Morrissey and Browne, 2004). The limitation of the number of criteria that a decision maker can handle is regarded to be between 7 and 12 criteria (Nijkamp et al., 1990 and Bouyssou, 1990 cited from Garfi et al., 2009). Following assessment of sustainable waste management that included consideration of resources and energy recovery, criteria for the sustainability of waste management were taken into account.

Based on a review of criteria used in literature as presented in **Table 5.1** and discussed in **section 5.2.2**, this study considers four main criteria (environmental (EV), economic (EC), social (SC) and technological (TN)), and 12 sub-criteria as given in **Table 5.5**. Environmental criteria were broken down into three sub-criteria comprising GHG emissions (EV1), diversion from landfill (EV2), and environmental impacts (EV3). Economic criteria were broken down into three sub-criteria representing capital costs (EC1), operational and maintenance costs (EC2), and revenue and benefits (EC3), while social criteria consist of two sub-criteria comprising creation of jobs (SC1) and public acceptance (SC2). Technical criteria address simplicity (TN1), maturity (TN2), local authority (TN3) and land requirements (TN4). Information related to these criteria was decomposed into **Table B-2** to provide supporting data for stakeholder decisions as further discussed in **section 5.5.3**. However, to support the sustainability of MSWM decision making, it not only simultaneously accommodates environmental, economic and social aspects, but also incorporates stakeholder participation into the decision making process (Hung et al., 2007). Hence, individuals and groups of stakeholders that were invited for assigning weightings in the decision making process are identified in next section.

5.5.1.3 Identifying relevant stakeholders

Identification of stakeholders and groups for policy making is a difficult task (Ananda and Herath, 2003) and there is no literature identifying relevant groups of stakeholders for MSW management. The process of stakeholder selection also plays an important role, since consensus methods are based on their opinions. For MSW management, the role of stakeholders has been transformed from one of being merely the recipients of environmental and health impacts to that of playing a key role in implementation, design and promotion of MSWM systems (Contreras et al., 2008), which reflects the situation where stakeholders can be affected both negatively and positively by decision making. In addition, many environmental issues in cities have been

addressed by the interaction of many stakeholder groups. Many groups of stakeholders can be identified if they have interest in the issue. Also, the composition of stakeholder groups depends on the problem and its possible solution.

Table 5.5: Description of criteria and input data in the model

Main criteria	Sub-criteria	Description
Environmental (EV)	Diversion from landfill	Capability of reducing waste before landfilling. Unit: percentage (%)
	GHG emissions	Amount of CO_2 and other GHG emitted to atmosphere (kg CO_2 per tonne of waste), minus (-) means GHG emissions reduction
	Environmental impacts	Recorded information of air pollution, wastewater released and other environmental impacts from technologies
Economic (EC)	Capital cost	Represents the amount to be expended to implement the alternative strategies (in infrastructure, equipment, vehicles, land). Unit: million Baht[**]/tonne.
	Operating and maintenance (O&M) cost	Related to the amount to be expended during alternative operation, in material, electricity, maintenance, labor, and to financial costs like annuity. Unit: Baht/tonne of waste.
	Revenue/benefit	Income from selling electricity and/or by products. In Baht/ tonne
Social (SC)	Public acceptance	Possibly promoting acceptability of local community, the alternative does not present negative impacts to quality of life.
	Creation of jobs	Number of jobs created for the operation of treatment equipment
Technical (TN)	Simplicity	Required personnel with medium level of knowledge to operate and control the alternative which is easy and uncomplicated.
	Maturity	Alternative has been developed and available technical information and cost that can be measured by the number of existing plants in Thailand.
	Local equipment	Availability of assembly technology and equipment in Thailand.
	Land requirement	Average land requirement in km^2/tonne of waste.
Inputs	MSW generation	In kg/capita/day during from 2015to 2030 (see **Table B-2**)
	MSW composition	Information on MSW composition is shown in **Figure 3.4** and **Table B-2** that provides information on the suitable fraction fed into systems.

According to Sarkis (2000), stakeholders are defined as 'people and organizations having an interest in good waste management, and participating in activities to make it possible'. They are also identified as several groups, such as organizations (governmental and non-governmental organization (NGOs)), enterprises and all others (Contreras et al., 2008). Broader definitions of stakeholders comprise planners, policy makers, administrators in government and NGOs, and other organizations who are interested in the issue at hand (Ananda and Herath, 2003). Hung et al. (2007) suggested that several groups of stakeholders, including government, business or private sector, experts or technicians and NGOs can be included in the participatory decision making process for MSW management. Three stakeholder groups, such as government and/or municipality and expert, are mostly involved in the models (Soltani et al., 2015). Government and/or municipality stakeholders are identified, as they are responsible for selecting and operating MSWM strategies. Also, experts are widely incorporated, as they have information and experience on criteria and alternatives, and are active in these fields of study (Soltani et al., 2015).

[**] 1 Baht = 0.028 USD

As reviewed in **Table 5.1**, four groups of stakeholders were identified as academic, governmental, local authority, and expert or technical (see **Table B-3)**. In this study, identification of stakeholders was based on their participation, responsibilities as decision makers, and research outputs (e.g., research articles, reports and specialist support in the country). Therefore, five groups of stakeholders such as governmental, academic, technical, local authority and NGOs were identified for assigning participatory weights in the AHP process, as discussed in **section 5.3**. Even though the private sector plays a key role in MSWM, in this study their participation was not included in the decision making process as their judgments may be skewed towards economic aspects only (Contreras et al., 2008; Khan and Faisal, 2008).

5.5.2 Hierarchical structure development

Based on the status of general MSW treatment and WTE treatment systems described in **Chapter 3,** and the identification of alternatives, sustainability criteria and stakeholders discussed in **section 5.5.1**, the evaluation framework was constructed with a hierarchical structure as described in this section. Through the hierarchical structure, the evaluation framework consists of several levels as shown in **Figure 5.2**. This framework was used to evaluate appropriate MSWM systems for both medium and small cities. The top level represents the goal of evaluating the most suitable MSW management system for each type of city. As presented in **Table 5.1**, and discussed in **section 5.5.1.2**, the second and third levels represent main criteria and sub-criteria respectively. The last level demonstrates alternatives with respect to sub-criteria. After constructing the hierarchical structure, the arrangement of supporting data for stakeholder decisions in pair-wise comparisons via the AHP model is needed (as described in the next step).

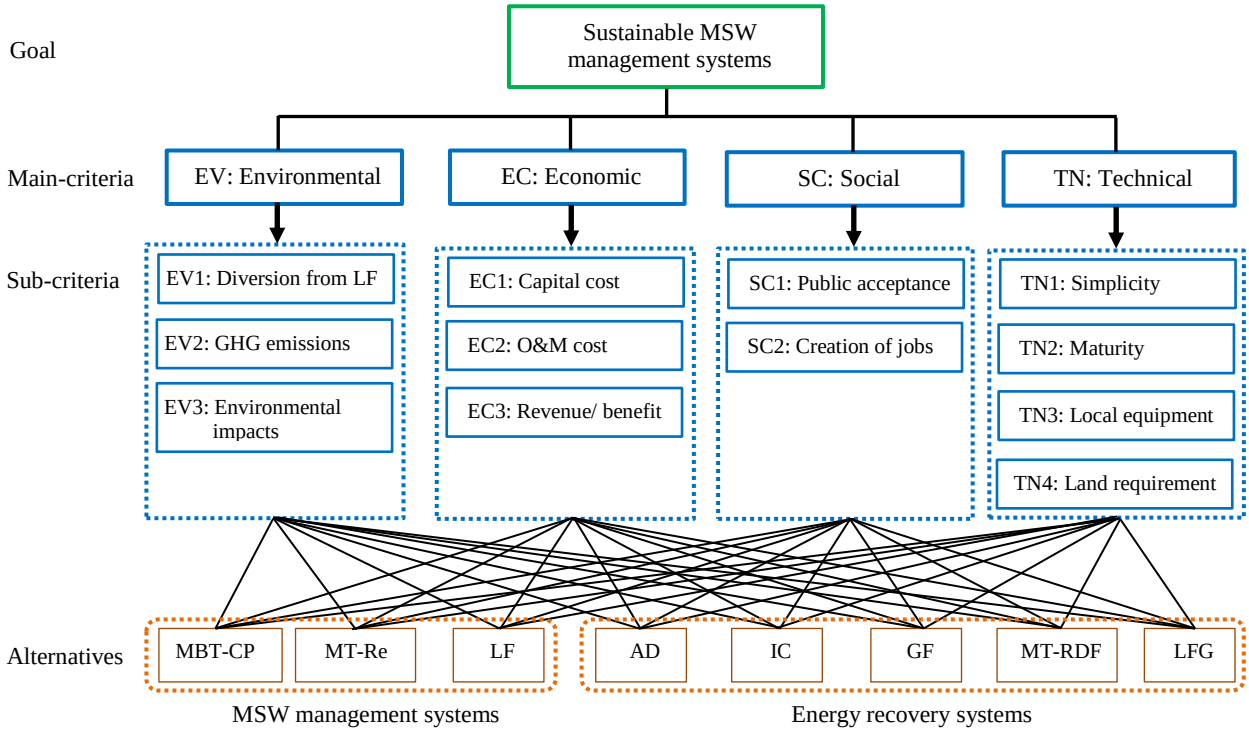


Figure 5.2: Decision hierarchy of AHP method

5.5.3 Information and data inputs

Based on the hierarchical structure constructed in the previous section, the arrangement of data related to MSWM systems is described in this section. Before assigning weights by stakeholders, collected data is arranged and grouped into sub-criteria categories and other important inputs, i.e., heating value, MSW quality and quantity (as outlined in **Table B-2**). This data is mainly used to guide stakeholder decisions for pair-wise comparisons via the AHP process. The output of alternative MSWM systems is also presented with respect to sub-criteria categories.

As shown in **Table B-2**, most data were gathered from PCD (2012a) who evaluated different types of existing MSW treatment technologies in Thailand and then made guidelines for local authorities for selecting suitable options through consideration of technological and economic criteria (PCD, 2014a). Given the lack of available data of some parameters (e.g., GHG emissions, public acceptance, maturity and MSW quantity and its forecast in Thailand), other sources of data were accessed. The definition of GHG emissions (EV1) is the amount of CO_2 and SO_2 emitted into the atmosphere, which is derived from waste composition or biodegradable waste buried in landfills. In this study, emissions resulting from collection and transportation, and electricity and fossil fuel consumed for treating waste were excluded from consideration. Diversion from landfill (EV2) is defined as the amount of solid waste reduced from treatment, with the rest disposed of in landfill. This indicates not only increasing the period of use of a landfill site, but also reducing environmental impacts (EC3) from landfilling. In evaluation of the investment cost (EC1), the cost of land, design and construction, facilities and equipment were taken into account, while operational and maintenance (O&M) costs (EC2) comprise labor, energy and other operating costs. Revenues and benefits (EC3) depend on each alternative: the revenue of fertilizer is taken into account for composting; anaerobic digestion, incineration, gasification and landfill gas take into account the price of electricity generated. Revenue from recycling is taken into consideration of the market price of recycled materials. The number of jobs created (SC1) in MSWM depends on labor-intensive activities of MSW treatment systems. Facilities for MSWM that require more hand sorting, recycling and collecting of recyclable materials provide approximately 10 times more jobs than waste disposal options such as landfilling and incineration (Murray, 1999 cited from Friends of the Earth, 2010). Given that public acceptance (SC2) cannot be measured and is defined as a qualitative criterion, this study derives this information from existing literature (see **Table B-2**). It can be concluded that public hearings addressing technologies can be acceptable and that there are no negative impacts on human health. For the technical aspect, simplicity (TN1) is defined as a system that can be easily designed, operated and can cope with local physical conditions, with sufficient availability of know-how and experience or skills for operation. Maturity (TN2) of MSW management systems is defined as the number of treatment plants that exist in Thailand, which indicates that the technology has already been developed over the long-term. Local equipment (TN3) is defined as equipment that is used for construction and maintenance, and is sufficient and locally available or would be possible to assemble in the local area. Land requirement (TN4) is one of the most important criteria due to the scarcity of land for treating and disposing MSW in Thailand. In this study, information on TN4 is provided in terms of the minimum area required per tonne of MSW.

Selection of an appropriate MSW system depends not only on addressing sustainability criteria, but also on consideration of the amount of waste generated and its composition (White et al., 1995 cited from Samah et al., 2010). Therefore, this study provides more information on the composition of waste and MSW quantity. Data on waste composition in medium and small cities was gathered from TGO (2014). The amount of waste generated in each type of city is presented in terms of the waste generation rate (in kg/capita/day). Due to the lack of time series data on the amount of waste generated in medium and small cities, the increasing rate of MSW at country level was assumed to be the same as for medium and small cities. Hence, the data on MSW generation rate in 2013 in medium and small cities was also gathered from TGO (2014) and forecast by using the increasing rate of 1.40% annually from 2013 to 2030 (as described in **Chapter 4**).

In this section, the arrangement of data is addressed and is based on a review of literature. This information is useful in the following steps for weighting alternatives, as stakeholders can make more informed decisions with adequate data supporting each type of MSWM system.

5.5.4 Implementing the pair-wise comparisons

Based on the hierarchical structure developed in the previous section, each level of the framework has different weights, reflecting the level of importance of criteria and alternatives with respect to sub-criteria. In this study, AHP was chosen to assign weights of criteria and alternatives, depending on their background, knowledge and the supporting data given in **section 5.5.3**. In order to assign weights, this section includes two steps as follows.

5.5.4.1 Questionnaire development and administration

Once information was arranged and stakeholders identified, the next step was to develop the questionnaire and distribute to stakeholders. The questionnaire was designed to elicit weightings from stakeholders on MSW management systems. It comprises three parts (see **Appendix C**). The first part of questionnaire queries stakeholder agreement on the number and types of proposed criteria and alternatives. In case of disagreement, stakeholders can give suggestions and propose other appropriate criteria and alternatives. The second part presents instructions for conducting the weightings in pair-wise comparisons. The last part consists of a set of questions asking each respondent to weight the relative importance between two evaluation items on a 9-point scale given in the second part. This pair-wise comparison is based on the hierarchical structure of the MSWM system which consists of four levels as presented in **Figure 5.2**. The first level represents the overall evaluation goal. The second level comprises four categories of main criteria: environmental, economic, social and technical. The third level contains 12 sub-criteria: GHG emissions, diversion from landfill, environmental impacts, capital costs, O&M costs, revenue and benefits, creation of jobs, public acceptance, simplicity, maturity, local equipment and land requirements. The last level contains eight MSWM system alternatives: mechanical biological treatment (MBT) integrated with composting (MBT-CP); mechanical technology (MT) for sorting recyclable materials (MT-Re); landfill (LF), and five WTE systems (anaerobic digestion (AD), incineration (IC), gasification (GF), refuse derived fuel (RDF) produced from MT (MT-RDF), and landfill gas (LFG)). Pairs of evaluation items at levels three and four were compared with respect to the categories to which they relate in the upper level. Also, each

evaluation item in level two was compared against other items at the same level. For each level of city, medium and small, a stakeholder was asked to assign weights by 355 pairs. Therefore, in total, 710 pairs were assigned weights by each stakeholder. Information about MSW composition and generation in medium and small cities, solid waste management systems (as described in **Chapter 3**), descriptions of alternatives and criteria (as described in **sections 5.5.1.1** and **5.5.1.2**) were also provided in the questionnaire distributed to stakeholders; however, this information is excluded in **Appendix C**.

Pretesting a questionnaire was suggested as an important process to improve the quality of the survey as it helps the questionnaire designer to diagnose questionnaire problems from potential respondents (DeMaio et al., 1998). Therefore, before distributing the questionnaire to relevant stakeholders, pretesting the questionnaire was conducted by distributing it to a few stakeholders. The development of a questionnaire should be equipped with information to ensure that stakeholder decisions on MSW management systems build upon an understanding about the sustainability assessment and the situation of MSW issues. Hence, the questionnaire used and distributed to relevant stakeholders is provided in **Appendix C**. However, the pretested questionnaire provided only one part of the pair-wise comparisons, while a full questionnaire included all essential information, including MSW composition and generation, and supporting data as mentioned above.

5.5.4.2 Establishment of the stakeholders

After stakeholders were identified and the questionnaire developed, the questionnaire's distribution to stakeholders is described in this step. The number of stakeholders can be highly varied. As indicated in **Table 5.1**, a wide range of participant numbers, from 1 to 192, is found in previous studies applying MCDM in building research. However, the large number of stakeholder groups would make the elicitation implementation became unworkable (Harrison and Qureshi, 2000). Identified stakeholders (see **section 5.5.1.3**) constitute five groups: governmental, academic, technical, local authority and NGOs.

For the AHP method, no discussion on the optimal size of the number of stakeholders has been made because AHP is not a statistics-based approach (Duke and Aull-Hyde, 2002). A 'sample size' of one (1) is enough for AHP implementation, because AHP was originally pioneered to enable a single decision maker to select the most suitable alternative among several options. The key issue is not whether the number of observations are enough for using AHP or not, but whether it is enough to be an accurate representation of the entire participation (Duke and Aull-Hyde, 2002). In this study, stakeholders who hold top positions, such as executive director, renewable energy expert or director of their organizations were chosen and the questionnaires distributed. They are expected to have a deep knowledge and good understanding of MSW management systems and its situation.

Prior calling and/or sending of e-mails to stakeholders introduced the overall picture of this study and asked about the possibility of answering questionnaires. Questionnaires were then distributed to 19 stakeholders including 3 government officers, 5 NGOs, 4 educational institutions, 5 local authorities, and 2 technicians. Among the 19 invited stakeholders, 11 responses were obtained which comprised a 58% return rate as presented in **Table B-4**. After distributing the

questionnaires, those stakeholders who expressed confusion about the weightings were personally consulted. For stakeholder preference analyses, the number of stakeholders in each group varied from 1 to 48 in previous studies in MSWM and other fields (Agha et al., 2012; Ananda and Herath, 2003; Contreras et al., 2008; Longden et al., 2007; Soma, 2003). Also, several stakeholders are involved in MCA to avoid any bias, otherwise a single participant is enough (Ishizaka and Labib, 2011). This study, therefore, distributed questionnaires to at least two stakeholders in each group, which was enough for the analysis. In addition, a group meeting and/or workshop was not conducted in this study due to the difficulty in inviting senior organizational stakeholders

5.6 **Results and discussions**

The AHP calculation was performed using Microsoft Excel. Since a large number of pairs and matrices were considered, this study presents the values of the consistency ratio (CR) as the average of each stakeholder group. The C.R. values in each matrix set of each individual stakeholder varied from less to more than 0.10 indicating consistency and inconsistency respectively. However, after taking groups of stakeholders into consideration by using the geometric mean method (GMM), most of C.R. values became less than 0.10 (or 10%). Results illustrate that the AHP models developed in this study provide good consistency with the maximum C.R. by 0.017 and 0.037 for medium and small cities respectively. The values of CR and the relative weights of all evaluation items are described below.

5.6.1 Weighting priorities of criteria

5.6.1.1 Preferences of stakeholder groups on main criteria

Based on group comparison matrices, the normalized consolidated values and CR values of each matrix (each group of stakeholders) were calculated as presented in **Appendix D**. **Table 5.6** and **Figure 5.3** present the relative weights or weight priorities of main criteria with respect to stakeholder preferences assigned by each stakeholder group. An analysis across stakeholder group preferences related to four main criteria revealed that environmental (EV) considerations had the highest weight (34-39%), followed by social (SC) (32%) and technical (TN) (16%) that had a weighting slightly higher than economic (EC) (14%) for a medium city but slightly lower than EC (18%) for a small city. This illustrates that stakeholder preferences focused on environmental performance, followed by social consideration, while economic and technical aspects were assigned almost equal weights for both medium and small cities. It also indicates that stakeholders consider strong sustainability more important than weak sustainability, as shown in **Figure 5.4**. The strong sustainability concept is based on more small-scale decentralization and greater self-reliance to create social and economic systems that are less environmentally destructive towards nature (Adams, 2006; Seadon, 2010). In contrast, Garfi et al. (2009) found a balance between environmental, social and technical criteria in Saharawi refugee camps in Algeria.

Key findings from the literature study (from **Table 5.1**) concerning large cities in developed countries indicated that environmental aspects were the most important consideration of stakeholders, followed by social, economic and technical matters respectively (Contreras et al., 2008; Longden et al., 2007). In contrast, other studies in developing countries found that economic considerations were viewed as the most important, followed by social, technical and environmental aspects respectively (Martowibowo and Riyanto, 2011; Milutinović et al., 2014; Parekh et al., 2014; Samah et al., 2010). In 2012, Suthapanich (2014) evaluated WTE technologies in a medium-sized city in Thailand and found that technical and environmental aspects had greater importance than those of economic and social ones. The different results obtained between the previous study (Suthapanich, 2014) and the current study may be due to two reasons. Stakeholders involved in the previous study not only considered environment, but also technologies because the main objective was to evaluate suitable technologies for energy recovery from MSW. On the other hand, the change in stakeholder opinion may have resulted from the crisis situation that Thailand faced at that time in 2014 when fire broke out at several dumping sites, displacing more than two hundred residents due to the release of poisonous gases (Fredrickson, 2014). This also indicates that the consideration of MSWM in Thailand shifted from one of weak to strong sustainability as mentioned above. Furthermore, environmental and social concerns have become more important in every process of MSW management in Thailand. Therefore, this study can say that the perspective of stakeholders strongly depends on any critical issue being faced in Thailand, and not only based on the economic status of the nation (e.g., developed or developing countries) or size of the city.

Stakeholders viewed economic (EC) considerations as the third most important category, which was more important than technical (TN) aspects in the case of a small city. Since a small city is insufficiently supported financially by the central government, stakeholder concern for economic aspects is not unexpected. Due to other costs (i.e., appropriate equipment, proper operation and maintenance, having skilled personnel, and right infrastructure) of MSW services, these expenditures are not recovered (Guerrero et al., 2013).

Table 5.6: Average weights of main criteria by stakeholder group for medium and small cities

Stakeholders	Relative weights							
	Medium city				Small city			
	Environmental	Economic	Social	Technical	Environmental	Economic	Social	Technical
Government	0.3275	0.1080	0.2517	0.3128	0.2826	0.1807	0.2683	0.2683
Academia	0.3726	0.0923	0.4155	0.1196	0.3926	0.1098	0.3686	0.1290
Technician	0.3882	0.1815	0.3648	0.0655	0.3000	0.3000	0.3000	0.1000
Local authority	0.4259	0.1633	0.3187	0.0921	0.3830	0.1602	0.3566	0.1002
NGOs	0.2711	0.1123	0.1815	0.4351	0.2705	0.1572	0.2722	0.3631
Overall	0.3872	0.1363	0.3165	0.1601	0.3363	0.1761	0.3243	0.1633
CR	1.2%				0.1%			

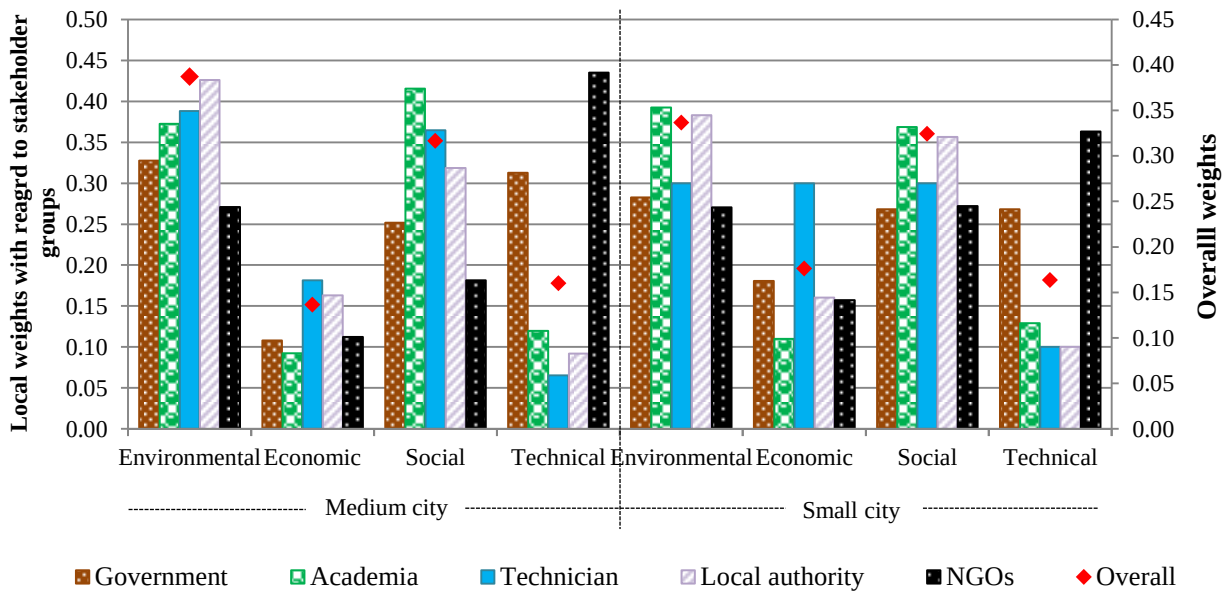
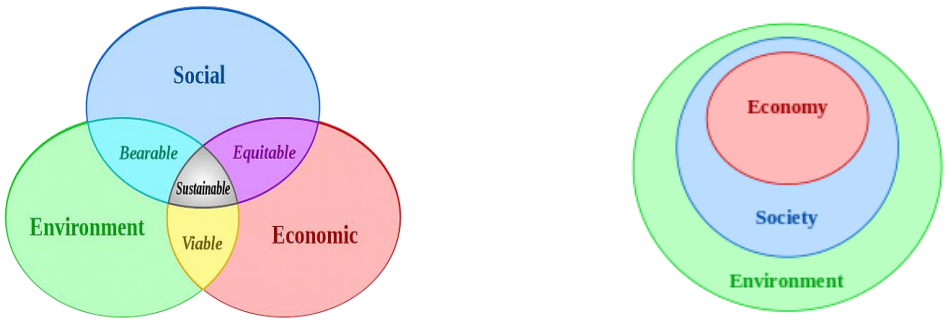


Figure 5.3: Average weights of main criteria with respect to different groups of stakeholders



a) Weak sustainability

b) Strong sustainability

Figure 5.4: Diagrams indicating the relationship between the three pillars of a sustainability, a) weak sustainability and b) strong sustainability[††]

From the governmental group's perspective, the environmental aspect had the greatest importance, followed by technical, social and economic performances respectively. This group represents policy makers who normally consider environmental plans and available technologies to encourage the local authority and public to manage MSW for the nation. According to the opinions of the technical group, technology does not matter much. Successful MSW management depends on source separation. Technologies are available worldwide, however the key issue is how to sort waste at source and input to facilities as implemented in developed countries. As a result, the performances of environmental, social and economic criteria were

[††] Source: By KTucker - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=17030898

assigned higher weights than technical aspects because they consider not only environmental and social impacts, but also require benefits from projects and the participation of the public. Similarly, the local authority group gave the highest weights to environmental aspects, followed by social economic and technical performances respectively. The local authority that takes a response to MSW management and needs public participation (Guerrero et al., 2013), as well as continuously managing MSW facilities, must consider social and economic aspects rather than technical aspects. On the other hand, the technical aspect is most important to NGOs because land requirements play an important role in selecting the type and location of MSW treatment facilities in Thailand (PCD, 2014a). In addition, most technologies used in Thailand have been imported from other countries, particularly from developed countries. These technologies are not suitable considering Thai MSW characteristics, so the most widely used options for solid waste disposal is open dumping and landfilling which require large areas and have high environmental impacts (PCD, 2015b). In the case of China, the government and private sector have developed their own technology (circulating fluidized bed incineration) to tackle the same problem and export this technology abroad (APO, 2007). As a result, NGOs considered technical aspects of highest important and suggested that appropriate technology for Thai MSW should be developed that require less land and have fewer environmental impacts.

5.6.1.2 Preferences on sub-criteria

Weights assigned to main and sub-criteria are useful for evaluating a MSW management system. Weights of main criteria were calculated from group comparison matrices and the normalized consolidated values as mentioned in the previous section. Similarly, weights of sub-criteria were also determined from group comparison matrices. The global weights of sub-criteria can then be determined by multiplying the weights of sub-criteria with the weights of their own main criteria.

A large number of pairs and matrices of stakeholder opinions were conducted in this study. Therefore, this section presents the aggregation of relative and global weights of sub-criteria for medium (**Table 5.7**) and small cities (**Table 5.8**). The normalized consolidated values and CR values of each matrix were carried out as shown in **Appendix E**. However, stakeholder group preferences on sub-criteria associated with the priorities of alternative MSWM systems are discussed later.

Considering the overall view of stakeholders for both medium and small cities, consideration of public acceptance (SC2) is viewed as the most important category (25%), followed by environmental impacts (EV3) (16%) and diversion from landfill (EV1) (12-13%), as presented in **Figure 5.5**.

The first three ranked sub-criteria mentioned above were assigned the same weights for both medium and small cities. The differences in priorities at each city level can be observed in the other ranks as presented in the last column of **Table 5.7** and **Table 5.8**. For medium-sized cities, GHG emissions was considered as the fourth rank (9.6%), followed by creation of jobs (6.2%) and O&M cost (5.5%) as fifth and sixth ranks respectively. In contrast, O&M cost is viewed as the fourth most important category (7.8%) from the perspective of small city stakeholders followed by creation of jobs (7.5%) and GHG emissions (6%). These indicate that small city stakeholders view economic considerations as more important than that for medium or larger

cities. Similarly, based on the literature studied, as mentioned in the previous section, stakeholders in developed countries assigned environmental considerations as more important whereas stakeholders in developing countries considered economic aspects as the most important (Contreras et al., 2008; Longden et al., 2007; Martowibowo and Riyanto, 2011; Samah et al., 2010). This is expected because a small city is supported by less finance from the central government compared to a medium city. So, small cities need to firstly expend their budget for basic infrastructure. Therefore, economic aspects play a role in selecting a suitable MSW management system for a small city.

Significant differences in priorities in both types of city can also be seen in the comparison of ranks. Since space is more available in a small city, consideration of land requirements is ranked as a lower priority for a small city (4.8%) than that for a medium city (4.9%). It is clear that a bigger city where urbanization and population density is increasing, must be more concerned on the availability of space required for selecting a MSW treatment system. Capital cost considerations for a small city is viewed as the seventh rank (5.3%), which is more important than that for medium city, i.e., the eleventh rank (3.4%) due to the lack of financial support by national government.

Considering other categories, it can be observed that these sub-criteria were viewed as similarly important and assigned as insignificant priorities between medium and small cities: local equipment (3.8% and 3.7% for medium and small cities respectively); revenue and benefit (4.7% and 4.5% for medium and small cities respectively); simplicity (4.2% and 4.8% for medium and small cities respectively); and maturity (3% for both cities). Furthermore, maturity was considered as the least important aspect for a medium city, which was the same as for a small city. This indicates that stakeholders viewed maturity as the least important aspect in the context of Thailand.

Table 5.7: Global weights of medium city sub-criteria

Main criteria	Weight priorities	Sub-criteria	Weight priorities	Global weight	Rank
Environmental	0.3872	Diversion from LF	0.3455	0.1334	3
		GHG emissions	0.2479	0.0960	4
		Environmental impacts	0.4075	0.1578	2
Economic	0.1363	Capital cost	0.2505	0.0341	11
		O&M cost	0.4055	0.0553	6
		Revenue & Benefit	0.3441	0.0469	8
Social	0.3165	Public acceptance	0.8045	0.2546	1
		Creation of jobs	0.1955	0.0619	5
Technical	0.1601	Simplicity	0.2626	0.0420	9
		Maturity	0.1938	0.0310	12
		Local equipment	0.2359	0.0378	10
		Land requirement	0.3077	0.0492	7

Table 5.8: Global weights of small city sub-criteria

Main criteria	Weight priorities	Sub-criteria	Weight priorities	Global weight	Rank
Environmental	0.3363	Diversion from LF	0.3523	0.1185	3
		GHG emissions	0.1772	0.0596	6
		Environmental impacts	0.4705	0.1582	2
Economic	0.1761	Capital cost	0.3015	0.0531	7
		O&M cost	0.4412	0.0777	4
		Revenue & Benefit	0.2574	0.0453	9
Social	0.3243	Public acceptance	0.7700	0.2497	1
		Creation of jobs	0.2300	0.0746	5
Technical	0.1633	Simplicity	0.2911	0.0475	8
		Maturity	0.1858	0.0304	12
		Local equipment	0.2270	0.0371	11
		Land requirement	0.2961	0.0484	10

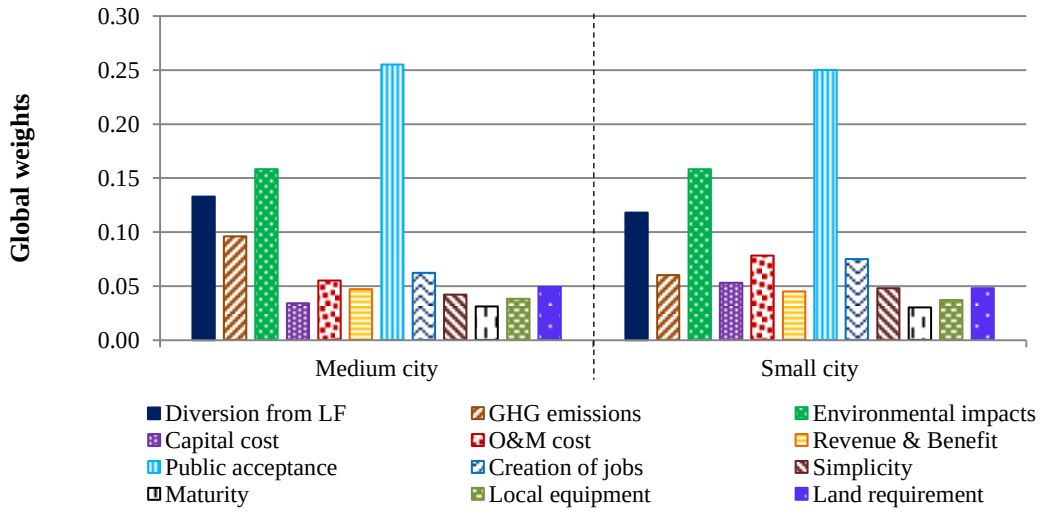


Figure 5.5: Aggregation of stakeholder preferences on sub-criteria

5.6.2 Priorities of MSWM systems

Based on the aggregation of stakeholder opinions on sub-criteria as discussed in the previous section, the preferences of each stakeholder group on alternative MSWM systems are discussed here. The aggregation of preferences in the comparison matrices of MSWM systems with respect to each sub-criteria, and the summed normalized values and CR values of each matrix were calculated and presented in **Appendix F**. Priorities of MSWM systems estimated by multiplying priority weight matrices of alternatives (see **Table 5.9** for medium city and **Table 5.10** for small city), which are the outputs from **Appendix F** with a matrix of global weights of sub-criteria resulted in **Table 5.7** and **Table 5.8** for medium and small cities respectively. **Table 5.11** shows the global weights of alternatives, including the priorities of each stakeholder group and the overall considerations for medium and small cities. In this section, priority weights of solid waste management systems calculated from the aggregation of all participant considerations are firstly presented, and the weights of each stakeholder group are then simultaneously discussed below.

1) Aggregation of stakeholder preferences

As presented in **Table 5.11** and illustrated in **Figure 5.6**, results show that MBT-CP (0.1459) is the most preferred for the medium city, followed by GF (0.1421), MT-RDF (0.1405), MT-Re (0.1375), IC (0.1247) and AD (0.1211). Similarly, the top six ranks of MSWM systems for a small city present that MT-RDF (0.1421) is the most preferred, followed by GF (0.1413), MBT-CP (0.1410), MT-Re (0.1377), AD (0.1285) and IC (0.1230), as shown in **Figure 5.7**. For both types of cities, landfilling (LF) (0.0948 for a medium city and 0.0955 for a small city) and landfill gas (LFG) (0.0935 and 0.0910 for a medium and small city respectively) were prioritized as the seventh and eighth ranks respectively. Landfilling is perceived to be the worst alternative because of higher environmental impacts, large space requirement, and the difficulty of public acceptance; Abba et al. (2013) also concluded the same. These results indicate that the preferences of stakeholders on waste-to-resource (WTR) are more preferred than on waste-to-energy (WTE), and much more than on treatment and disposal. Zaman (2013) also found that stakeholder viewpoints on waste technologies shifted from 'waste' to 'resource' for sustainable MSW management in Sweden.

Regarding a medium city, composting (MBT-CP) is most preferred due to high organic or food waste fractions in the MSW stream (see **Figure 3**.**4**). Kaosol (2009) concluded that the biological decomposition process is a suitable option for Thailand due to the high proportion of food waste and high biodegradable waste with high moisture content. It should be noted that composting would be favored, if organic fractions make up the bulk in solid waste stream. Composting can minimize the amount of waste buried in landfill, thereby preserving landfill space and extending life of a given landfill site (AIT, 2004; Chang and Davila, 2008). Despite stakeholder consensus on composting as the most acceptable option, the implementation of MSW composting is still limited in Thailand (Tippayawong and Vichadee, 2009). A few large full-scale MSW composting systems are in operation for treating biodegradable wastes in Bangkok and Nakhon Ratchasima, which represent central composting facilities that need a large input of organic wastes, sorting facilities and composting process, in order to minimize costs. However, it is difficult to separate organic waste from mixed MSW collected at end-pipe treatment. This has led to interruption of the sorting system (MBT) (e.g., bag breakers, floating tank, and conveyers) at the Nakhon Ratchasima site, and has completely halted operations in other treatment and disposal facilities due to the insufficient amount of biodegradable waste fed into these systems. Also, composting has not been successfully practiced in ASEAN countries due to high O&M costs and the high cost of compost compared to private commercial fertilizers and the lack of market opportunities (Ngoc and Schnitzer, 2009).

Table 5.9: Matrix of priority weights of MSWM systems with respect to each sub-criteria for a medium city

	Diversion from LF	GHG emissions	Environmental impacts	Capital cost	O&M cost	Benefits	Public acceptance	Creation of jobs	Simplicity	Maturity	Local equipment	Land requirement	Priority weights	Ranked
MBT-CP	0.0776	0.1486	0.1500	0.1491	0.1207	0.0773	0.2097	0.0877	0.1577	0.1916	0.1628	0.0951	0.1459	1
MT-Re	0.1251	0.1060	0.1374	0.1074	0.1091	0.1374	0.1675	0.1829	0.1380	0.0819	0.1245	0.1174	0.1375	4
LF	0.0505	0.0604	0.1307	0.1394	0.1566	0.0352	0.0543	0.0467	0.2301	0.2634	0.1665	0.1164	0.0948	7
AD	0.0627	0.1014	0.0835	0.1376	0.1200	0.0978	0.1847	0.0865	0.1216	0.1359	0.1545	0.1300	0.1211	6
IC	0.2739	0.1079	0.1065	0.1194	0.0995	0.1657	0.0728	0.1776	0.0944	0.0958	0.0487	0.1084	0.1247	5
GF	0.2476	0.1564	0.1237	0.1606	0.1437	0.2389	0.1094	0.1651	0.0668	0.0463	0.0476	0.1167	0.1421	2
MT-RDF	0.1091	0.1943	0.1453	0.0951	0.1342	0.1300	0.1426	0.1836	0.0887	0.0810	0.1197	0.1863	0.1405	3
LFG	0.0536	0.1251	0.1230	0.0913	0.1164	0.1178	0.0589	0.0699	0.1028	0.1042	0.1757	0.1298	0.0935	8

Table 5.10: Matrix of priority weights of MSWM systems with respect to each sub-criteria for a small city

	Diversion from LF	GHG emissions	Environmental impacts	Capital cost	O&M cost	Benefits	Public acceptance	Creation of jobs	Simplicity	Maturity	Local equipment	Land requirement	Priority weights	Ranked
MBT-CP	0.0771	0.1490	0.1355	0.1181	0.1152	0.0746	0.2072	0.0995	0.1546	0.1921	0.1570	0.0993	0.1410	3
MT-Re	0.1098	0.0954	0.1490	0.1024	0.1014	0.1390	0.1656	0.1942	0.1293	0.0833	0.1265	0.1376	0.1377	4
LF	0.0519	0.0583	0.1069	0.1415	0.1611	0.0346	0.0534	0.0496	0.2265	0.2548	0.1699	0.1131	0.0955	7
AD	0.0629	0.1150	0.1040	0.1417	0.1081	0.1039	0.1915	0.0987	0.1230	0.1349	0.1680	0.1200	0.1285	5
IC	0.2819	0.1289	0.1099	0.1180	0.1019	0.1597	0.0721	0.1479	0.0954	0.0915	0.0467	0.1036	0.1230	6
GF	0.2520	0.1692	0.1171	0.1624	0.1593	0.2415	0.1095	0.1433	0.0742	0.0504	0.0486	0.1233	0.1413	2
MT-RDF	0.1120	0.1651	0.1614	0.1221	0.1472	0.1214	0.1437	0.1940	0.0900	0.0838	0.1118	0.1791	0.1421	1
LFG	0.0525	0.1191	0.1162	0.0937	0.1056	0.1254	0.0571	0.0727	0.1070	0.1092	0.1714	0.1241	0.0910	8

Table 5.11: Global weights of MSW management systems regarding stakeholder group preferences for medium and small cities

Options	Global weights											
	Medium city						Small city					
	Government	Academia	Technician	Local authority	NGOs	Overall	Government	Academia	Technician	Local authority	NGOs	Overall
MBT-CP	0.1339	0.1287	0.1581	0.1560	0.1286	0.1459	0.1534	0.1348	0.1597	0.1579	0.1326	0.1410
MT-Re	0.1466	0.1286	0.1662	0.1093	0.1379	0.1375	0.1588	0.1318	0.1421	0.1103	0.1982	0.1377
LF	0.0819	0.1037	0.0899	0.1030	0.1112	0.0948	0.0809	0.1062	0.1038	0.1069	0.0921	0.0955
AD	0.1035	0.1450	0.1074	0.1199	0.1163	0.1211	0.1100	0.1427	0.1369	0.1271	0.1086	0.1285
IC	0.1472	0.1218	0.1157	0.1349	0.1269	0.1247	0.1263	0.1164	0.1029	0.1282	0.1285	0.1230
GF	0.1593	0.1683	0.1116	0.1369	0.1299	0.1421	0.1426	0.1666	0.1121	0.1333	0.1506	0.1413
MT-RDF	0.1365	0.1127	0.1536	0.1405	0.1507	0.1405	0.1406	0.1118	0.1427	0.1391	0.1690	0.1421
LFG	0.0910	0.0913	0.0975	0.0995	0.0986	0.0935	0.0873	0.0898	0.0999	0.0972	0.0833	0.0910

Remarks: MBT-CP – Mechanical Biological Treatment integrated with composting process; MT-Re – Mechanical Treatment system used to sort recyclable materials as the main products; LF – Landfilling; AD – Anaerobic Digestion; IC – Incineration; GF – Gasification; MT-RDF – Mechanical Treatment system used to produce Refuse Derived Fuel as the main products; LFG – Landfill Gas

According to Storey et al. (2015), WTR initiatives including composting, anaerobic digestion and recycling, are appropriate options for sustainable MSWM in secondary cities and small towns because the fractions of MSW in these cities consist of high organic wastes (50-80%) and recyclable materials (10-20%). These WTR were initially implemented successfully in Sri Lanka and Viet Nam. However, it depends on many factors such as sorting at source, effective participation of communities, and predictable sources and steady revenue streams. Therefore, in this study, small scale MBT-CP is considered as the most suitable option offering low-tech, low-cost, decentralized and community-based management of MSW in medium and small cities (Storey et al., 2015; UNESCAP, 2015), as defined in **Figure 3**.**5** (a).

Based on the literature study discussed in Table 5.1, four studies evaluated the most suitable MSWM in small and medium cities. Among these, only two studied other medium cities while the rest are in Thailand. Taboada-Gonzalez (2014) concluded that among three options (i.e., anaerobic digestion (AD), downdraft gasifier and plasma gasifier), AD is most preferred for major rural communities of Ensenada, Baja California, Mexico. Antonopoulos (2014) considered three options of MSWM (i.e., MBT-aerobic digestion, MBT-AD and incineration) and found that incineration with energy recovery is the most suitable for a medium-sized city in Greece. For large cities in other countries, Martowibowo and Riyanto (2011), Abba et al. (2013) and Milutinović et al. (2014) found that among various MSWM systems (i.e., composting (CP), anaerobic digestion (AD), gasification (GF), incineration (IC), recycling (Re) and landfill (LF)), CP is the most sustainable option for large cities in developing countries such as cities of Bandung, Indonesia; Johor Bahru, Malaysia; and Niš, Serbia respectively. In the case of Thailand, a study by Hanko (2007) also concluded that CP is the most appropriate system for Bangkok, followed by AD, LF, non-combustion system, IC and WTE systems due to the high proportion of organic and food waste.

For a small city, MBT-CP is ranked as the third alternative MSW management system due to a lower organic fraction compared to a medium city. In contrast, the mechanical treatment system producing RDF (MT-RDF) is most preferred due to higher proportions of combustible materials, i.e., plastic, paper, textiles, rubber and leather, and woody matter and associated with less food waste fractions in the MSW stream (**Figure 3**.**4**) (Tippayawong and Vichadee, 2009). In addition, the MT-RDF system is considered as the most attractive option to eliminate the amount of landfill space required, reduced environmental impacts and savings on O&M costs, and is especially accepted by the public (as shown in **Figure 5.7**). There are three existing thermal treatment systems with energy recovery, two incineration systems and one gasification system, as well as three cement kilns in Thailand using RDF as fuel and co-fired fuel respectively. As mentioned in **section 3.7.2.1**, a large number of local authorities including small, medium and large cities in ten provinces, such as Saraburi, Ayutthaya, Phathumthani, Nakhonnayok, Nakhon Ratchasima, Ratchburi, Burirum, Surin, Supanburi and Singburi, have delivered and sold their RDF and MSW to cement kilns for co-firing and producing RDF respectively. Some local authorities have produced RDF at their own disposal sites, then transported and sold to cement kilns and WTE plants located in nearby cities (Intharathirat and Abdul Salam, 2016). This illustrates that RDF plays an important role in treating and reducing a huge amount of MSW in Thailand. In addition, encouraging the use of RDF produced from MSW can also significantly reduce GHG emissions from the waste sector. TGO (2014) states that MSW converted to RDF

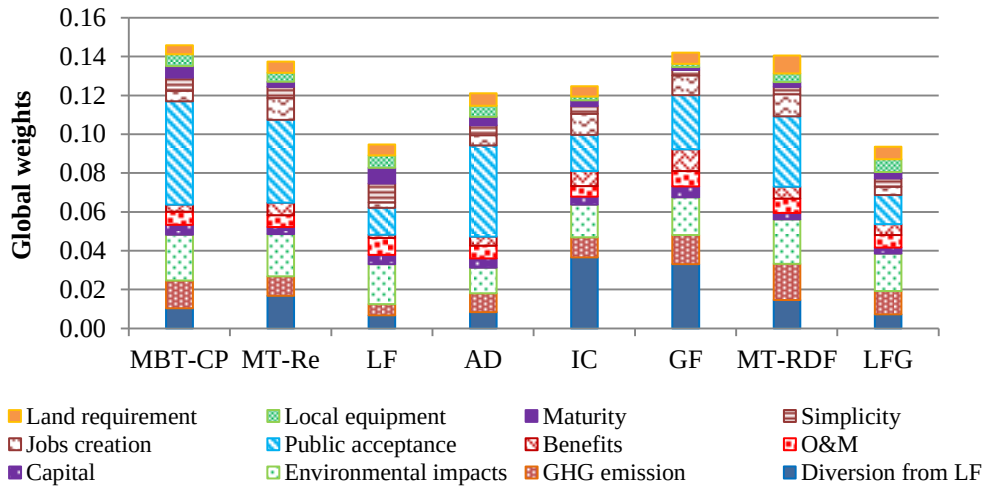


Figure 5.6: Priority weights of MSWM systems for a medium city

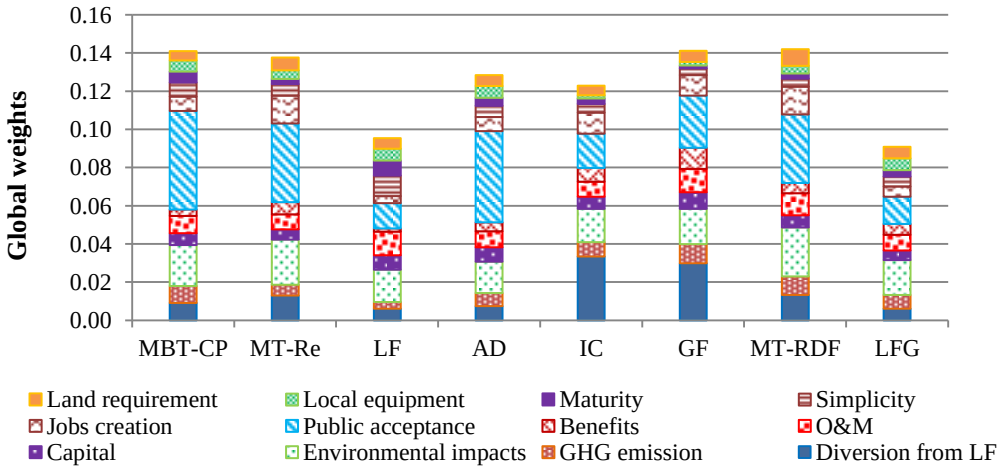


Figure 5.7: Priority weights of MSWM systems for a small city

has a higher potential to reduce approximately 19% of GHG emissions from 4.7 Million tCO_2eq emitted in 2015 to 3.8 Million tCO_2eq emitted in 2050. In addition, Salam et al. (2015) suggests that a combination of waste reduction policy, recycling and producing RDF has been found to offer maximum emission reduction in Thailand.

Based on the other alternatives, gasification (GF) was ranked as the second priority for both types of cities. Gasification-based WTE systems are successfully and continuously operated in Japan, Korea and Europe (Arena, 2012). In Japan, the transportation of collected MSW from one civic area to another is illegal (Themelis and Mussche, 2013). As a result, gasification is widely used in Japan due to its capability of small scale, low emissions and producing a vitrified ash which can be utilized beneficially outside landfill compared to a conventional combustion process (Themelis and Mussche, 2013). These reasons influenced stakeholders to assign high

weight priorities to three important sub-criteria: the capability of reducing the amount of waste buried in landfill, possibility of public acceptance and reduced environmental impacts. The MT-Re system was ranked as the fourth priority, because by-products consisting of recyclable materials (i.e., plastic, paper, glass and metals) which comprise about 35% and 43% of MSW for medium and small cities respectively, and 30% of recyclable materials, are found in a large city. It should be noted that the information on MSW composition was normally investigated from waste collected at trucks and disposal sites. This means that a large amount of recyclable materials in a large city have already been sorted by scavengers from garbage bins, collection systems and disposal sites. Also, due to the huge amount of waste generated, valuable recyclable materials and a greater number of junk shops are located in large rather than medium and small cities (PCD, 2012b). Considering financial benefits from the MT-Re system, recyclable materials obtained from the system in medium and small cities may be stored and then transported and sold in other civic areas. This is similar to the case of waste management in Texas which has shipped recyclable materials far away from the Valley to Houston for selling (Chang and Davila, 2008). Therefore, it is not an attractive option compared to others. For IC and AD systems, it should be understood that these systems are suitable for large city or clustering/integrated waste management. IC and AD require large amounts of commingled MSW and organic waste respectively as feedstock due to their high capital and O&M costs, as discussed in **Chapter 3**. Also, many AD systems are operating inefficiently and their operation at some sites was halted and no new AD project is currently planned in Thailand (Intharathirat and Abdul Salam, 2016). It is clear that LF is more suitable than LFG for both medium and small cities because of the huge amount of MSW required to produce landfill gas, as discussed in **Chapter 3**, and its simplicity, and low capital and O&M costs.

2) Governmental group preferences

Governmental stakeholder preferences on MSWM options in terms of sub-criteria are illustrated in **Figure 5.8** and **Figure 5.9** for medium and small cities respectively. For a medium city, WTE (i.e., GF (0.1593) and IC (0.1472)) systems are preferred compared to WTR (i.e., MT-Re (0.1466) and MBT-CP (0.1339)), while WTR (i.e., MT-Re (0.1588) and MBT-CP (0.1534)) are more suitable than WTE (i.e., GF (0.1426) and IC (0.1263)) systems for a small city. For both cities, AD was ranked sixth, while LFG and LF were ranked seventh and last respectively.

As shown above, WTE is preferred for a medium city in which governmental stakeholders assigned higher weight priorities to diversion from landfill, simplicity and creation of jobs criteria than others. In contrast, public acceptance, environmental impacts and local equipment were assigned higher weight priorities than others, which meant that the WTR scheme was identified as the most suitable for a small city. It should be noted that stakeholders gave high weights to simplicity criteria for WTE systems which are unreliable and also give doubtful results. This may be due to their experiences and backgrounds: the Thai government currently focuses on clustering waste management and WTE schemes rather than standalone MSWM systems and the WTR scheme. Also, no workshop and discussion between stakeholders was conducted in this study due to the difficulty in inviting senior organizational stakeholders as mentioned in **section 5.5.4.2**.

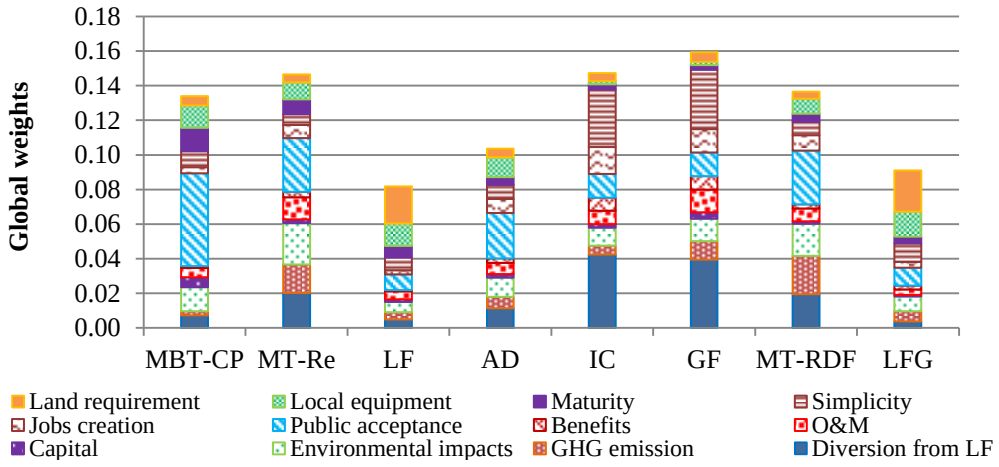


Figure 5.8: Preferences of governmental group on MSWM systems for a medium city

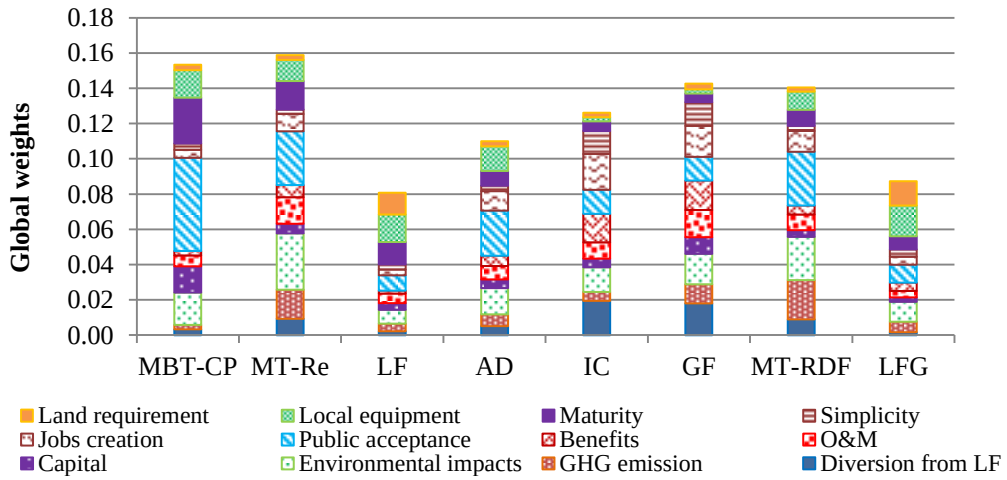


Figure 5.9: Preferences of governmental group on MSWM systems for a small city

3) Academic group preferences

For both types of cities, academic stakeholders ranked WTE systems such as GF (0.683 for a medium city and 0.1666 for a small city) and AD (0.1450 for a medium city and 0.1427 for a small city) as first and second priorities respectively. WTR systems (i.e., MBT-CP and MT-Re) are similarly considered as third and fourth priorities, which are lower than WTE systems as mentioned above and presented in **Figure 5.10** and **Figure 5.11**. Almost all MSWM system priorities for a medium city are the same as for a small city. This is based on relative weights assigned by academia who gave the same scores on every level of the hierarchical structure, i.e., main criteria, sub-criteria and alternatives for both cities. In addition, IC and MT-RDF are ranked fifth and sixth respectively, while LF and LFG were ranked as the seventh and last priorities respectively.

Based on first and second preferences for both cities described above, the weight priorities of GF and AD systems assigned by academic stakeholders with respect to sub-criteria revealed that public acceptance is much higher than others for both cities, followed by diversion from landfill, revenue and benefits, and environmental impacts.

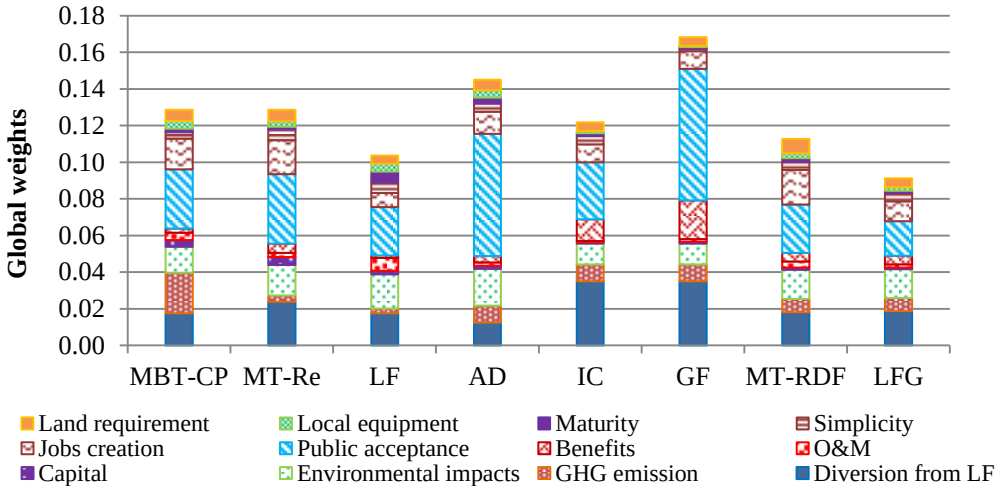


Figure 5.10: Academic group preferences on MSWM systems for a medium city

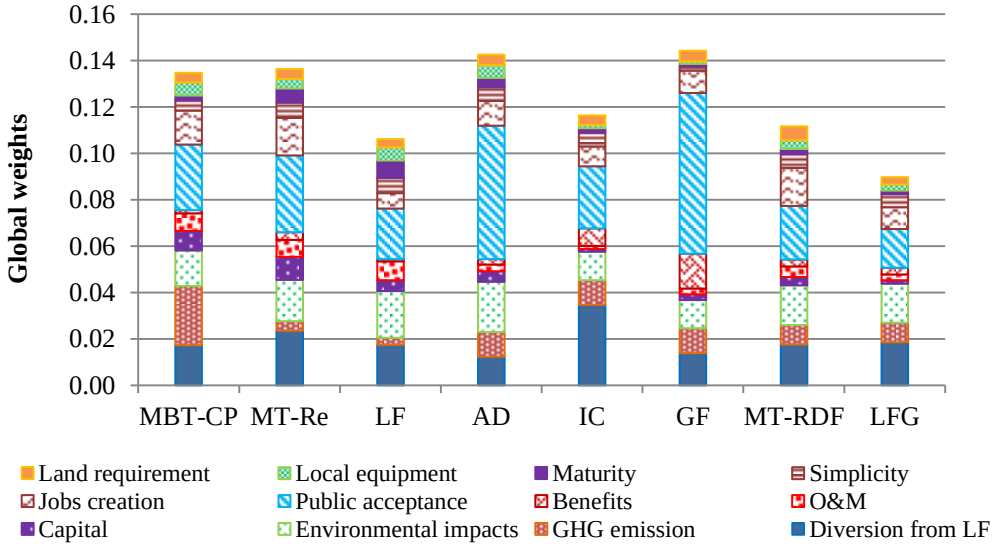


Figure 5.11: Academic group preferences for MSWM systems in a small city

4) Technical group preferences

As shown in **Figure 5.12**, the technical group's opinions showed that WTR is more preferred than the WTE scheme for both medium and small cities. For a medium city, MT-Re (0.1662) is considered as the most suitable MSWM system, followed by MBT-CP (0.1581). Similarly, MBT-CP (0.1597) and MT-Re (0.1421) were prioritized as the first and second appropriate options respectively for a small city, as shown in **Figure 5.13**. Five WTE systems (i.e., RDF, GF, IC, AD and LFG respectively), were viewed as lower priorities than WTR systems due to possible environmental impacts, complex operation, lack of maturity and local equipment, and non-acceptability by the public. Similarly, LF was ranked last for a medium city, though it was ranked sixth for a small city due to its simplicity and low capital and O&M costs.

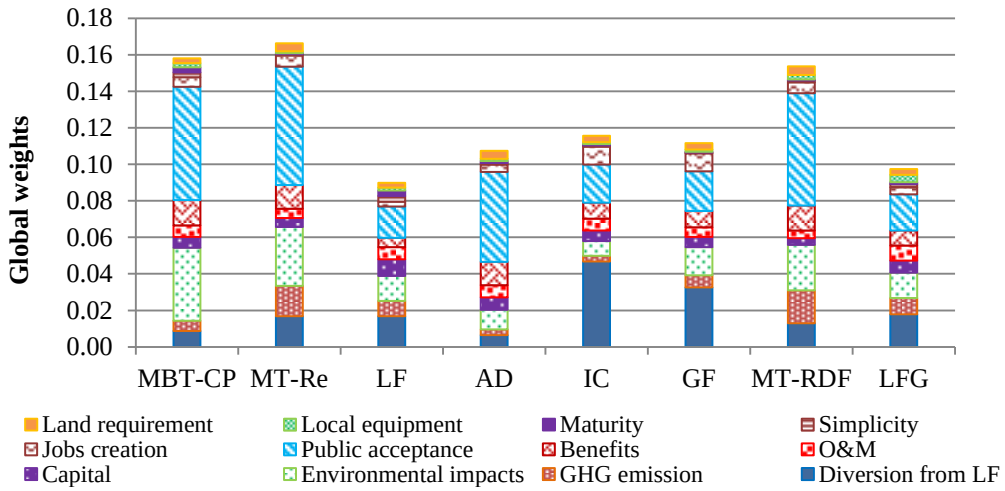


Figure 5.12: Technical group preferences of MSWM systems for a medium city

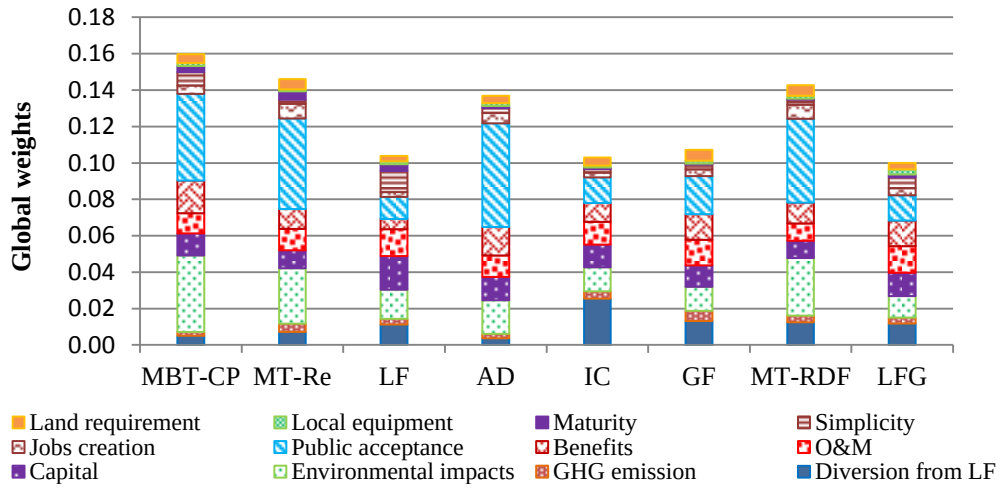


Figure 5.13: Technical group preferences of MSWM systems for a small city

5) Local authority group preferences

Figure 5.14 and **Figure 5.15** illustrate the aggregation of local authority opinions for medium and small cities respectively. These show that MBT-CP (0.1560 for medium and 0.1579 for small city) is the most preferred option, followed by MT-RDF (0.1405 for medium and 0.1391 for small city) for both cities. Considering the first two priorities, it indicates that local authorities focus on WTR rather than on the WTE scheme, which is similar to the technical group's point of view. However, compared to the considerations of other groups, thermal treatment systems, such as IC and GF, were ranked higher than AD and MT-Re due to their high relative weights on four sub-criteria, such as diversion from landfill, environmental impacts, GHG emissions, and creation of jobs. This may be due to their background, which currently focuses on clustering and integrated MSW management and WTE rather than standalone systems and WTR, as evidenced from governmental stakeholders. As discussed in **Chapter 3**, in Thailand, the local authority is usually responsible for solid waste management including collecting, transporting, recycling, treatment and disposal, while the central government is responsible for enhancement, encouragement and decision making of MSWM policies. LF and LFG were prioritized at the seventh and the last rank respectively for both cities.

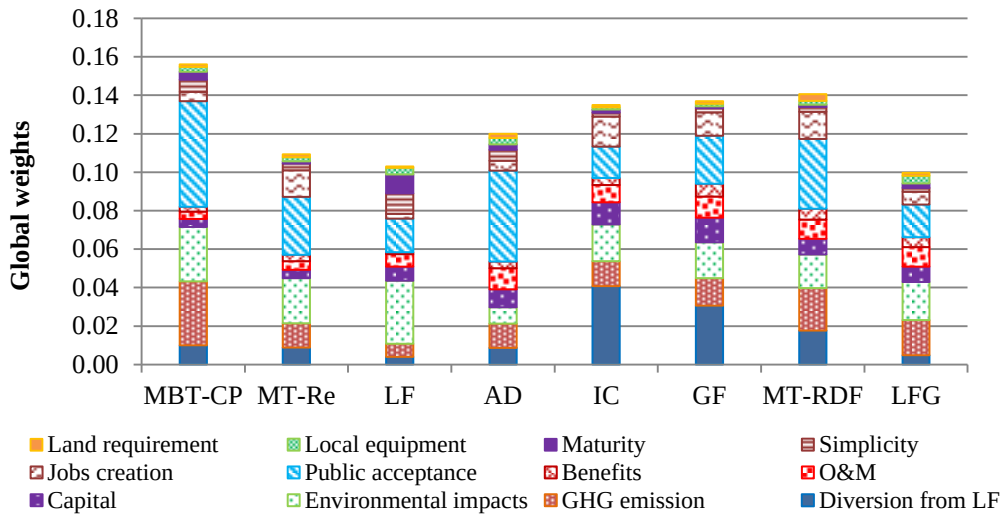


Figure 5.14: Local authority group preferences of MSWM systems for a medium city

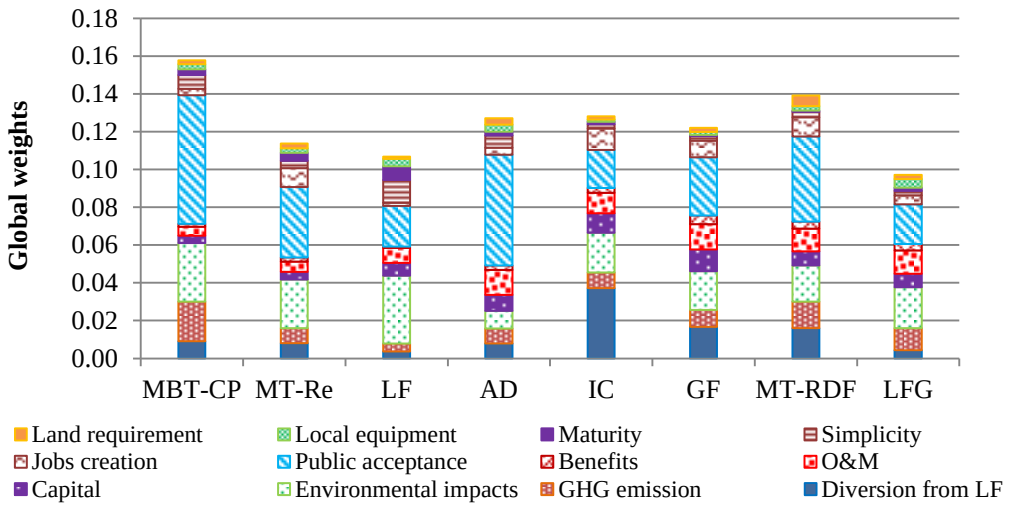


Figure 5.15: Local authority group preferences of MSWM systems for a small city

6) NGO group preferences

NGO stakeholders ranked MT-RDF (0.1507) as the most preferred for a medium city, followed by MT-Re (0.1379) and MBT-CP (0.1286). Similarly, MT-Re (0.1982) is viewed as the most preferred option for a small city, followed by MT-RDF (0.1690) and MBT-CP (0.1326). For both cities, GF ranked fourth while IC ranked fifth. AD and LF were ranked as sixth and seventh priorities respectively, as shown in **Figure 5.16** and **Figure 5.17**. The last priority for NGO stakeholders was LFG. These results indicate that NGO stakeholders prefer WTR compared to WTE.

Based on the priorities of MSWM systems for both cities ranked by NGO stakeholders, as discussed above, the predominant sub-criterion of land requirement was assigned the highest relative weight followed by environmental impacts and public acceptance. Also, recycling systems (e.g., MT-Re and MT-RDF) and biological treatment systems (e.g., MBT-CP and AD) were ranked with higher priorities than others due to higher ranking of important sub-criteria such as public acceptance and land requirement aspects. Compared to other stakeholder considerations, these reveal that not only public acceptance and environmental impacts, but also consideration of land requirement plays a relevant role for the NGO stakeholder group. For LF and LFG systems, almost all sub-criteria, particularly diversion from landfill, GHG emissions, benefits and creation of jobs, were considered of low importance by NGOs.

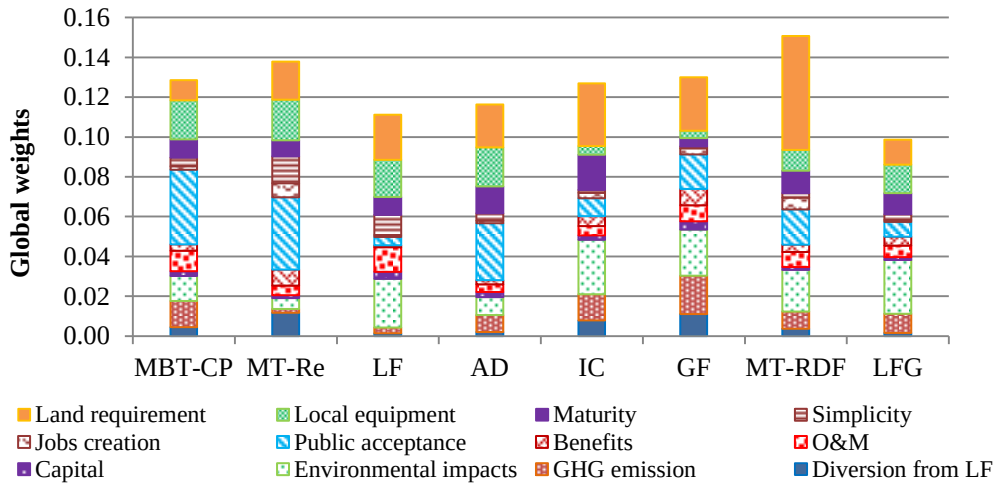


Figure 5.16: NGO group preferences of MSWM systems for a medium city

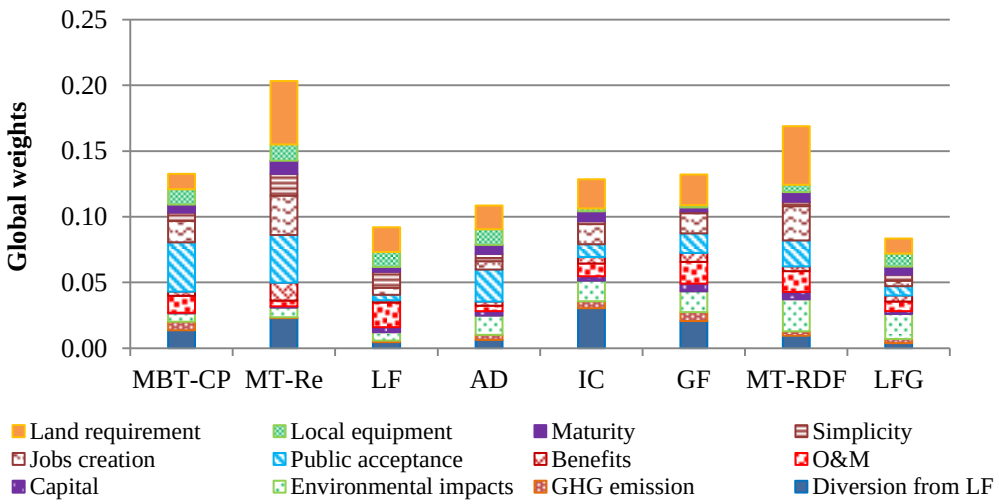


Figure 5.17: NGO group preferences of MSWM systems for a small city

5.6.3 Sensitivity analysis

Sensitivity analysis (SA) is performed to investigate the stability of the priorities resulting from the AHP model with regard to the control of main-criteria priorities through increasing and decreasing one of four main criteria while others were kept as the same proportion. Considering the relationship between environmental criteria and MSW management system alternatives for a medium city, SA illustrates that the share of GF system increases and MBT-CP decreases, while the weight of environmental criteria increases as shown in **Figure 5.18** (a). This implies that the GF system has positive features and the MBT-CP system has negative features in terms of environmental aspects. The priority can be changed, from MBT-CP to GF, when the weight

assigned to the environmental criteria is more than 4.00, keeping other criteria with equal weight. At this point, GF becomes the best option compared to other alternatives. According to economic considerations, SA presents results that are sensitive to change in weights of the economic aspect (**Figure 5.18** (b)): the ranking of the alternatives changes from MBT-CP, MT-RDF, MT-Re, GF, IC, AD, LF and LFG (for 0% economic weight) to GF, IC, MT-RDF, MT-Re, AD, MBT-CP, LFG and LF (for 100% economic weight). Based on economic considerations, it can be asserted that the weight of the economic aspect affects the MBT-CP alternative negatively and influences GF positively. In this sense, the GF alternative is the most suitable option from an economic point of view. However, when the sensitivity is realized according to the weight of the social consideration, the MBT-CP alternative has positive features and its rank does not change when the social weight is more than 0.30, whereas the GF alternative has negative features and its rank changes to the fifth priority (**Figure 5.18** (c)). The analysis of social criteria shows that the priority of the MBT-CP alternative increases as the weight of social control criterion increases, while the priorities of GF, IC, LG and LFG decrease as the weight of social criteria increases. When the sensitivity is realized according to the weight of the technical aspect (**Figure 5.18** (d)), the MBT-CP alternative becomes less preferred and the LF option more preferable if the weights of technical aspects increase with more than 0.63, due to simplicity, maturity and local equipment of LF. It is interesting to observe that the MBT-CP system is not sensitive to technical considerations and its weight remains the same. The relative robustness of the ranking of the alternatives shows that the MBT-CP system is the most appropriate MSW management system for a medium city in the context of the study area as summarized in **Box 1**.

Box 1. Summary of evaluating MSW management systems in medium and small cities

Medium city:
Composting (MBT-CP) is the most preferred option for a medium-sized city due to the high organic or food waste fraction in the MSW stream. This option can minimize the amount of waste buried in landfill and preserve landfill space and extend life of landfill areas. GHG emitted from landfilling can also be reduced by the MBT-CP system.

Small city:
The MT-RDF system is considered as the most attractive option for a small city to eliminate the amount of landfill space required, environmental impacts and save O&M cost, and is especially accepted by the public. This option is very attractive in Thailand because many thermal treatment systems and cement kilns use RDF as fuel by co-firing with coal.

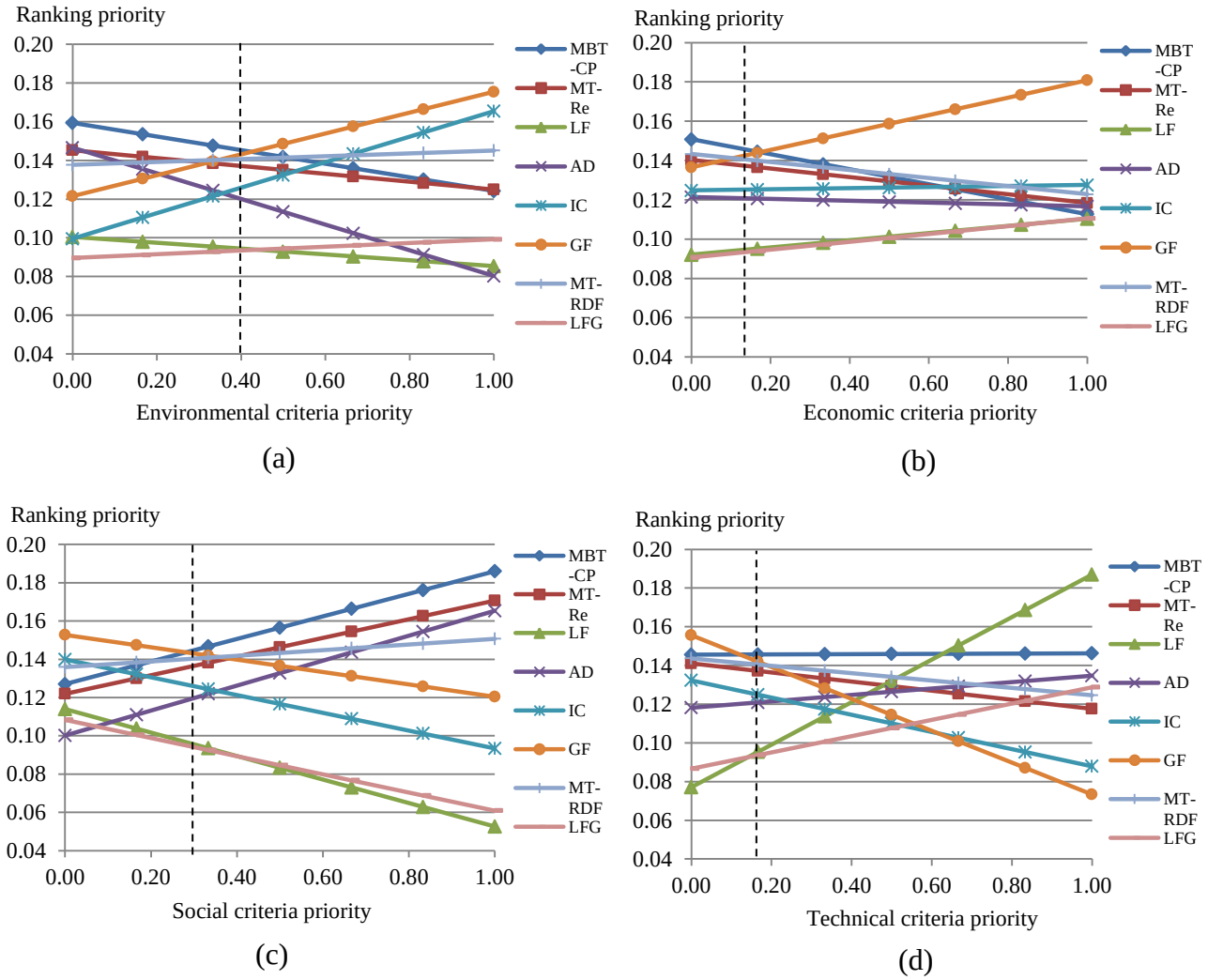


Figure 5.18: Sensitivity analysis for a medium city on the control criteria: (a) environmental, (b) economic (c) social and (d) technical

In order to verify results of the AHP model for a small city, starting with consideration of environmental performance, the results show that GF, IC, MT-RDF and LFG increase and other alternatives decrease, while the weight of environmental performance increases (as shown in **Figure 5.19** (a)). These indicate that GF and IC have positive features and MT-RDF and LFG have slightly positive features, while others have negative features. These also show that IC and GF are sensitive to the changes in the weight of the environmental aspect while MT-RDF is not sensitive, however, the rank of MT-RDF falls from fourth to third priority when the weight of the environmental criterion increases. It can be concluded that WTE systems are chosen based on their potential to divert solid waste from landfill and to generate energy from MSW (Annepu, 2012). According to the economic dimension **Figure 5.19** (b), the overall results of SA are less sensitive than that of the environmental dimension. The ranking of MT-RDF changes from the third priority (for 0% economic weight) to the second priority (for 100% economic weight). This

implies that the increase in the weight of economic criteria affects the GF alternative sharply positively while MT-RDF is slightly affected negatively but it is not sensitive. The analysis of social criteria indicates that the results are sensitive (**Figure 5.19** (c)): the ranking of alternatives changes from GF, IC, MT-RDF, MT-Re, MBT-CP, LF, AD and LFG for 0% social weight, to AD, MBT-CP, MT-Re, MT-RDF, GF, IC, LFG and LF for 100% social weight respectively. These show that MBT-CP, AD, MT-Re and MT-RDF have positive features, whereas GF, IC, LF and LFG have negative features. When the relationships between technical aspects and MSW management alternatives are considered, it becomes clear that share of MBT-CP, AD, LF and LFG increase and MT-Re, MT-RDF, IC and GF decrease, while the weight of technical criteria increases (**Figure 5.19** (d)). This shows that MBT-CP, AD, LF and LFG have positive features and the rest have negative features. Similarly, the MT-RDF alternative becomes less preferred and the LF option more preferable when the technical weights increase to more than 0.60 due to simplicity, maturity and local equipment of LF.

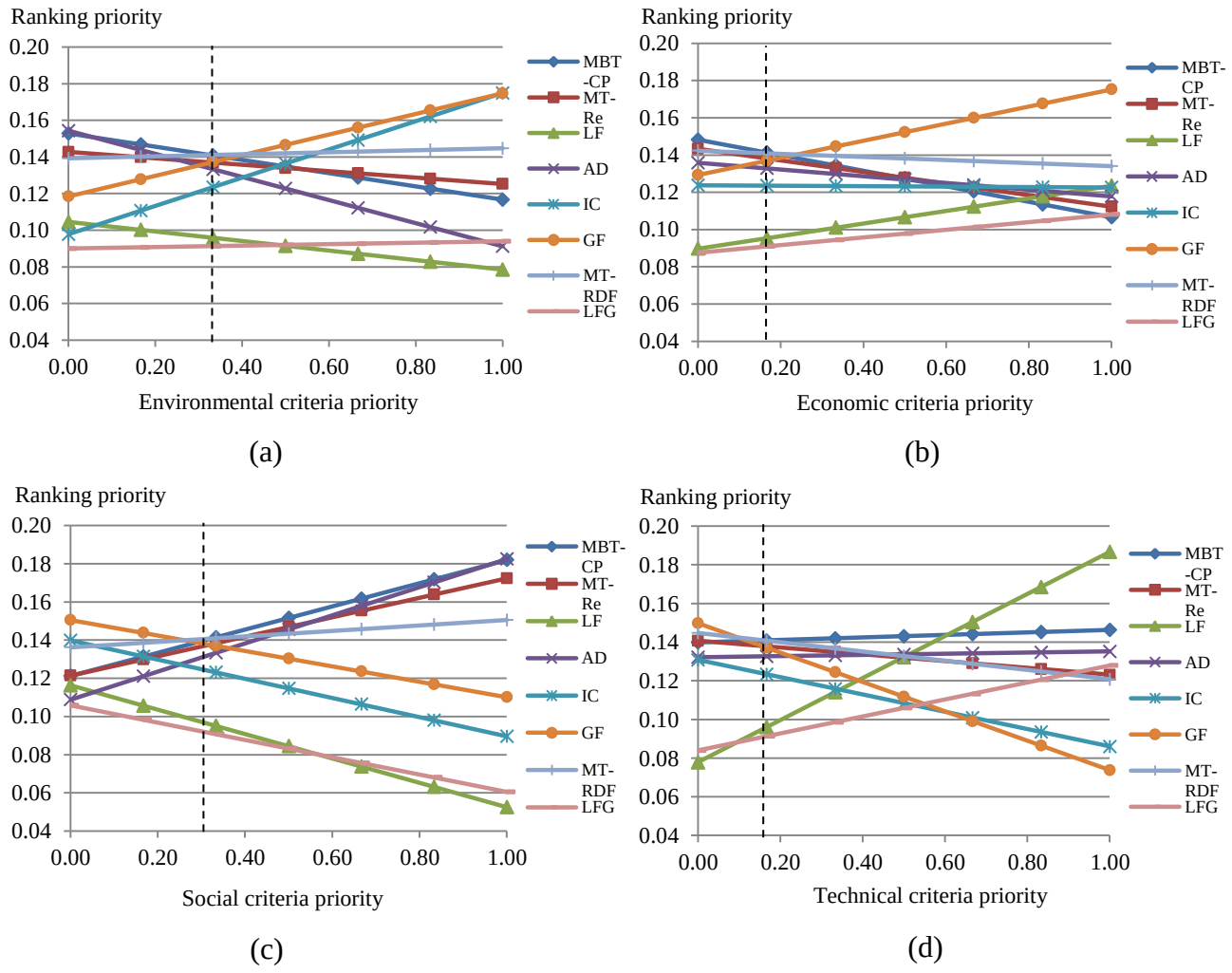


Figure 5.19: Sensitivity analysis for a small city on the control criteria: (a) environmental, (b) economic (c) social and (d) technical

5.7 **Problems faced and limitations in this study and recommendations related to MSWM policies**

The problems and limitations faced in a decision making process, as well as key findings related to current MSWM policies are discussed here. The preferences of alternative MSWM systems changed across stakeholder groups affecting the priority of preferred alternatives (Contreras et al., 2008). Stakeholders holding top positions of their organizations were chosen and the questionnaires distributed because they were expected to have a deep knowledge and good understanding of MSW management systems and its situation. Neither a group meeting nor workshop was conducted in this study, which represents one of its limitations. As discussed in Chapter 1 and Chapter 3, this study excludes the consideration of clustering MSW management. Also, the policies related to solid waste management (e.g., enhancing WTE implementation) are known by stakeholders. However, preferences of stakeholders who hold senior positions reflect knowledge about clustering and WTE. Furthermore, it is difficult to review their considerations due to their lack of time and/or willingness to participate. Similarly, a previous study by Antonopoulos et al. (2014) found that the performance of ranked alternatives was strongly dependent on the weights of criteria, which is a crucial process and is neglected sometimes by decision makers and administrators. The effective pair-wise comparison process depends on guidelines concerning details of the process and the use of measurement scales. It should be highlighted that preference analysis is a subjective judgment with error originating not only due to the value of inconsistency, but also from insufficient experience and knowledge of the stakeholders (Cabala, 2010). In addition, stakeholders may not give strong opinions on particular judgments and have assigned weights to the entire process that slowed down due to a large number of pairs (Ishizaka and Labib, 2011). Another reason is based on the channel capacity of human ability to process any information. In each level of the hierarchical structure, two plus or minus from seven items was recommended by Miller (1956) and confirmed by Saaty (2003); the number of items should be kept to seven or less to serve both redundancy and consistency. In spite of the number of criteria used by previous studies in MSWM decision making that varies from one (1) to 192 and the capacity of decision makers being limited in the range from 7 to 12 comparison criteria (Nijkamp et al., 1990 and Bouyssou, 1990 cited from Garfi et al., 2009), there is no study that investigates how many criteria people can handle in the waste management field. Also, it is necessary to use the analytical network process (ANP) instead of AHP in case of correlation between criteria. In this study, there is the possibility of correlation occurring between sub-criteria: maturity–local equipment; land requirement–environmental impacts; diversion from landfill–land requirement; simplicity–maturity; and creation of jobs–O&M cost. However, it is necessary to develop a methodology or a guideline, which has not been found, for investigating the correlation between the criteria used in decision making models.

Most Asian developing countries including Thailand are attempting to address the MSWM crisis and have no strong regulation, such as paying as you throw (enhancing the sorting at source implementation) and prohibiting transportation of MSW from one municipality to another as seen in Japan (Themelis and Mussche, 2013). This leads them to being interested in large scale end-pipe treatment systems. For instance, the Thai government announced the Roadmap of MSW management in 2014 focusing on WTE implementation by subsidy for electricity generation sold into the grid (Intharathirat and Abdul Salam, 2016) and emphasizing the clustering concept with large-scale integrated treatment systems (Kaosol, 2009), e.g. MBT,

incineration and gasification. Nevertheless, it may fail, if the end-pipe treatment technologies are utilized in these regions without any alteration for local situations, because these technologies are mostly designed in developed countries. Incineration, mass burning or moving grate technology that require minimal pre-treatment is widely used in Thailand (Intharathirat and Abdul Salam, 2016). For these reasons, it would have further aggravated the problem of 3Rs implementation in Thailand which has not achieved targets (Vanapruk, 2012) due to a large number of MSW delivered to incinerators without separation, as discussed in **Chapter 3**. Also, it is unsustainable waste management, if many local authorities deliver their waste to a central treatment system without effective source separation.

Given that most municipalities/cities in developing countries are of small to medium size, it should be highlighted that most cities in these regions could apply low-cost, locally adapted and integrated solid waste management (ISWM) systems (Menikpura et al., 2013). Source separation is recognized as one of the options to achieve sustainability of MSWM associated with efficient resource use. Separation at source also provides a promising alternative with economic and environmental benefits, as seen by its contribution of high quality materials recovery with cost savings for local authorities (Xevgenos et al., 2015). Therefore, this study provides some key findings and proposes a decentralized concept and community-based approach[g] related to current policies that have focused on the clustering concept and WTE implementation as follows.

1) Lessons learned from successful waste-to-resource (WTR) initiatives in Sri Lanka and Viet Nam should be taken into consideration. The WTR projects are small-scale systems comprising MBT-CP and AD systems, and are low-tech, low-cost, decentralized and community-based for managing MSW in medium and small cities (Storey et al., 2015; UNESCAP, 2015). This system seems appropriate for tropical Asian cities, such as in Thailand, due to high humidity and warm climate which facilitates biodegradation (Hanko, 2007).

2) The current policy targets of waste recover rate (**Table 3.1**) should be broken down into recycling rate (e.g., for paper, glass, plastic, metals) and recovery rate (e.g., for energy and composting), or WTR (recycling and composting) and WTE (waste converted to heat and/or electricity) rate to emphasize 3Rs implementation which represents more sustainable waste management than WTE.

3) In the case of WTE systems, the government has to provide a larger budget for feed-in-tariff (FiT) and expand transmission lines to support electricity sold into the grid. This presents unsustainable waste management because the government has to budget for a large amount of finance to private enterprise and loses benefits in the long-term.

4) It has been recognized that incineration systems have some drawbacks, including the possibility of toxic air pollution (e.g., SO_x, chlorinate compounds and dioxins). This may also be expensive for the government to monitor and manage due to the sampling procedures and analyses required for dioxin contamination.

[g] Society separates recyclable, combustible and non-combustible materials from MSW stream

5.8 **Summary**

This chapter describes the evaluation of sustainable MSWM systems consisting of eight alternatives comprising three general MSW treatement systems (MBT-CP, MT-Re and LF) and five WTE treatment systems (AD, IC, GF, MT-RDF and LFG) for medium and small cities by using the AHP model in Thailand. The analytical hierarchical structure was constructed into four levels: study problem, main criteria, sub-criteria and alternatives. Four sustainability main criteria and twelve important sub-criteria were identified and considered into pair-wise comparisons by five stakeholder groups comprising governmental, academic, technical, local authority and NGOs.

For both medium and small cities, the consensus of stakeholder preferences on the main criteria illustrates that the environmental aspect is the most important, followed by social considerations, while economic and technical aspects have equal weight. It can be concluded that stakeholders focus on strong sustainability rather than weak sustainability. The strong sustainability concept is based on a small-scale decentralized approach and greater self-reliance to create social and economic systems that are less destructive towards the environment.

Considering the overall view of stakeholder opinions on sub-criteria for both medium and small cities, public acceptance consideration is viewed as the most important category, followed by environmental impacts and diversion from landfill. The differences in priorities in each type of city can be observed, where GHG emission was ranked fourth in a medium city followed by creation of jobs and O&M cost respectively. In contrast, O&M cost is viewed as the fourth most important category for a small city, followed by creation of jobs and GHG emissions respectively. These indicate that stakeholders view economic considerations for a small city as more important than that for medium or larger cities. Based on the literature study, stakeholders preferred environmental considerations in developed countries as being more important than in developing countries where economic aspects are the most important.

The global weights of alternative results show that the most suitable option for a MSW management system is the mechanical biological treatment combined with composting (MBT-CP) for medium cities, due to the high proportion of food waste and biodegradable waste with high moisture content in the MSW stream. Mechanical treatment combined with RDF (MT-RDF) is the preferred option for small cities due to the lower organic fraction compared to medium cities (see **Box 1**). Also, MSW composition in small cities consists of a high proportion of combustible materials, such as plastic, paper, textiles, rubber and leather, and woody matter. Both landfilling and landfill gas are still shown to be the worst options in medium and small cities. To achieve a sustainable MSW management system, results show that the stakeholder consensus of opinion is to prefer waste-to-resource (WTR) rather than waste-to-energy (WTE), and much more than only treatment and disposal. Sensitivity analysis confirmed that the results obtained from this evaluation are acceptable and the model is robust. However, some limitations of constructing a hierarchical structure occurred in this study, namely: i) the knowledge and background of stakeholders on clustering and WTE policies may be are out of scope of this study; ii) the lack of time and willingness of stakeholders to participate; iii) guidelines and measurement scales are missing due to a lack of discussion between stakeholders; iv) insufficient experience and knowledge of stakeholders; v) the workshop or group meeting was not conducted

due to the impossibility for inviting the most senior stakeholders of each organization; vi) stakeholders may not give their strong opinions and slowed down due to a large number of pairs; vii) the suitable number of criteria; viii) no methodology for carrying out the correlation of criteria; and ix) the ANP method should be conducted and/or compared with the AHP method.

This study recommends low-cost, locally adapted and integrated solid waste management systems as the most preferred option for a MSWM system for medium and small cities. This system emphasizes the implementation of source separation, which is recognized as one of the options to achieve sustainability of MSWM associated with efficient resource use. Therefore, this study provides key findings and proposes a decentralized concept and community-based approach related to current MSWM policies that have focused on the central system and WTE implementation, as follows: i) successful WTR initiatives should be studied; ii) the current recovery rate target should be revised; iii) focusing on the WTE system only is not preferred according to the consideration of stakeholders and it is not a sustainable way for MSW management; and iv) the government takes responsibility for controlling air pollution and monitoring dioxin contamination from WTE plants, which is very expensive and needs substantial resources, finance and technical expertise.

Chapter 6

Conclusions

This chapter concludes the study by presenting brief summary of the main findings of the study. The contribution of new knowledge and recommendations to improve the present study are also highlighted.

6.1 **Summary of conclusions**

This study highlighted the evaluation of the most appropriate MSWM systems for medium and small-sized cities. The process of evaluating MSWM in both medium and small cities is complicated due to the lack of reliable historical data and participation of relevant stakeholders. To address these issues, this research assessed existing MSW management systems, particularly WTE treatment, to comprehensively understand the operation of commercial facilities, and the barriers and challenges in a case study of Thailand.

This study also addressed data and information gaps to provide a systematic methodology for MSW forecasting by using limited data associated with various factors affecting MSW generation. For this purpose, a review of influencing factors used in previous studies was conducted to identify and classify into residential and commercial sectors. Grey relational analysis (GRA) was used to quantify the relationship between these factors and MSW quantity in the case of Thailand. Alternative grey models (GM) were then developed by using limited historical time series data. Among these, the most accurate model was used to forecast MSW quantity with prediction intervals (PI) for the long term period from 2013 to 2030.

After addressing information gaps concerning the assessment of MSWM systems and forecasting of MSW quantity, the evaluation of MSWM systems was conducted by using the analytical hierarchy process (AHP). Eleven stakeholders assigned weights in pair-wise comparison matrices of main criteria, sub-criteria and alternatives; these stakeholders were categorized into governmental, academic, technical, local authority and NGO groups. This study identified four main criteria (environmental, social, economic and technical) and 12 sub-criteria (diversion from landfill, GHG emissions, environmental impacts, capital cost, O&M cost, revenue & benefit, public acceptance, creation of jobs, simplicity, maturity, local equipment) to be simultaneously considered for selecting the most suitable MSWM systems among eight alternatives. The preferences of stakeholder groups for each criterion and alternative for medium and small cities were also investigated.

Results indicated that identification of MSW management systems consists of two categories—general MSW management systems (MSW management without energy recovery) and WTE treatment systems. The MBT+CP, MT+Re and LF were identified as general MSW management systems in this study, as MT+Re and LF represent existing waste management systems in Thailand and MBT+CP are successfully practiced for medium and small cities in Sri Lanka and Viet Nam. Other existing WTE treatment systems comprise AD, IC, GF, RDF and LFG. These WTE systems can be used to treat 2.54 Mt of MSW per year (9.5% of total 26.8 Mt generated in 2013) and generate 66 MW of electricity as well as 78.26 ktoe of heat. It is estimated that about

8.17 Mt of MSW (30.5%) will be treated that will generate 319 MW of electricity as well as 78.26 ktoe of heat.

Of the 15 alternative models examined (see **section** 4.4.2), the grey model with convolution integral GMC (1, 5) was found to be the best representative model for forecasting MSW collected giving the lowest error of 1.16% MAPE; of the models evaluated, two were traditional (Naïve and Trend curve analysis), three were univariate grey models (GM (1,1), GM (1,1)-0.1 and GM (1,1)-1.0), and ten were multivariate grey models (GM (1,2) – GM (1,6) and GMC (1,2) – GMC (1,6)). This model indicates that the amount of MSW collected would increase by 1.40% per year, which is in the range from 43,435 to 44,994 t/d in 2013, 47,735 to 49,293 t/d in 2020, and 55,177 to 56,735 t/d in 2030. The increase of MSW collected may be reflect representative factors of the commercial sector (population density, urbanization and proportion employment) rather than those of the residential sector (household size). It was also observed that demographic factors were more important than socio-economic factors.

The evaluation of MSWM was based on information gathered in the above steps. Results show that stakeholder preferences concerning the main criteria focused on environmental performance, followed by social considerations, while economic and technical aspects were assigned almost equal weighting for both medium and small cities. Similarly, key findings from the literature study concerning large cities in developed countries indicated that environmental aspects were the most important, followed by social, economic and technical aspects respectively (Contreras et al., 2008; Longden et al., 2007). In contrast, other studies in developing countries found that economic considerations were the most important, followed by social, technical and environmental issues respectively (Martowibowo and Riyanto, 2011; Milutinović et al., 2014; Parekh et al., 2014; Samah et al., 2010). In 2012, Suthapanich (2014) evaluated WTE technologies in a medium-sized city in Thailand and found that technical and environmental aspects had greater importance than those of economic and social ones. The different results obtained between the previous study (Suthapanich, 2014) and the current study may be due to the main objective being to evaluate WTE systems and the change in stakeholder opinion, which may have resulted from the crisis situation that Thailand faced at that time in 2014 when fire broke out at several dumping sites.

Research also indicates that stakeholders consider strong sustainability more important than weak sustainability. The strong sustainability concept is based on a small-scale decentralized approach and greater self-reliance to create social and economic systems that are less destructive towards the environment. In contrast, Garfi et al. (2009) found a balance between environmental, social and technical criteria in Saharawi refugee camps in Algeria. Therefore, this study suggests that the stakeholder perspectives strongly depend on any critical issue being faced in Thailand, and not only based on the economic status of the nation (e.g., whether a developed or developing country) or size of city.

For both medium and small cities, stakeholder preferences on sub-criteria show that public acceptance is the most important criterion, followed by environmental impacts and diversion from landfill. It was observed that the GHG emissions criterion was considered at a higher rank for a medium city than for a small city. In contrast, O&M cost was viewed at a higher rank for a

small city than for a medium city. These also indicate that stakeholders view economic considerations for small cities as being more important than for medium-sized cities.

For a medium city, the most suitable MSWM system is the mechanical biological treatment combined with composting (MBT-CP), while mechanical treatment combined with RDF (MT-RDF) is suitable for a small city. Landfilling and landfill gas present the worst options for both medium and small cities. Similarly, Martowibowo and Riyanto (2011), Abba et al. (2013) and Milutinović et al. (2014) found that among various MSWM systems (composting (CP), anaerobic digestion (AD), gasification (GF), incineration (IC), recycling (Re) and landfill (LF)), CP is the most sustainable option for large cities in developing countries. In the case of Thailand, a study by Hanko (2007) also concluded that CP is the most appropriate system for Bangkok, followed by AD, LF, non-combustion system, IC and WTE systems due to the high proportion of organic and food waste.

These results indicate that stakeholder preferences on waste-to-resource (WTR) are more preferred than for waste-to-energy (WTE) and much more than for treatment and disposal. Zaman (2013) also found that stakeholder viewpoints on waste technologies shifted from 'waste' to 'resource' for sustainable MSW management in Sweden.

Sensitivity analysis confirmed that the model is robust and the results are acceptable. Therefore, this study finds that the low-cost, locally adapted, and integrated solid waste management systems are the most preferred MSWM system for medium and small cities. In addition, this study provides some key findings and proposes a decentralized concept and community-based approach to current MSWM policies that have previously focused on a centralised system and WTE implementation. The following recommendations are made based on the findings of this study: i) we should learn from successful WTR initiatives; ii) the current recovery rate target should be revised; iii) the focus on WTE only is not preferred in the consideration of stakeholders and not a sustainable way for MSW management; and iv) the government is responsible for controlling and monitoring dioxin contamination from WTE plants, which is very expensive and needs considerable resources, finance and technical expertise.

6.2 **Contribution of new knowledge**

The contribution of new knowledge from this study can be considered with respect to four aspects: theoretical, methodological, practical, and key policy implications.

6.2.1 Theoretical contribution

6.2.1.1 Systematic approaches for identifying and classifying influencing factors

The identification and selection of suitable factors plays an important role in obtaining greatest accuracy in developing forecasting models. Previous work typically identified and selected such factors based on a literature review and their objectives. From a review of influencing factors used in MSWM research, a few studies categorized these factors into residential and commercial groups and used them to forecast MSW quantity by developing existing models, or by applying

regression analysis and GIS. This research provides a systematic approach as defined by the following steps (as presented in section 4.4 and summarized below):

i) identifying influencing factors based on statistical and mathematical approaches;

ii) classifying these factors into socio-economic, demographic and representative factors of residential and commercial sectors; and

iii) selecting suitable factors by considering six criteria created in this research (as mentioned in section 5.5.1).

These approaches are useful for indicating those factors (socio-economic or demographic) that are representative in each sector (e.g. commercial or residential) that substantially affect MSW quantity. Also, this can help decision makers in developing measures and policies for waste management, including: the implementation of new strategies in commercial and residential sectors; focusing on the Thai sufficiency economic philosophy to reduce consumption; and control the increase of population density and urbanization. The systematic approaches in this research can therefore be considered as a unique, comprehensive and inclusive approach in selecting influencing factors when multivariate forecasting models are taken into account.

6.2.1.2 The use of outliers in Grey Models

Continuous time series data is required to support and improve the reliability of a grey forecasting model. Implementation of grey models in previous studies reveals that a single or a few outliers are acceptable, and this is also one advantage of the grey model over that of statistical regression analysis. However, if frequent outliers occur, the grey model is not an appropriate choice. A key finding of this study shows that an outlier cannot be used for training/developing multivariate grey models, i.e., GM (1, n) and GMC (1, n). However, it can be used for validation, as in this study in Thailand and discussed in section 4.4.2.

6.2.2 Methodological contribution

6.2.2.1 Methodological framework for developing alternative MSW forecasting models using limited data

This study contributes to existing knowledge by developing a methodological framework for forecasting MSW quantity (as shown in Figure 2.2, section 4.3 and the paper mentioned in section 6.2.1.2.). This framework was developed from a critical review of MSW forecasting models and influencing factors, as well as on statistics-based data analysis and econometric model principles. This research provides an insight into how to forecast MSW quantity with limited data and provides a systematic approach that is simple and accurate compared to existing models. Consequently, the grey model has advantages over existing tools in terms of accuracy, simplicity, ability for explaining influencing factors affecting MSW generation, and flexibility for using data that correlate with each other and/or abnormal distributions as in the statistics-based analysis. This framework is likely to be very useful for practitioners who encounter limited data and particularly for those working in developing countries.

6.2.2.2 Integrated analysis of data and quantification of influencing factors

As described in section 6.2.1.4, this research provides systematic approaches for data analysis and quantifies selected influencing factors, including: i) testing of data before use in model development (i.e., correlation analysis which is a statistics-based approach and stationary analysis which is an econometric-based approach) in order to ensure that the series can strongly influence its behavior and properties; and ii) quantifying of influencing factors by using grey relational analysis (GRA), which is a mathematics-based approach.

6.2.2.3 Forecasting with prediction intervals

Based on the review literature discussed in section 4.2.1, there is no methodology to forecast MSW generation with a range of possible outcomes. Literature often forecasts MSW generation as single numbers or point forecasts that gave no guidance as to their likely accuracy. Prediction intervals (PI) present an important part of the forecasting process intended to indicate the likely uncertainty in point forecasts and of the different planning strategies for the range of possible outcomes. This research aims to fill this knowledge gap by forecasting MSW quantity using PI.

6.2.3 Practical contribution

6.2.3.1 Comprehensive assessment of WTE in Thailand

In this study, the choice of the most appropriate waste management system requires consideration of all available types of MSWM. Criteria for assessing options includes addressing the potential performance of existing systems, policies related to MSWM, costs, potential to divert waste from disposal, technical capabilities, ability to maintain local control, compatibility of the option with the current system, flexibility, level of change to the existing system required, and public acceptance.

The assessment of MSWM and WTE systems and the potential of energy recovery from waste is not a new exercise. A number of studies have investigated MSWM and WTE in various countries (e.g., India, China, Malaysia and Nigeria) and regions (e.g., Asia and South East Asia) and worldwide. Similar studies have also been conducted in Thailand. However; they focused only on particular systems such as anaerobic digestion, incineration, landfill gas, RDF and sustainable MSWM. Also, information on private enterprise WTE systems is not available or is difficult to access. This study tries to fill this knowledge gap by providing a comprehensive assessment of overall commercial MSWM and WTE systems and the comparative analysis of these systems, as well as identifying challenges to their success in the context of Thailand. The findings of this study therefore provide an insight into the status of MSWM and WTE systems (as detailed in chapter 3), which are also addressed in the paper entitled "*Valorization of MSW-to-Energy in Thailand: Status, Challenges and Prospects*", which is published in Waste and Biomass Valorization, volume 7, issue 1, pages 31–57.

6.2.3.2 Critical review of influencing factors affecting MSW quantity and existing MSW forecasting models

The most important influencing factors affecting MSW quantity were based on a review of 50 studies that were addressed at the level of household, city and country. These influencing factors were identified, classified and selected the suitable factors for developing the models. This research summarizes influencing factors used and the changes of MSW generation from previous studies to clarify their relationships (as described in section 4.2.2). Research further categorized MSW forecasting models into five groups and provided the number and type of data used and the number of regions studied. Among these, traditional models were developed with the aim of forecasting MSW quantity with and without consideration of influencing factors, and were supported by sufficient historical data. Findings of the review indicate the lack of conceptual framework and methodology for forecasting MSW quantity based on limited data, and the classification, selection and quantification of influencing factors affecting MSW generation. In addition, the development of existing models reveals some limitations that cannot be applied to developing countries where data is scarce. Application of the innovative model, and particularly the grey model (with convolution integral) to forecast MSW quantity is still limited. In consideration of such limitations, improvements in the MSW forecasting model are suggested to encourage wider application in other developing countries and fields of study. The details of these findings can be found in Chapter 4 and in the paper entitled "*Forecasting of municipal solid waste quantity in a developing country using multivariate grey models*", which is published in Waste Management, volume 39, pages 3–14.

6.2.3.3 Improvement of MSW forecasting in developing countries

Multivariate grey model (GM (1, n)) and grey model with convolution integral (GMC (1, n)) offer accurate forecasting models, but their applications are very limited. This research integrated these models as alternatives in the systematic method as mentioned above. Alternative models comprising two traditional models, three univariate grey models and ten multivariate grey models (five of each GM (1, n) and GMC (1, n)) were developed to forecast MSW quantity by using thirteen MSW data sets collected in Thailand. This method can inform future research in forecasting MSW quantity in developing countries or in other fields of study. Using factors affecting the amount of MSW from this study, Salam et al. (2015), from the Asian Institute of Technology (AIT), prepared a report on "*Decision making paper on mitigation options in the Thai waste sector (post 2020) and their contributions to GHG mitigation*" for the Office of Natural Resources and Environmental Policy and Planning (ONEP), where they developed alternative grey models to forecast the future amount of MSW and wastewater to 2050.

6.2.3.4 Evaluation of MSWM systems and the analysis of stakeholder preferences on criteria and alternatives for medium and small cities

The evaluation of various criteria (environment, economy, society and technique) for considering appropriate MSW treatment and management systems has been widely conducted for large cities. Only a few studies have been carried out for medium and small cities. Among 13 studies of large cities, only two addressed stakeholder preferences in developed countries and four in developing countries. It can be concluded that stakeholder preferences, according to the three

pillars of sustainability criteria, viewed environmental performance as the most important in developed countries, followed by social and economic aspects. In contrast, in developing countries, economic considerations were viewed as most important, followed by social and environmental aspects. This research tries to bridge the gap where few studies have evaluated MSWM systems by additionally examining stakeholder preferences for medium and small cities. This approach is useful for ranking of criteria that should be considered, and the options of MSWM systems that should be developed for medium and small cities.

6.2.4 Key policy implications

Findings related to MSWM policies in this research can be categorized according to MSW forecasting and evaluation of MSWM systems. Firstly, this study provides policy makers with an understanding of waste quantity patterns in Thailand through consideration of three representative factors from the commercial sector (population density, urbanization and proportion employment) and one from the residential sector (household size). Influencing factors from the commercial sector affect MSW quantity more than that of the residential sector. This shows that commercial activities can produce more waste than residential, for instance, as hotels offer services, more food is produced and more waste is discarded. In the long term, these results can help decision makers in developing measures and policies for waste management: new targets for 3R and WTE strategies in commercial and residential sectors; strong enhancement of the 3R strategy for hotels, supermarkets, restaurants and institutes; focusing on the Thai sufficiency economic philosophy to reduce consumption; and controlling the increase of population density and urbanization.

Secondly, this study found that there was preference for a decentralized concept for managing MSW and recommends community-based management rather than the clustering concept and WTE implementation (the current policies) as listed as follows:

i) Successful examples of waste-to-resource (WTR) initiatives in Sri Lanka and Viet Nam should be taken into consideration. This system seems appropriate for tropical Asian cities, as in Thailand, with higher ambient humidity and temperatures that facilitate more rapid biodegradation.

ii) This research recommends that the Thai government revise its targets on 3Rs and WTE implementation separately.

iii) It can be concluded that the current policy of MSWM, and specifically WTE, is unsustainable as the government significantly subsidies the private sector and PEA has to construct further transmission lines for buying electricity from private suppliers. In addition, the WTE scheme requires substantial financial support for monitoring air pollution, and especially for dioxins and furans released into the environment.

6.3 **Limitations and recommendations for further research**

The limitations of the study and future work for improving this research are suggested in this section.

Representative factors of the commercial sector affect MSW quantity more than that of the residential sector. However, no separate information on MSW generated from residential and commercial sectors is available in Thailand. Future research on estimating MSW quantities and spatial distributions in residential and commercial sectors is needed.

The forecast of influencing factors in this research was conducted by using the GM (1, 1) model given its maturity. However, to improve the accuracy of MSW forecasting, these values should be gathered from other available sources (e.g. NESDB, NSO, or Ministry of Energy), which consider other parameters for forecasting each influencing factor (for instance, forecasting population size, growth rate, mortality rate, and fertility rate should be considered in the models). In this research, it is impossible to determine all forecast values of influencing factors as data of only a few factors are available (e.g. population density and urbanization).

Given the lack of time series data on the amount of waste generated in medium and small cities in Thailand, it is assumed that the increasing rate of MSW at country level is the same as that at city level (for both medium and small cities) by using the increasing rate (of 1.40% annually) from 2013 to 2030 (this was carried out in **Chapter 4)**. From this assumption, the amount of waste generated in each type of city is presented in terms of the waste generation rate (in kg/capita/day) gathered from TGO (2014). Therefore, further work on the assessment of MSW characteristics in each type of city is recommended.

Limitations and research gaps faced in this study are listed for further application in constructing a hierarchical structure as presented below:

i) guidelines and measurement scales are missing due to the lack of discussion between stakeholders;
ii) stakeholders may not give their strongest opinions and had difficulty in considering a large number of pairs;
iii) suitable number of criteria that should be five to nine;
iv) no methodology for carrying out the correlation of criteria;
v) the results of the study carried out at country level could have been validated with data from selected small and medium cities in Thailand;
vi) source level and community level waste processing through decentralized systems should have been considered in the case of small and medium towns to ensure affordability and public participation;
vii) the sensitivity analysis of stakeholders' preferences with reference to sample size should be investigated in future work; and
viii) the ANP method should be conducted and/or compared with the AHP method.

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Appendices

Appendix A

Questionnaire for WTE Sites Visiting

This questionnaire is a part of the framework of the assessment MSW management systems which is aimed to assess the recovery of municipal solid waste. To assess the situation of energy recovery from waste, it is necessary to have understanding about technical experiences, the existing WTE plants, challenges and barriers in the context of Thailand. Therefore, this questionnaire is aimed to investigate the current use of MSW in each WTE technology including its pros and cons related to MSW management and socio-economic aspects. It also investigates the possibility of the proposing alternatives of MSW management and WTE treatment systems in order to evaluate the appropriate systems for MSW management in Thailand.

The questionnaire consists of two parts:
Part 1 contains questions related to general data i.e., operating technicians and organizations.
Part 2 contains questions of the collecting and disposal information.
Part 3 contains questions of the treatment systems information.
Part 4 contains questions of financial management information.

Part 1: General data
1.1 Name of the contributor
☐ Mr ☐ Mrs ☐ Miss……..……position……
1.2 Name of the organization……
Address ……Road……..….Sub-district…..……..……..District……..…..…
Province……Code……Tel….……...…….
Fax …..…...…… Mobile Phone……e-mail.…….…….…
1.3 Service area/municipality area …….…….…….…km^2
1.4 Amount of population and household in this area (data in year.....)
1.4.1 Population by registrars …….…..
1.4.2 Household by registrars …….…..
1.4.3 Underlining population (including tourists) …….……..…

Part 2: collecting and disposal information
2.1 MSW generation per day ……tons (in year……)
2.2 Under-serviced households for waste collection……households or……%
2.3 Weight of collected waste data ……ton/day (in year……) which is determined from: ☐ weighting at treatment plants ☐ estimation.
2.4 Recycling waste .....ton/day or.....% which is determined from:
☐ Averaging from buying-old-stuffs store, ☐ Estimation.
2.5 How do you manage MSW?
☐ By your organization (yourself) ☐ Cooperation with private company
☐ Private company employed……THB/……, contract……years
☐ Investment and operation by private company……THB/……, contract……years
☐ Other……

2.6 Do you have any transfer station ☐ Yes ☐ No
2.7 If yes, Distance between the service area and transfer station……km.
Distance between transfer station and disposal/treatment plants……km.
2.8 If no, distance between the service area and disposal/treatment plants……km.

Part 3 Treatment system data
3.1 Designed date since (month)……year……to (month) ……year……
3.2 Construction budget.....THB
3.3 From the center government.....THB, your own.....THB
3.4 Loan.....THB, Payment period.....year, Interest.....%
3.5 Constructing period since (month).....year .....to (month).....year.....
3.6 Operation from (month).....year……
3.7 Present status: ☐ Under operation and estimated remaining time by year…….
☐ Operation Halted since (month) ……year……
3.8 Cause of operation halted
☐ Restrict from people
☐ Lack of operating budget
☐ Technical problems
☐ insufficient system management
☐ Lack of operating specialist
☐ Lack of deep knowledge in operation
☐ Not necessary to treat by this technology
☐ Other causes.....
3.9 Total amount of MSW treated in this plant…… tonnes/day
3.9.1 Averaging MSW treated from your responding area……tonnes/day
3.9.2 Amount of MSW treated from others are……tonnes/day (fill the detail: name of organization…… tonnes/day)
……
……
……

3.10 MSW characteristics (please add and attach more data, if you have more than one)
Sampling data (month). ……year……

physical		chemical	
detail	Proportional (%)	detail	Proportional (%)
Paper and cardbroad		<u>Proximate analysis</u>	
Food waste		Ash	
plastic		Moisture content	
metal		Calorific value (HHV)	
glass		volatile matter	
leave/ wood		fixed carbon	
textiles		<u>Ultimate analysis</u>	
rubber/leather		Carbon	
Stone/debris		Oxygen	
others.....		hydrogen	
.....		nitrogen	
.....		sulfur	

3.11 Address of treatment plant……Road……
Sub district……District……Province……
3.12 Area……Rai, operation started since…..…….. , space……..…..… Rai

☐ Your own land (bought it since year……)
☐ Other organization (its name) ……
☐ Private company's land
  ☐ No charging
  ☐ Charging with rectal rate ……THB/year since year……to year……
☐ Other……

3.13 Treatment system

1) Working period……hours/day……days/week……weeks/year
2) Plant Load Factor……%
3) Energy (electricity or heat) generation for…….. (unit/year)
4) Energy used for started up and operating system (please fill unit detailed such as liters/year etc.)

☐ Other fuels (please fill detailed: oil, NGV etc.)……amount……..
☐ Parasitic energy from power generation for……
5) Power generation can be sold for……kWh/year

3.14 Pretreatment system:

1) Waste residues into landfill disposal treatment……tonnes/day
2) Water consumption……m^3/day

order	Equipment	unit	size	number	Residue from each system	
					Composition of waste	amount* (t/d)
....	Open dumping for waste drying Storage building or area - Back hoe - Tractor - Crane	Rai m^2 HP HP HP				
....	- Motor of belt - Silo and Conveyor	Watt ton				
.....	Manual sorting - Motor of its conveyor	Watt				
.....	Screening conveyor.....	Watt				
.....	Bag opening	Watt				
.....	Trommel Screening	Watt				
.....	Hydraulic separation	Watt				
.....	Air Classifier	Watt				
.....	Magnetic Separation	Watt			Metal	
.....	dewatering	Watt				
.....	Size reduction type: ….....	Watt				
.....	Plastic chipper	Watt				
.....	Plastic heating device	Watt				
.....	Compactor	Watt			RDF	

Remark: * For instance, the manual sorting can separate recycling waste (e.i. metal, wood, etc.) for 10 t/d

3.15 Waste treatment system (in case of integrated waste treatment system, can fill more than one option)

1) Amount of MSW into the systems is ……tonnes/day

Using (√)	Technologies	unit	capacity	Products and wastes (unit/day)	
				products	waste
…….	**Anaerobic digestion**	t/d			
……	Water consumption	m^3			
……	Biogas production	m^3			
……	Added energy (e.i.: electricity, gas, fossil fuel)	unit			
……	Reused water	m^3			
……	Digestated sludge (wet weight)	ton			
	Components				
……	- Acid formation tank	m^3			
……	- Methane generation tank	m^3			
……	- Stirring system	Watt			
……	- Pump of recycling water	HP			
……	- Gas cleaning system.....	m^3/d			
……	- Waste water treatment system.....	m^3/d			
……	**Aerobic Composting**	t/d			
……	- shredder	HP			
……	- Blower	HP			
……	- Tractor	HP			
……	- Garbage turning	Watt			
…...	- Other.....	……...			
…...	**Landfill gas**	t/d			
…...	- Pump	HP			
…...	- Gas treatment system	m^3/d			
	- Flaring……..	……...			
……	**Incineration: type:**	t/d			
……	- Flue gas cleaning system.....	m^3/d			
……	**Gasification type:**	t/d			
……	- Syngas cleaning system.....	m^3/d			

3.16 Power generation system

Using (√)	Technologies	Unit	Capacity	Capacity	Energy production	
					Heating (MW)	Electricity (MWh)
.....	Boiler					
.....	Steam turbine					
.....	Internal combustion engine					
.....	Gas turbine					
.....	Gas engine					
.....	Combined heat and power					

3.17 Do you have any operating problems, what are those problems?

☐ No, we don't have any problem ☐ Yes, we have following problems;

☐ Budget ☐ Low efficiency of technology ☐ Lack of knowledge and specialist

☐ Conflict with neighbor ☐ Mechanical problem, please explain more detail:
……
……

Part 4: Financial management information

4.1 In case waste delivered from other organizations, do you gain the tipping fee?

☐ No, I do not.

☐ Yes, I do. Tipping fee rate is……THB/tonne or……THB/year

4.2 Payment of disposal treatment systems

Detail	Costs (THB/year)
Salary of the employee who work for MSW management	
Collecting cost for private company or local community	
Disposal cost for private company	
Repair and maintenances	
Utilities (water supply, electricity, telephone, etc.)	
Spare parts, devices, chemical	
Covering soil	
Other.....	
Total	

4.3 Do you apply the Clean Development Mechanism (CDM) Project or not?

☐ No, I don't.

☐ Yes, I do. Since (Date/month/year)……..

☐ Under operation ☐ Halted operation since Date/month/year)……

CO_2 emission reduction……tonnes of CO_2eq and fee level for……THB/year

4.4 Do you have any policy about "3Rs: reduce and recycle" and/or "Low carbon society" and/or "waste-to-energy" or not? How?

☐ No, I don't.

☐ Yes, I do. For example,

1) ……
2) ……
3) ……
4) ……
5) ……

Recommendation……
……
……
……
……
……
……

Appendix B

Evaluation of MSWM systems for medium and small cities

This appendix gives relative information and methodology for evaluating MSWM systems in medium and small cities in case of Thailand.

Table B-1: Identification and categorization of criteria used

Study area	Criteria (no. of studies or frequency of use)				
	Technical	Environmental	Economic	Social	Others
Country level (8)	Complexity/Simplicity (2), Land occupation, Energy content of fuel, Net electricity output, Parasitic loads, Retention time, Pre-treatment, Reliability at international system	Diversion from landfill (3), Emissions/ Global climate (2), Environmental awareness/ impacts (2), National environmental target (2), Fossil fuel substitution, Resource consumption	Net gained/Benefit (3), Capital cost (3), Energy produced (2), O&M cost, RE contribution, Generation cost ($/kWhe), Waste tax, Resource value	Public acceptance (2), Population, behavior, local practices, urbanization	Risk criteria: Market establishment, Regulations and policies, Producer responsibility, Consumer accountability
Large city (13)	Technical maturity (3), Local equipment (2), Know-how (2), Personnel, Technical implication, Land demand, Feasibility, Coverage, Transportation	GHG emission/reduction (5), Volume reduction (4), Human toxicity/health & safety (4), Low wastewater (3), Resources consumption (3), Recycling rate (2), Plant site footprint (2), Plant visual impact (2), Low noise and odor, Soil contaminated, Costs of waste road process, Fauna & Flora, Stream ecology, Habitat depletion, Vibration, Abiotic depletion, Acidification, Photochemical oxidation, Gross energy requirement, Rules and regulations, Geographical location, Ecological impacts, Disposal, Segregation, recover, recycle, Environmental aspect, Landslide potential,	Capital cost (8), O&M cost (8), Revenues/ benefits (3), Fuel cost, Cost of waste transfer station, Flexibility and strategic value, Budget control, Market for by-products, Estimated cost, Financial management, Energy recovery	Public acceptance (6), High potentiality of job creation (3), Health risk (2), Lorry traffic impact on local communities, Economic efficiency, Fee, Odor, Social justice, Social welfare, Location, Cooperation, Interest message, Outcome	Regulations and policies
Medium city (3)	Suitability of composition, Availability for amount of MSW, Accessibility of technologies, Availability of local expertise, local technique, similar usage in local area, Scaling up, amount generated, type of waste	Air pollution (2), Low wastewater (2), GHG emission/reduction, Low energy consumption, Low water consumption, Low noise and odor, Less space required, Soil contaminated, Abiotic depletion Eutrophication, Acidification, Human toxicity, Photochemical oxidation	Capital cost (3), O&M cost (3), Short payback period, High benefit-cost (B/C), Investors attractiveness, Availability of co-financing, Market for products and by-products	High potentiality of job creation (3), Public acceptance (2), Improvement of quality of life, Safety and health conditions, Odor	Approval of decision-makers, Legislative and regulatory aspects
Small city (1)	No criteria considered				

Table B-2*:* Inputs and the characteristics of MSW management systems

Sub-criteria	unit	Alternatives							
		MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG
GHG emissions	kg eqCO_2/t of waste	199.9 kg eqCO_2 /t of organic waste (Menikpura et al., 2013)	4.189 kg eqCO_2 /t of organic waste [a]	572 (Menikpura et al., 2013)	0.2 (Hartmann and Ahring, 2005)	0.22 (Hartmann and Ahring, 2005)	0.114 (Hartmann and Ahring, 2005)	0.381 kg CO_2/kg steam generated[r]	1-1.2 [s]
Diversion from landfill	%	40 [b]	50 (Menikpura and Sang-Arun, 2013)	-	35 [c]	90	90	35 [c]	-
Environmental impacts (PCD, 2012a)	-	Unpleasant odor and leachate	Unpleasant leachate	High	Low	Moderate	Moderate	Low	Moderate
Capital cost (PCD, 2012a)	MBaht[§§]/ tonne MSW	0.50-1.0 (for 500-50 t/d)	0.19-1.28 (for 500-50 t/d)	1.65-2.67 (for >500 - 50 t/d)	0.33-2.81 (for >500-50 t/d)	3.5-6.0 (for >500-50 t/d)	3.0-4.0 (for >500-50 t/d)	2.0-3.5 (for 250-10 t/d)	3.5-5.0 (for >500-50 t/d)
O&M cost (PCD, 2012a)	Baht/tonne MSW	200-300 (for 500-50 t/d)	314-600 (for 500-50 t/d)	150-160 (for >500-50 t/d)	335-610 (for >500-50 t/d)	1150-2000 (for >500-50 t/d)	430-800 (for >500-50 t/d)	350-400 (for 250-10 t/d)	380-700 (for >500-50 t/d)
Revenue/benefit (PCD, 2012a)	Baht/tonne MSW	175 (for fertilizer and recyclable - materials)	656 (recyclable materials)	-	370	1531.88	3202.33	495.52	518.4
Appropriate capacity (PCD, 2012a)	t/d	30-500	1-300	All size	>60	140-720	70-280	1-30	>137
Job creation	Jobs	59 [d]	112 [d]	11 [d]	34 (Taboada-Gonzalez et al., 2014)	69 (Longden et al., 2007)	66 (Longden et al., 2007)	112 [d]	>11 [d]
Public acceptance[e]	-	Acceptable (PCD, 2012a)	Acceptable (PCD, 2012a)	Unacceptable (PCD, 2012a)	More acceptable (Hartmann and Ahring, 2005)	Acceptable (Hartmann and Ahring, 2005)	More acceptable (Hartmann and Ahring, 2005)	Acceptable (PCD, 2012a)	Unacceptable (Hartmann and Ahring, 2005)

[§§] 1 USD = 35.64 Baht

Table B-2*:* Inputs and the characteristics of MSW management systems **(**Cont**'**d)

Sub-criteria	unit	Alternatives							
		MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG
Simplicity (PCD, 2012a)	-	Moderate	Easy	Easy	Moderate	Moderate	Complicate	Moderate	Moderate
Maturity	Plants (MW)	At least 2	At least 2	92 (PCD, 2012a)	4 (2.5) (Intharathirat et al., 2015)	2 (34) (Intharathirat et al., 2015)	2 (7.2) (Intharathirat et al., 2015)	3 (78.26) (Intharathirat et al., 2015)	4 (23) (Intharathirat et al., 2015)
	(Findfing issues (Intharathirat et al., 2015))	-	-	-	Sorting waste is an issue, no planning project	Suitable for large size, many planning projects	Suitable for small size, many planning projects	many small plants deliver RDF to 3 cement kilns	No new LFG project
Local equipment	-	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Land requirement (PCD, 2012a)	m^2/tonne MSW	800	320	1040	160	112	160	32	1328
Heating value (PCD, 2012a)	Kg cal/kg	No limit	No limit	No limit	No limit	>1680	>1680	No limit	No limit
MSW composition (PCD, 2012a)	-	should has OFMSW more than 90%	No condition	No condition	should has OFMSW more than 90%	Should be combustible fraction	Should be combustible fraction	No condition	No condition
MSW quantity	kg/capita/day	1.15 in 2013 and would be1.42 (1.4% increasing annually (Intharathirat et al., 2015)) in 2030 for medium city and assumed waste generated 50 t/d [f] .103 in 2013 and would be1.27 (1.4% increasing annually (Intharathirat et al., 2015)) in 2030 for small city and assumed waste generated 10 t/d [f]							

Remarks [a] adapted from (Menikpura and Sang-Arun, 2013) using 100 years GWP; [b] adapted from (Milutinović et al., 2014) by reducing OFMSW of 80% and assuming 50% organic fraction, so about 40% of mixed MSW can be reduced; [c] adapted from (Hartmann and Ahring, 2005) by reducing OFMSW of 70% and assuming 50% organic fraction, so about 35% of mixed MSW can be reduced; [d] More labour-intensive processes such as recycling, manual separation, the level of jobs is higher than that without recycling (Murray, 1999 cited from Friends of the Earth, 2010); [e] public hearing study concluded that this technology can be acceptable and does not release negative impacts to human health.; [f] adapted from (TGO, 2014) which are the average MSW generated in each city.

Table B-3*:* Identification of relevant stakeholder groups for MSWM

References	Government	Academia	Private sector	Local authority	NGOs	Resident	Expert/ technician	Politician	Student
Suthapanich (2014)	√	√	√						√
Milutinović et al. (2014)		√		√					
Samah et al. (2010)	√	√		√		√	√		
Abba et al. (2013)				√					
Taboada-Gonzalez et al. (2014)						√			
Garfi et al. (2009)						√	√	√	
Contreras et al. (2008)				√	√	√			
Pires et al. (2011a)		√				√	√		
Begum et al. (2012)	√								
Antonopoulos et al. (2014)		√							
Nixon et al. (2013)	√	√		√					
Khan and Faisal (2008)	√	√		√	√		√		
Yap and Nixon (2015)		√							
Hung et al. (2007)	√		√		√		√		
Longden et al. (2007)	√								
Parekh et al. (2014)		√	√	√	√		√		
Martowibowo and Riyanto (2011)						√	√		√
Total	7	9	3	7	4	6	7	1	2

Table B-4: The number of invited and responded stakeholders

Stakeholder groups	Invitation	Response	Responded agencies
National government	3	2	Ministry of Natural Resources and Environment, Ministry of Energy
NGOs	5	2	Thai Environmental health Association (TEHA); Thai Environmental and Community Development Association (Magic eyes)
Academia	4	2	Kasetsart University (KU), Asian Institute of Technology (AIT)
Local authority	5	3	Khon Kaen municipality (large city), Muang Phon municipality (medium city), Phang Khon municipality (small city)
Technician	2	2	Development of Environment and Energy Foundation (DEE), Petroleum Authority of Thailand (PTT)
Total	19	11	58% responses

Appendix C

Evaluation form for the Stakeholders' Weighting on the Selection of the Appropriate MSW Management Systems for Medium and Small Cities

This evaluation from is a part of the framework of the evaluating of MSW management systems which is aimed to quantify the relative importance or weights of such measurement issues by using the Analytical Hierarchical Process (AHP). To measuring the stakeholders' opinions for selecting the most suitable MSW management systems for medium and small cities in this study, this evaluation form contains three parts i.e., i) the supporting information, ii) weighting criteria and alternatives for medium city, and iii) weighting and alternatives for small city. However, this section particularly provides the quantifying criteria and alternatives or the pairwise comparison matrices which is used for the various scale of cities as presented below.

The evaluation form comprises two parts:
Part 1 contains Stakeholders' opinions on the proposing criteria and alternatives
Part 2 contains the instruction for conducting the AHP method
Part 3 contains the pairwise comparisons matrices

Part 1: Stakeholders' opinions on the proposing criteria and alternatives
Before weighting and scoring the criteria and alternatives, please give your opinion and provide suggestion in order to improve this study.

Do you agree with the proposed criteria and alternatives as mentioned above?

☐ Agree on: ☐ Not agree on:
☐ 4 main criteria ☐ 12 sub-criteria ☐ 8 technologies

<u>If you not agree</u>, please suggest the suitable criteria and alternatives (put the number and detail)

No.....main criteria	No.....sub-criteria	No.....technologies

Part 2: Instruction for conducting the AHP method
The stakeholder's participation plays a key role for weighting and scoring the main criteria, sub-criteria and the alternatives which are pair-wise compared for their importance with respect to each criterion. In this study, four main criteria, twelve sub-criteria and eight technologies are proposed. Four main criteria comprise environmental, economic, social and technical. Eight MSW management systems in this study consist of eight alternatives categorizing three (3) MSW management systems without energy recovery and five (5) WTE treatment systems. Mechanical Biological Treatment (MBT) integrated with composting (MBT+CP), Mechanical Treatment (MT) for sorting recyclable material (MT+Re), and sanitary landfill (LF) are categorized as MSW management systems. While anaerobic digestion (AD), incineration (IC), gasification (GF), refuse derived fuel (MT+RDF), and landfill gas (LFG) are defined as WTE treatment systems. With the AHP method, a pair of measurement issues is compared with respect

to their criteria, sub-criteria and alternatives. The expert is requested to give the number of scale 1-9 in each comparison. The comparison scales are described below.

Scale **1** means equal importance	Scale **1** means equal importance
Scale **3** means weakly importance	Scale **1/3** means weakly unimportance
Scale **5** means definitely importance	Scale **1/5** means definitely unimportance
Scale **7** means very strongly importance	Scale **1/7** means very strongly unimportance
Scale **9** means absolutely importance	Scale **1/9** means absolutely unimportance
Scale **2**, **4**, **6** and **8** intermediate values between the two adjacent scale values	Scale **1/2**, **1/4**, **1/6** and **1/8** intermediate values between the two adjacent scale values

Example: a pair-wise comparison between "Environmental" criteria and "Economic" criteria

The expert judges that "Environmental" criteria is <u>very strongly important</u> than "Economic" criteria, so scale " 7 " is given in a pair-wise comparison metrix.

It means that we compare other columns with the first

	Environmental	Economic	Social	Technical
Environmental		7		
Economic				
Social				
Technical				

Part 3: the pairwise comparisons matrices

C3.1 Weighting and scoring the criteria and alternatives using pair-wise comparisons

<u>C3.1.1 Main criteria</u>

	Environmental	Economic	Social	Technical
Environmental				
Economic				
Social				
Technical				

<u>C3.1.2 Sub-criteria</u>

1) <u>Sub-criteria with respect to a main criteria: **Environmental criteria**</u>

	Diversion from landfill	GHG emissions	Environmental impacts
Diversion from landfill			
GHG emissions			
Environmental impacts			

2) <u>Sub-criteria with respect to a main criteria: **Economic criteria**</u>

	Capital cost	O&M cost	Revenue/benefit
Capital cost			
O&M cost			
Revenue/benefit			

3) Sub-criteria with respect to a main criteria: **Social criteria**

	Public acceptance	Creation of jobs
Public acceptance		
Creation of jobs		

4) Sub-criteria with respect to a main criteria: **Technical criteria**

	Simplicity	Maturity	Local equipment	Land requirement
Simplicity				
Maturity				
Local equipment				
Land requirement				

C3.2 Weighting and scoring the alteratives respected to each sub-criterion

In this step, scale 1-9 from Part 2 will also be used to score the pair-wise comparison between alternatives with respected to each sub-criterion.

1) Alternatives with respect to sub-criteria: **Diversion from landfill**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

2) Alternatives with respect to sub-criteria: **GHG emissions**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

3) Alternatives with respect to sub-criteria: **Environmental impacts**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

4) Alternatives with respect to sub-criteria: **Capital cost**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

5) Alternatives with respect to sub-criteria: **O&M cost**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

6) Alternatives with respect to sub-criteria: **Revenue/benefit**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

7) Alternatives with respect to sub-criteria: **Public acceptance**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

8) Alternatives with respect to sub-criteria: **Creation of jobs**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

9) Alternatives with respect to sub-criteria: **Simplicity**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

10) Alternatives with respect to sub-criteria: **Maturity**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

11) Alternatives with respect to sub-criteria: **Local equipment**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

12) Alternatives with respect to sub-criteria: **Land requirement**

	MBT+CP	MT+Re	Landfill	AD	Incineration	Gasification	MT+RDF	LFG
MBT+CP								
MT+Re								
Landfill								
AD								
Incineration								
Gasification								
MT+RDF								
LFG								

Recommendation

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Appendix D
Group Comparison Matrices, the Normalized Consolidated Values and the Consistency Ratio of Main Criteria regarding to Stakeholders' Preferences

1) Medium city

D.1 Comparison matrix, relative weight of main criteria with respected to governmental group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	5.196	1	1	1.3101	0.3275
Economic	0.192	1	0.267	0.707	0.4319	0.1080
Social	1	3.742	1	0.447	1.0067	0.2517
Technical	1	1.414	2.236	1	1.2514	0.3128
					C.R.	12.4%

D.2 Comparison matrix, relative weight of main criteria with respected to academic group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	3.873	1	3	1.4903	0.3726
Economic	0.258	1	0.258	0.632	0.3694	0.0923
Social	1	3.873	1	4.583	1.6620	0.4155
Technical	0.333	1.581	0.218	1	0.4784	0.1196
					C.R.	1.3%

D.3 Comparison matrix, relative weight of main criteria with respected to technical group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	2.828	1	5	1.5529	0.3882
Economic	0.354	1	0.447	3.873	0.7260	0.1815
Social	1	2.236	1	5	1.4592	0.3648
Technical	0.2	0.258	0.2	1	0.2619	0.0655
					C.R.	2.1%

D.4 Comparison matrix, relative weight of main criteria with respected to local authority group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	4.718	1	3.557	1.7037	0.4259
Economic	0.212	1	0.693	2.080	0.6531	0.1633
Social	1	1.442	1	3.557	1.2750	0.3187
Technical	0.281	0.481	0.281	1	0.3683	0.0921
					C.R.	5.3%

D.5 Comparison matrix, relative weight of main criteria with respected to NGOs group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	2.236	1.732	0.577	1.0844	0.2711
Economic	0.447	1	0.577	0.258	0.4494	0.1123
Social	0.577	1.732	1	0.447	0.7258	0.1815
Technical	1.732	3.873	2.236	1	1.7404	0.4351
					C.R.	0.4%

D.6 Comparison matrix and overall weights of main criteria (aggregation weights)

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	3.685	1.105	2.093	1.5487	0.3872
Economic	0.271	1	0.435	1.055	0.5452	0.1363
Social	0.905	2.298	1	1.864	1.2659	0.3165
Technical	0.478	0.948	0.536	1	0.6402	0.1601
					C.R.	1.2%

2) Small city

D.7 Comparison matrix, relative weight of main criteria with respected to governmental group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	1.732	1	1	1.1305	0.2826
Economic	0.577	1	0.707	0.707	0.7227	0.1807
Social	1	1.414	1	1	1.0734	0.2683
Technical	1	1.414	1	1	1.0734	0.2683
					C.R.	0.2%

D.8 Comparison matrix, relative weight of main criteria with respected to academic group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	3.873	1	3	1.5704	0.3926
Economic	0.258	1	0.333	0.816	0.4390	0.1098
Social	1	3	1	3	1.4744	0.3686
Technical	0.333	1.225	0.333	1	0.5162	0.1290
					C.R.	0.2%

D.9 Comparison matrix, relative weight of main criteria with respected to technical group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	1	1	3	1.2000	0.3000
Economic	1	1	1	3	1.2000	0.3000
Social	1	1	1	3	1.2000	0.3000
Technical	0.333	0.333	0.333	1	0.4000	0.1000
					C.R.	0%

D.10 Comparison matrix, relative weight of main criteria with respected to local authority group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	2.759	1	3.557	1.5319	0.3830
Economic	0.362	1	0.481	1.710	0.6409	0.1602
Social	1	2.080	1	3.557	1.4262	0.3566
Technical	0.281	0.585	0.281	1	0.4010	0.1002
					C.R.	0.3%

D.11 Comparison matrix, relative weight of main criteria with respected to NGOs group

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	1.732	1	0.707	1.0820	0.2705
Economic	0.577	1	0.577	0.447	0.6286	0.1572
Social	1	1.732	1	0.775	1.0888	0.2722
Technical	1.414	2.236	1.291	1	1.4523	0.3631
					C.R.	0%

D.12 Comparison matrix and overall weights of main criteria (aggregation weights)

	Environmental	Economic	Social	Technical	Sum Normalized	Weight
Environmental	1	2.060	1	1.979	1.3452	0.3363
Economic	0.485	1	1.105	1.105	0.7042	0.1761
Social	1	1.755	2.012	2.012	1.2973	0.3243
Technical	0.505	0.905	1	1	0.6533	0.1633
					C.R.	0.1%

Appendix E

Group Comparison Matrices, the Normalized Consolidated Values, the Consistency Ratio, and Aggregation Weights of Sub-Criteria

1) Medium city

E.1 Comparison matrix, aggregation weights of sub- criteria: Environmental aspect

	EV1	EV2	EV3	Sum Normalized	Weight
EV1	1	1.743	0.675	1.0336	0.3445
EV2	0.574	1	0.753	0.7438	0.2479
EV3	1.481	1.327	1	1.2226	0.4075
				C.R.	2.5%

E.2 Comparison matrix, aggregation weights of sub- criteria: Economic aspect

	EC1	EC2	EC3	Sum Normalized	Weight
EC1	1	0.593	0.758	0.7514	0.2505
EC2	1.687	1	1.131	1.2165	0.4055
EC3	1.319	0.884	1	1.0322	0.3441
				C.R.	0.1%

E.3 Comparison matrix, aggregation weights of sub- criteria: Social aspect

	SC1	SC2	Sum Normalized	Weight
SC1	1	4.116	1.6091	0.8045
SC2	0.243	1	0.3909	0.1955
			C.R.	0%

E.4 Comparison matrix, aggregation weights of sub- criteria: Technical aspect

	TN1	TN2	TN3	TN4	Sum Normalized	Weight
TN1	1	1.548	1.123	0.736	1.0505	0.2626
TN2	0.646	1	0.852	0.691	0.7751	0.1938
TN3	0.890	1.174	1	0.811	0.9437	0.2359
TN4	1.359	1.447	1.233	1	1.2306	0.3077
					C.R.	5.3%

2) Small city

E.5 Comparison matrix, aggregation weights of sub- criteria: Environmental aspect

	EV1	EV2	EV3	Sum Normalized	Weight
EV1	1	2.313	0.645	0.7467	0.3523
EV2	0.432	1	0.434	0.3229	0.1772
EV3	1.551	2.307	1	0.9304	0.4705
				C.R.	1.1%

E.6 Comparison matrix, aggregation weights of sub- criteria: Economic aspect

	EC1	EC2	EC3	Sum Normalized	Weight
EC1	1	0.621	1.288	0.5669	0.3015
EC2	1.610	1	1.562	0.9178	0.4412
EC3	0.776	0.640	1	0.5124	0.2574
				C.R.	0.4%

E.7 Comparison matrix, aggregation weights of sub- criteria: Social aspect

	SC1	SC2	Sum Normalized	Weight
SC1	1	3.347	1.5339	0.7700
SC2	0.299	1	0.4601	0.2300
			C.R.	0%

E.8 Comparison matrix, aggregation weights of sub- criteria: Technical aspect

	TN1	TN2	TN3	TN4	Sum Normalized	Weight
TN1	1	1.832	1.204	0.892	1.1643	1.2911
TN2	0.546	1	0.833	0.714	0.7433	0.1858
TN3	0.830	1.201	1	0.741	0.9079	0.2270
TN4	1.121	1.400	1.349	1	1.1845	0.2961
					C.R.	0.5%

Appendix F

Aggregation of Group Comparison Matrices, the Normalized Consolidated Values, Relative Weights and Consistency Ratio, of MSW management systems

1) Medium city

F.1 Comparison matrix, aggregation weights of alternatives respected to diversion from landfill

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.630	2.406	1.335	0.192	0.206	0.580	1.882	0.6204	0.0776
MT-Re	1.588	1.000	2.558	1.856	0.431	0.595	1.204	2.463	1.0006	0.1251
LF	0.416	0.391	1.000	0.591	0.260	0.272	0.553	0.782	0.4037	0.0505
AD	0.749	0.539	1.691	1.000	0.220	0.220	0.385	1.446	0.5019	0.0627
IC	5.195	2.320	3.847	4.551	1.000	1.065	3.292	4.059	2.1912	0.2739
GF	4.847	1.680	3.673	4.551	0.939	1.000	2.891	3.615	1.9806	0.2476
MT-RDF	1.723	0.830	1.809	2.598	0.304	0.346	1.000	2.480	0.8726	0.1091
LFG	0.531	0.406	1.279	0.691	0.246	0.277	0.403	1.000	0.4291	0.0536
									C.R.	2.8%

F.2 Comparison matrix, aggregation weights of alternatives respected to GHG emissions

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.527	2.208	1.213	1.261	1.116	0.889	1.185	1.1889	0.1486
MT-Re	0.655	1.000	2.200	0.844	1.017	0.802	0.435	0.896	0.8478	0.1060
LF	0.453	0.455	1.000	0.570	0.582	0.438	0.286	0.522	0.4829	0.0604
AD	0.825	1.184	1.755	1.000	0.872	0.519	0.549	0.640	0.8109	0.1014
IC	0.793	0.984	1.718	1.147	1.000	0.611	0.524	0.974	0.8632	0.1079
GF	0.896	1.246	2.282	1.926	1.636	1.000	0.864	1.297	1.2513	0.1564
MT-RDF	1.125	2.298	3.500	1.821	1.907	1.158	1.000	1.442	1.5542	0.1943
LFG	0.844	1.116	1.916	1.562	1.026	0.771	0.693	1.000	1.0007	0.1251
									C.R.	0.9%

F.3 Comparison matrix, aggregation weights of alternatives respected to environmental impacts

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.267	0.705	1.681	1.451	1.693	1.080	1.213	1.1997	0.1500
MT-Re	0.789	1.000	0.843	1.643	1.216	1.188	1.105	1.482	1.0990	0.1374
LF	1.418	1.186	1.000	0.924	0.902	0.847	1.105	0.990	1.0453	0.1307
AD	0.595	0.609	1.082	1.000	0.698	0.589	0.492	0.533	0.6677	0.0835
IC	0.689	0.823	1.109	1.433	1.000	0.675	0.691	0.798	0.8520	0.1065
GF	0.591	0.842	1.180	1.698	1.481	1.000	0.591	1.163	0.9897	0.1237
MT-RDF	0.926	0.905	0.905	2.031	1.447	1.691	1.000	1.059	1.1626	0.1453
LFG	0.824	0.675	1.010	1.876	1.253	0.860	0.944	1.000	0.9840	0.1230
									C.R.	2.5%

F.4 Comparison matrix, aggregation weights of alternatives respected to capital cost

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.782	0.867	1.340	1.649	1.403	1.248	1.505	1.1924	0.1491
MT-Re	1.279	1.000	0.719	0.724	0.808	0.683	0.992	0.854	0.8595	0.1074
LF	1.154	1.390	1.000	1.062	1.084	0.848	1.341	1.482	1.1155	0.1394
AD	0.746	1.382	0.941	1.000	1.048	0.860	1.556	1.964	1.1010	0.1376
IC	0.606	1.238	0.923	0.954	1.000	0.591	1.551	1.367	0.9551	0.1194
GF	0.713	1.464	1.179	1.163	1.691	1.000	2.056	1.756	1.2849	0.1606
MT-RDF	0.801	1.008	0.746	0.643	0.645	0.486	1.000	1.134	0.7612	0.0951
LFG	0.664	1.171	0.675	0.509	0.731	0.569	0.882	1.000	0.7303	0.0913
									C.R.	2.0%

F.5 Comparison matrix, aggregation weights of alternatives respected to O&M cost

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.088	0.707	1.017	1.150	0.962	0.811	1.181	0.9652	0.1207
MT-Re	0.919	1.000	0.634	0.901	1.008	0.829	0.884	0.963	0.8726	0.1091
LF	1.413	1.577	1.000	1.322	1.278	1.050	1.014	1.610	1.2524	0.1566
AD	0.984	1.110	0.756	1.000	1.090	0.858	0.920	1.134	0.9600	0.1200
IC	0.869	0.992	0.782	0.917	1.000	0.504	0.712	0.750	0.7963	0.0995
GF	1.039	1.206	0.952	1.165	1.985	1.000	1.102	1.046	1.1492	0.1437
MT-RDF	1.233	1.131	0.986	1.087	1.404	0.907	1.000	1.017	1.0733	0.1342
LFG	0.847	1.038	0.621	0.882	1.333	0.956	0.984	1.000	0.9310	0.1164
									C.R.	0.7%

F.6 Comparison matrix, aggregation weights of alternatives respected to revenue/ benefit

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.438	3.760	0.559	0.473	0.403	0.528	0.495	0.6182	0.0773
MT-Re	2.284	1.000	4.780	1.521	0.574	0.451	1.158	1.201	1.0988	0.1374
LF	0.266	0.209	1.000	0.287	0.272	0.225	0.276	0.319	0.2818	0.0352
AD	1.789	0.657	3.482	1.000	0.439	0.353	0.657	0.930	0.7828	0.0978
IC	2.113	1.743	3.675	2.276	1.000	0.568	1.268	1.234	1.3256	0.1657
GF	2.480	2.219	4.445	2.835	1.761	1.000	1.970	2.051	1.9108	0.2389
MT-RDF	1.894	0.864	3.624	1.522	0.789	0.508	1.000	1.190	1.0398	0.1300
LFG	2.019	0.833	3.131	1.075	0.811	0.488	0.841	1.000	0.9422	0.1178
									C.R.	2.5%

F.7 Comparison matrix, aggregation weights of alternatives respected to public acceptance

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.562	4.140	0.974	2.619	1.998	1.562	3.183	1.6774	0.2097
MT-Re	0.640	1.000	4.111	0.984	2.246	1.551	1.000	2.881	1.3402	0.1675
LF	0.242	0.243	1.000	0.409	0.579	0.589	0.390	0.905	0.4342	0.0543
AD	1.026	1.017	2.448	1.000	2.989	1.743	1.556	2.667	1.4774	0.1847
IC	0.382	0.445	1.726	0.335	1.000	0.564	0.473	1.292	0.5828	0.0728
GF	0.501	0.645	1.699	0.574	1.772	1.000	0.811	2.005	0.8756	0.1094
MT-RDF	0.640	1.000	2.564	0.643	2.113	1.233	1.000	2.743	1.1411	0.1426
LFG	0.314	0.347	1.105	0.375	0.774	0.499	0.365	1.000	0.4715	0.0589
									C.R.	1.0%

F.8 Comparison matrix, aggregation weights of alternatives respected to creation of jobs

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.344	2.051	1.123	0.385	0.418	0.481	2.051	0.7016	0.0877
MT-Re	2.909	1.000	3.206	2.124	1.253	1.362	0.864	1.689	1.4629	0.1829
LF	0.488	0.312	1.000	0.418	0.286	0.303	0.274	0.640	0.3737	0.0467
AD	0.890	0.471	2.391	1.000	0.489	0.499	0.449	1.233	0.6918	0.0865
IC	2.598	0.798	3.493	2.044	1.000	1.201	0.918	2.741	1.4205	0.1776
GF	2.391	0.734	3.300	2.003	0.833	1.000	0.850	2.968	1.3210	0.1651
MT-RDF	2.080	1.158	3.650	2.225	1.090	1.177	1.000	2.329	1.4690	0.1836
LFG	0.488	0.592	1.562	0.811	0.365	0.337	0.429	1.000	0.5594	0.0699
									C.R.	1.8%

F.9 Comparison matrix, aggregation weights of alternatives respected to simplicity

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.852	0.494	1.413	1.877	2.932	2.108	1.588	1.2614	0.1577
MT-Re	1.174	1.000	0.746	1.147	1.213	1.756	1.246	1.413	1.1038	0.1380
LF	2.026	1.340	1.000	1.998	2.368	3.326	2.824	1.979	1.8406	0.2301
AD	0.707	0.872	0.501	1.000	1.659	2.654	0.993	0.955	0.9731	0.1216
IC	0.533	0.825	0.422	0.603	1.000	1.457	1.062	1.062	0.7552	0.0944
GF	0.341	0.569	0.301	0.377	0.686	1.000	0.985	0.712	0.5341	0.0668
MT-RDF	0.474	0.802	0.354	1.007	0.941	1.015	1.000	0.819	0.7099	0.0887
LFG	0.630	0.707	0.505	1.048	0.942	1.405	1.221	1.000	0.8220	0.1028
									C.R.	1.7%

F.10 Comparison matrix, aggregation weights of alternatives respected to maturity

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	2.703	0.529	1.481	2.602	3.662	2.465	1.808	1.5328	0.1916
MT-Re	0.370	1.000	0.311	0.653	1.000	1.626	0.977	0.873	0.6552	0.0819
LF	1.889	3.215	1.000	2.012	2.894	3.870	3.175	2.592	2.1071	0.2634
AD	0.675	1.531	0.497	1.000	1.686	3.418	1.970	0.970	1.0868	0.1359
IC	0.384	1.000	0.346	0.593	1.000	2.194	1.433	1.301	0.7665	0.0958
GF	0.273	0.615	0.258	0.293	0.456	1.000	0.441	0.362	0.3702	0.0463
MT-RDF	0.406	1.023	0.315	0.508	0.698	2.266	1.000	0.847	0.6479	0.0810
LFG	0.553	1.145	0.386	1.031	0.769	2.760	1.181	1.000	0.8333	0.1042
									C.R.	1.5%

F.11 Comparison matrix, aggregation weights of alternatives respected to local equipment

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.603	1.000	0.977	2.760	3.155	1.505	1.000	1.3024	0.1628
MT-Re	0.624	1.000	0.696	0.828	2.524	2.705	1.279	0.782	0.9958	0.1245
LF	1.000	1.437	1.000	0.955	2.835	3.082	1.577	1.279	1.3319	0.1665
AD	1.023	1.208	1.048	1.000	2.607	2.748	1.362	1.055	1.2362	0.1545
IC	0.362	0.396	0.353	0.384	1.000	0.905	0.294	0.218	0.3898	0.0487
GF	0.317	0.370	0.324	0.364	1.105	1.000	0.289	0.224	0.3810	0.0476
MT-RDF	0.664	0.782	0.634	0.734	3.401	3.457	1.000	0.544	0.9574	0.1197
LFG	1.000	1.279	0.782	0.948	4.595	4.460	1.838	1.000	1.4053	0.1757
									C.R.	1.4%

F.12 Comparison matrix, aggregation weights of alternatives respected to land requirement

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.686	0.892	0.844	0.784	0.645	0.474	1.038	0.7610	0.0951
MT-Re	1.457	1.000	1.197	0.920	0.825	0.698	0.671	1.102	0.9389	0.1174
LF	1.121	0.836	1.000	0.985	1.077	1.049	0.570	1.177	0.9312	0.1164
AD	1.185	1.087	1.015	1.000	1.116	1.158	1.000	1.004	1.0397	0.1300
IC	1.276	1.213	0.929	0.896	1.000	0.939	0.453	0.707	0.8674	0.1084
GF	1.551	1.433	0.953	0.864	1.065	1.000	0.439	0.744	0.9332	0.1167
MT-RDF	2.108	1.491	1.754	1.000	2.208	2.276	1.000	0.955	1.4904	0.1863
LFG	0.964	0.907	0.850	0.996	1.415	1.344	1.048	1.000	1.0382	0.1298
									C.R.	2.1%

2) Small city

F.13 Comparison matrix, aggregation weights of alternatives respected to diversion from landfill

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.729	2.351	1.335	0.182	0.202	0.554	1.882	0.6165	0.0771
MT-Re	1.372	1.000	2.423	1.856	0.303	0.418	1.141	2.281	0.8780	0.1098
LF	0.425	0.413	1.000	0.591	0.260	0.272	0.557	0.905	0.4150	0.0519
AD	0.749	0.539	1.691	1.000	0.215	0.215	0.445	1.481	0.5032	0.0629
IC	5.480	3.305	3.847	4.657	1.000	1.065	2.780	4.059	2.2554	0.2819
GF	4.960	2.392	3.673	4.657	0.939	1.000	2.368	3.615	2.0158	0.2520
MT-RDF	1.805	0.876	1.795	2.245	0.360	0.422	1.000	2.538	0.8961	0.1120
LFG	0.531	0.438	1.105	0.675	0.246	0.277	0.394	1.000	0.4200	0.0525
									C.R.	2.6%

F.14 Comparison matrix, aggregation weights of alternatives respected to GHG emissions

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.574	2.108	1.105	1.115	1.116	1.036	1.250	1.1921	0.1490
MT-Re	0.635	1.000	2.052	0.707	0.771	0.627	0.470	0.793	0.7634	0.0954
LF	0.474	0.487	1.000	0.467	0.455	0.406	0.309	0.522	0.4667	0.0583
AD	0.905	1.413	2.143	1.000	0.753	0.504	0.741	0.948	0.9200	0.1150
IC	0.897	1.297	2.198	1.327	1.000	0.671	0.707	1.190	1.0309	0.1289
GF	0.896	1.594	2.465	1.985	1.491	1.000	1.105	1.390	1.3534	0.1692
MT-RDF	0.965	2.128	3.240	1.349	1.413	0.905	1.000	1.190	1.3210	0.1651
LFG	0.800	1.261	1.916	1.055	0.841	0.719	0.841	1.000	0.9524	0.1191
									C.R.	0.9%

F.15 Comparison matrix, aggregation weights of alternatives respected to environmental impacts

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.038	0.705	1.442	1.283	1.323	1.031	1.098	1.0838	0.1355
MT-Re	0.964	1.000	1.087	1.521	1.334	1.375	1.158	1.448	1.1921	0.1490
LF	1.418	0.920	1.000	0.605	0.684	0.673	0.758	0.830	0.8555	0.1069
AD	0.694	0.657	1.652	1.000	0.892	0.920	0.516	0.789	0.8321	0.1040
IC	0.779	0.750	1.462	1.121	1.000	0.782	0.583	0.974	0.8789	0.1099
GF	0.756	0.727	1.486	1.087	1.279	1.000	0.511	1.163	0.9369	0.1171
MT-RDF	0.970	0.864	1.319	1.939	1.714	1.958	1.000	1.206	1.2913	0.1614
LFG	0.911	0.690	1.205	1.267	1.026	0.860	0.829	1.000	0.9294	0.1162
									C.R.	2.5%

F.16 Comparison matrix, aggregation weights of alternatives respected to capital cost

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.850	0.599	1.048	1.194	1.031	0.875	1.107	0.9450	0.1181
MT-Re	1.177	1.000	0.742	0.769	0.771	0.663	0.813	0.820	0.8196	0.1024
LF	1.670	1.348	1.000	0.890	1.076	0.815	1.177	1.505	1.1318	0.1415
AD	0.955	1.300	1.123	1.000	1.065	0.826	1.274	1.996	1.1339	0.1417
IC	0.838	1.297	0.929	0.939	1.000	0.570	1.097	1.230	0.9443	0.1180
GF	0.970	1.509	1.227	1.210	1.755	1.000	1.469	1.626	1.2992	0.1624
MT-RDF	1.143	1.231	0.850	0.785	0.911	0.681	1.000	1.680	0.9768	0.1221
LFG	0.903	1.219	0.664	0.501	0.813	0.615	0.595	1.000	0.7494	0.0937
									C.R.	1.5%

F.17 Comparison matrix, aggregation weights of alternatives respected to O&M cost

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.055	0.598	1.033	1.186	0.985	0.744	1.188	0.9220	0.1152
MT-Re	0.948	1.000	0.701	0.964	0.941	0.652	0.655	0.954	0.8116	0.1014
LF	1.671	1.427	1.000	1.451	1.308	1.100	1.020	1.864	1.2885	0.1611
AD	0.968	1.038	0.689	1.000	0.784	0.671	0.833	1.253	0.8649	0.1081
IC	0.843	1.063	0.765	1.276	1.000	0.481	0.691	0.739	0.8154	0.1019
GF	1.015	1.533	0.909	1.490	2.080	1.551	1.030	1.121	1.2748	0.1593
MT-RDF	1.344	1.527	0.980	1.201	1.447	0.971	1.000	1.427	1.1778	0.1472
LFG	0.842	1.048	0.536	0.798	1.354	0.892	0.701	1.000	0.8451	0.1056
									C.R.	2.1%

F.18 Comparison matrix, aggregation weights of alternatives respected to revenue/ benefit

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.499	2.787	0.586	0.463	0.403	0.611	0.495	0.5968	0.0746
MT-Re	2.005	1.000	4.563	1.274	0.793	0.652	1.158	1.038	1.1119	0.1390
LF	0.359	0.219	1.000	0.272	0.266	0.225	0.274	0.274	0.2772	0.0346
AD	1.708	0.785	3.673	1.000	0.439	0.353	0.802	0.974	0.8309	0.1039
IC	2.162	1.261	3.760	2.276	1.000	0.568	1.307	1.178	1.2776	0.1597
GF	2.480	1.535	4.445	2.835	1.761	1.551	2.031	1.958	1.9316	0.2415
MT-RDF	1.636	0.864	3.650	1.246	0.765	0.492	1.000	1.028	0.9709	0.1214
LFG	2.019	0.964	3.650	1.026	0.849	0.511	0.973	1.000	1.0031	0.1254
									C.R.	2.4%

F.19 Comparison matrix, aggregation weights of alternatives respected to public acceptance

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.562	4.236	0.882	2.700	2.060	1.562	3.257	1.6576	0.2072
MT-Re	0.640	1.000	4.206	0.890	2.316	1.599	1.000	2.947	1.3245	0.1656
LF	0.236	0.238	1.000	0.396	0.593	0.602	0.390	0.905	0.4273	0.0534
AD	1.134	1.123	2.524	1.000	2.921	1.882	1.630	2.814	1.5316	0.1915
IC	0.370	0.432	1.687	0.342	1.000	0.624	0.459	1.322	0.5764	0.0721
GF	0.485	0.625	1.660	0.531	1.603	1.551	0.712	2.005	0.8763	0.1095
MT-RDF	0.640	1.000	2.564	0.613	2.179	1.405	1.000	2.871	1.1496	0.1437
LFG	0.307	0.339	1.105	0.355	0.756	0.499	0.348	1.000	0.4566	0.0571
									C.R.	2.0%

F.20 Comparison matrix, aggregation weights of alternatives respected to creation of jobs

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.417	2.051	1.017	0.544	0.591	0.583	2.051	0.7961	0.7961
MT-Re	2.399	1.000	3.282	2.124	1.653	1.797	0.864	1.729	1.5539	1.5539
LF	0.488	0.305	1.000	0.379	0.366	0.388	0.280	0.640	0.3968	0.3968
AD	0.984	0.471	2.642	1.000	0.687	0.701	0.463	1.301	0.7898	0.7898
IC	1.838	0.605	2.731	1.456	1.000	1.201	0.696	2.481	1.1835	1.1835
GF	1.691	0.557	2.580	1.427	0.833	1.551	0.644	2.320	1.1461	1.1461
MT-RDF	1.715	1.158	3.567	2.158	1.437	1.552	1.000	2.385	1.5520	1.5520
LFG	0.488	0.578	1.562	0.769	0.403	0.431	0.419	1.000	0.5818	0.5818
									C.R.	2.7%

F.21 Comparison matrix, aggregation weights of alternatives respected to simplicity

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.852	0.447	1.413	1.877	2.912	2.108	1.437	1.2366	0.1546
MT-Re	1.174	1.000	0.712	1.038	1.097	1.716	1.128	1.221	1.0347	0.1293
LF	2.239	1.404	1.000	1.864	2.192	3.352	2.677	1.791	1.8118	0.2265
AD	0.707	0.964	0.536	1.000	1.659	2.574	0.993	0.926	0.9839	0.1230
IC	0.533	0.911	0.456	0.603	1.000	1.340	1.062	1.038	0.7635	0.0954
GF	0.343	0.583	0.298	0.389	0.746	1.551	1.000	0.842	0.5933	0.0742
MT-RDF	0.474	0.887	0.374	1.007	0.941	1.000	1.000	0.782	0.7202	0.0900
LFG	0.696	0.819	0.558	1.080	0.964	1.188	1.279	1.000	0.8560	0.1070
									C.R.	3.1%

F.22 Comparison matrix, aggregation weights of alternatives respected to maturity

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	2.703	0.646	1.436	2.484	3.662	2.465	1.577	1.5364	0.1921
MT-Re	0.370	1.000	0.380	0.624	0.955	1.626	0.977	0.842	0.6665	0.0833
LF	1.547	2.633	1.000	1.980	2.983	3.960	3.274	2.672	2.0383	0.2548
AD	0.696	1.603	0.505	1.000	1.670	2.799	2.031	0.970	1.0790	0.1349
IC	0.403	1.048	0.335	0.599	1.000	2.194	1.000	1.197	0.7323	0.0915
GF	0.273	0.615	0.253	0.357	0.456	1.551	0.435	0.349	0.4035	0.0504
MT-RDF	0.406	1.023	0.305	0.492	1.000	2.298	1.000	0.790	0.6705	0.0838
LFG	0.634	1.188	0.374	1.031	0.836	2.864	1.266	1.000	0.8734	0.1092
									C.R.	2.3%

F.23 Comparison matrix, aggregation weights of alternatives respected to local equipment

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	1.531	0.905	0.905	2.846	3.253	1.505	1.000	1.2563	0.1570
MT-Re	0.653	1.000	0.696	0.749	2.662	2.853	1.413	0.864	1.0121	0.1265
LF	1.105	1.437	1.000	0.911	2.924	3.178	1.652	1.413	1.3590	0.1699
AD	1.105	1.335	1.097	1.000	2.903	3.060	1.664	1.221	1.3439	0.1680
IC	0.351	0.376	0.342	0.344	1.000	0.905	0.290	0.213	0.3738	0.0467
GF	0.307	0.350	0.315	0.327	1.105	1.551	0.285	0.219	0.3892	0.0486
MT-RDF	0.664	0.707	0.605	0.601	3.451	3.509	1.000	0.456	0.8946	0.1118
LFG	1.000	1.158	0.707	0.819	4.701	4.563	2.194	1.000	1.3710	0.1714
									C.R.	2.9%

F.24 Comparison matrix, aggregation weights of alternatives respected to land requirement

	MBT-CP	MT-Re	LF	AD	IC	GF	MT-RDF	LFG	Sum Normalized	Weight
MBT-CP	1.000	0.731	0.926	0.911	0.754	0.620	0.509	1.194	0.7943	0.0993
MT-Re	1.368	1.000	1.213	1.354	1.098	0.929	0.955	1.206	1.1006	0.1376
LF	1.080	0.825	1.000	0.985	1.044	1.017	0.557	1.134	0.9049	0.1131
AD	1.097	0.739	1.015	1.000	1.177	1.105	0.838	1.060	0.9598	0.1200
IC	1.326	0.911	0.957	0.850	1.000	0.850	0.456	0.723	0.8287	0.1036
GF	1.612	1.077	0.983	0.905	1.177	1.551	0.460	0.761	0.9862	0.1233
MT-RDF	1.967	1.048	1.794	1.194	2.194	2.173	1.000	0.977	1.4330	0.1791
LFG	0.838	0.829	0.882	0.944	1.383	1.314	1.024	1.000	0.9926	0.1241
									C.R.	2.9%

Appendix G

Author's Publications

International Journal Paper

1. Intharathirat, R., Salam, P.A., Kumar, S., and Untong, A. 2015. Forecasting of municipal solid waste quantity in a developing country using multivariate grey models. Waste Management (39), 3-14. (I.F. = 3.22)

2. Intharathirat, R. and Salam, P.A. 2016. Valorization of MSW-to-Energy in Thailand: Status, Challenges and Prospects. Waste and Biomass Valorization (7), 31-57. (I.F. = 1.06)

International Conference

1. Intharathirat, R. and Salam, P.A. 2014. Uncertainty of Forecasting Municipal Solid Waste Generation and Composition: A Case Study of Thailand. EURASIA 2014 Waste Management Symposium, 28-30 April 2014, Istanbul, Turkey.