

A Study on Development Methodology of Sustainable Solid  
Waste Management System by Using Multi-Objective Decision  
Making Model – A case study in Hoi An City, Vietnam

September 2017

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Dissertation submitted to  
Graduate School of Environmental and Life Science  
of  
Okayama University  
for partial fulfillment of the requirements  
for the degree of  
Doctor of Philosophy

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Okayama University, September 2017



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## ABSTRACT

Solid waste generation is the result of human activities in their production and consumption cycle. Rapid development in Vietnam causes significant increases in municipal solid waste (MSW) generation and negative impacts on the Environment and human health due to the inappropriate waste management system. A sustainable waste management system which ensures environmental safety and human health becomes a critical target of Viet Nam. However, hardly any study provides holistic methods for planning a sustainable waste management that is *environmentally effective, economically affordable* and *socially acceptable* in socioeconomic conditions of developing countries. Also, study on methods for evaluating social acceptance for waste management still lagged behind environmental and economic objectives.

Thus, this dissertation aims at developing a methodology for planning a sustainable waste management system in the social-economic conditions of Vietnam including following main contents: (1) Development of useful sampling procedure and appropriate statistical analysis in waste characterization. The method is readily applicable to medium and small cities in Vietnam for waste characterization study. (2) Identification of relevant factors influencing on household waste generation as well as prediction of MSW generation using multivariate linear regression model (3) Development of Multi-objective Decision-making (MODM) models to identify the optimal solutions in the selection of MSW system. Decision variables as results of the model show the efficient waste flows, and appropriate treatment technologies to satisfy all objectives. (4) Development of an approach to optimize the social acceptance objective in MODM techniques by using Consensus Analysis Model (CAM) and Reference Point Method (RPM). Those help to identify compromise solution over questionnaire survey and direct discussion with related decision makers including authorities, stakeholders and citizen representatives.

To apply these methods to actual targets, a case study was conducted in Hoi An, a well-known tourist city in Vietnam. Firstly, a sampling of municipal waste and analysis of composition and generation were carried out in 2015. To determine the waste characteristics from various sources of the city, not only waste from 321 households but also waste from tourist sources including 9 hotels (HT), 6 restaurants (RBC), and 3 streets (STR) of tourist corners were

chosen. Waste collected was classified into 10 physical categories and 18 subcategories; then, 37 samples were brought to Japan for chemical analysis. The result showed that the daily per capita household waste generation was  $0.223 \text{ kg capita}^{-1} \text{ day}^{-1}$ . People living in rural area generated about a half of the amount of daily waste produced by residents in the urban area. Hotels generated about  $0.6 \text{ kg room}^{-1} \text{ day}^{-1}$  and one restaurant in HAC produced  $26.18 \text{ kg day}^{-1}$  in average. Waste generation from tourist streets was  $6.99 \text{ kg } 100\text{m}^{-1} \text{ day}^{-1}$  in average. The composition of municipal waste in the city had food waste as the largest proportion (42%) and hazardous waste as the smallest contributor (less than 1%). Total biodegradable waste (food and yard trimmings) was approximately 53%, and combustible waste was the second significant component of about 16% while other recyclable contributed about 20% of the municipal waste composition.

Secondly, a questionnaire survey of households (during the period of waste characterization sampling) was conducted to address the relevant factors regarding household waste generation. The Bayesian model average method was used to identify factors significantly associated with waste generation. Multivariate linear regression analysis was then applied to evaluate the impacts of significant factors on household waste production. The model obtained from this study indicated that household location, household size, house area per person, and family economic activity are important determinants of the waste generation rate. The models could explain about 34% of the variation of the per capita daily waste generation rate. Diagnostic tests and model validation results showed that the regression model could provide reliable results of estimated household waste. The study revealed that per capita urban household waste generation is 70–80% higher compared to a rural household. That provides a reliable information of waste generation in different areas for better calculation and arrangement of vehicles, labours, collection routes. The models also showed that if a family ran a business from home, the household waste generation rate would increase by about 35%. Thus, the waste fee for business sector might be a major factor that local authorities should take into account in waste collection and management planning. Two other significant variables (family size and house area per capita) do not contribute much (less than 20%) to waste generation. Variables accounting for household income, the presence of a garden, number of rooms in a house, and percentage of members of different ages were proven to be not significant. The study provides a reliable



method for estimating household waste generation, offer decision makers useful information for waste management policy development.

Next, a single-objective model is formulated to minimise the total cost of the system in addition to landfill waste reduction target. For sensitive analysis, various values of waste separation efficiency were employed as constraints of the model. 12 scenarios were developed using combinations of 3 waste-to-landfill targets (LT: 50%, 25% and 10%) and 4 values of waste separation rate (SE: 100%, 90%, 80%, 70%). The model identified optimal waste flows, and proper treatment options to ensure minimum cost for each scenario. As a result, they were evaluated: the influence of landfill reduction policies and waste separation efficiency to the cost, pollutants emissions ( including CH<sub>4</sub>, CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub>, Heavy Metal, VOC, N<sub>2</sub>O emission) and GHG emission of the system. It is infeasible to reach 10% of waste to landfill with the separation rate of 70% (Scenario SC12). It means that to achieve the landfill reduction target to 10% as expected, the waste separation efficiency of the city should be higher than 80%. System cost is proportional with the landfill target, the higher landfill reduction target, the higher cost for the system. Also, the comparison among a group of scenarios with the same landfill target (SC1-SC4 (LT:50%), SC5-SC8 (LT:25%) and SC9-SC11(LT:10%)) shows that the separation efficiency affects significantly to the system cost. The lower rate of waste sorting at source, the higher the system cost. The Scenario SC1 (LT: 50% and SE: 100%) provided the lowest cost of about 1500 US\$/day and the highest GHG emission due to the complete waste separation but the amount of waste-to-landfill is high (50% of total MSW being landfilled). The system cost and emission are increased in SC2, SC3 and SC4 because of lower separation efficiency while the GHG emission remains the same. Analyzing the results of SC5 to SC11, waste incineration is seemed an effective technology to deal with the low rate of waste separation for waste-to-landfill amount control. However, increasing of waste incineration also causes higher CO<sub>2</sub> emission and air pollutants emission as the result of the analysis. Composting appears as a reliable technology for Hoi An due to low cost and low emission. The percentage of 25% waste to landfill is an achievable target based on the current condition of Hoi An city. Also, the model suggested that the cost is about 1800 US\$ per day and the pollutant emission is 40 tonnes per day with SC5(LT: 25% and SE: 100%) in a combination of incineration, composting and landfill as main treatment technologies.

Then, a multi-objective optimization model was developed for identifying the optimal solution in selecting a sustainable waste system. Firstly, a face-to-face interview survey was conducted in 2016 with 18 local experts including authorities, stakeholders, waste managers, scientists and citizens to draw out the appropriate waste treatment technologies and priorities of waste management of the city. The result of the survey was analysed by consensus analysis model (CAM) for choosing treatment options and objective functions in optimisation models. The consensus result (CR) of Minimising Cost (CR=0.722), Minimising Emission (CR=0.512) and Minimizing Landfill (CR=0.931) were higher than other objectives such as maximising benefit (CR=0.222) or minimising GHG emission (CR=0.271), etc. Also, the degree of consensus (DC) equalled to 0.808, 0.876 and 0.927 for Cost, Emission and Landfill respectively, which means that there was significant consensus for the objectives of the system among local experts. Also, seven waste treatment options were chosen by local experts as potential treatment alternatives for Hoi An city as the results of CAM. Thus, the model proposed accounts for the above three objectives including minimising cost, minimising emission and minimising waste to landfill with chosen treatment alternatives to achieve the goal of sustainability. An optimisation model proposes proposing the efficient waste-flow-allocation and the capacity of disposal facilities as decision variables. The reference point method (RPM) is applied for solving the model to get an optimal solution. Reference points (RP) are chosen by decision makers (DM) who present for different groups involving in waste management such as civil authority, stakeholder and residents throughout a meeting for decision making. The final solution will determine the optimal decision variables and values of objectives which can satisfy all involving DMs. An experiment of the decision-making process was conducted. Three colleagues were invited to play the role of three DMs representing the city authority, the waste management company and citizen in making decisions. Finally, a compromise solution was determined as a result of decision-making which includes intense discussion and agreement between DMs. As a consequence, a Decision Support System using Multi-Objective Decision-Making model was developed which support a variety of policy makers in making decisions. The method provides direct results of the proposed system and also the graphical visibility of chosen solution helping the DMs to discuss adjustment to the final goal. As a result, it takes a shorter time to converge to the compromise decision. The solution indicates that as a cost of about 2183 US\$ per day, waste

incinerator (no energy recovery) and anaerobic digestion combined with composting plants should be applied associated with informal recycling activities and home treatment for degradable waste. The amount of waste to landfill was 20 tonnes per day ( about 29.4%) and pollution emission of 35 metric tons per day and GHG emission of 0.38 thousand tonnes CO<sub>2</sub>-eq per day.

In conclusion, the dissertation could propose the methodology from waste sampling and characterization until decision-making process by using Multi-objective decision-making model through identification of a statistical model of waste generation. The study proposed a systematic SWM planning process supporting various decision makers including authority, business sector and residents working together to obtain compromise solution in decision-making. Also, the system model developed is reliable to apply in Viet Nam cities. In Viet Nam, such process and system are not implemented yet, and a Decision Support System which considers and optimize social acceptance is firstly proposed. Before drastically increasing of waste generation, designing sustainable SWM system which is suitable for the local condition is inevitable. The author proposed an effective approach to realise this situation in Viet Nam. The model and decision support method will be consistently improved for application in the decision-making process of waste management in different city scales in Viet Nam for our future study.

**Key words:** *Decision-making process, Interactive method, MODM model, Optimization model, Sustainable waste management, Waste characterization, Waste generation model.*

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## ABBREVIATIONS

BMA	Bayesian model averaging
BIC	Bayesian information criterion
CBA	Cost – Benefit Analysis
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbone dioxide
DSS	Decision support system
EIA	Environmental Impact Analysis
EU	European Union
Eq.	Equation
GDP	Gross domestic product
GHG	Greenhouse gas
HAC	Hoi An city
MAE	Mean absolute error
MFA	Material Flow Analysis
m <sup>2</sup>	Cubic meter
MSW	Municipal solid waste
MODM	Multi-objective decision making
NRMSE	Normalized root mean square error
MSWM	Municipal solid waste management
OECD	Organization for Economic Co-operation and Development
P-value	Probability value
%	Percentage
R <sup>2</sup>	Coefficient of determination
RMSE	Root mean square error
SWM	Solid Waste Management



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# 1. INTRODUCTION

## 1.1 Background

### 1.1.1 Problem Statements

Healthy municipal solid waste management (MSW) is a pressing issue worldwide. Annually, global MSW generation is approximately 1.3 billion tonnes, and it is forecasted to increase to approximately 2.2 billion tonnes in 2025 ([Hoorweg & Bhada-Tata, 2012](#)). MSW generation is affected by economic development, the degree of industrialisation, residents' habits, and cultures. Income level and rate of urbanisation are highly correlated. As income and living standard increase, consumption of goods and services correspondingly increases, as the amount of waste produced. Therefore, the amount of MSW generated is expected to rise steeply in the next decades. Much of the increase coming in fast-growing cities in developing countries, will be a threat to the environment, public health and safety, so are the financial and social ramifications.

The threat of waste is an urgent issue in less developed nations. Uncollected waste due to inappropriate waste collection and management is typically heaviest near less affluent neighbourhoods and slums. The frequency of illness such as diarrhoea and acute respiratory infection, linked to water pollution and the open burning of waste respectively is much higher, especially in lower developed areas.

MSW also causes a financial burden for municipalities. In general, solid waste management is given a very low priority in developing countries, except perhaps in the capital and large cities. Normally, cities in developing countries spend 20% to 50% of their budgets for dealing with waste management, and 90% of the annual budget provided for solid waste management was probably used up within the first six months in a developing city ([Ogawa, 2008](#)). According to [Hoorweg and Bhada-Tata \(2012\)](#), the cost of waste management will increase 3-4 times in developing countries from about 20 billion US\$ in 2010 to approximately 80 billion US\$ in 2025. The rate of cost increase is higher in lower developed countries.

In addition, Climate change has become a matter of public concern, the concentration of CO<sub>2</sub> and Methane (CH<sub>4</sub>) were increased 35% and 100%, respectively ([ISWA, 2010](#)). According to the report of [IPCC \(2007\)](#), the amount of Greenhouse gas (GHG) emission from waste sector

accounted for about 3% of total artificial GHG emission, in which 90% is methane gas ([Scheutz, Kjeldsen, & Gentil, 2009](#)). In term of Methane emission, Waste sector only contributed around 18% globally ([Bogner, 2007](#)), mainly from landfill and wastewater treatment facilities. However, MSW management is a small contributor to GHG emission, but it is becoming a significant GHG mitigator due to its potential for material and energy recovery ([UNEP, 2010](#)).

Thus, a sustainable MSW management system has become crucial for the sustainable development strategy of developing countries. To develop a sustainable solid waste management system, a variety of procedures should be conducted efficiently including sampling, surveying to address the problem and obtain waste information, modelling and simulation the reality, calculation economic and environmental impacts of potential management options, implementation of the decision-making process. However, the lack of attention in the study on how to develop a sustainable waste management has led to the improper waste management system in developing countries. The relative importance of procedures which play a major role in waste management planning are explained in the following.

Firstly, planning, design, and operation of a sustainable MSW management system require the understanding of the features the waste stream ([Abu Qdais, Hamoda, & Newham, 1997](#); [Chang & Pires, 2015b](#)). For integrated waste planning, accurate and reliable data on the waste composition and generation are needed for evaluation of optimal treatment options. However, physical, geographical, sociocultural, economic, and political factors may have influences on the composition and generation of municipal solid waste (MSW) ([Gallardo, Carlos, Peris, & Colomer, 2014](#); [Gidakos, Havas, & Ntzamilis, 2006](#)). Especially, economic development may lead to significant influences to the environment on resource consumption as well as pollution generation. For instance, one of the major impacts of tourist development is the change in generation rate and composition of MSW as well as household waste. Some previous studies have reported the increase in MSW in the tourist areas resulting from the high number of tourists during the tourist season ([Denafas et al., 2014](#); [Espinosa Lloréns et al., 2008](#); [Shamshiry et al., 2011](#); [Teh & Cabanban, 2007](#)). Thus, waste composition and waste generation rates can be different in places influenced by many relevant factors mentioned above. However, studies on waste have still lagged behind where it concerns waste arising from developing countries due to

the near absence of reliable data on MSW management and lack of attention from authorities and waste managers ([Ezeah, Fazakerley, & Byrne, 2015](#)).

Secondly, the prediction of MSW generation also plays a major role in a solid waste management planning. Apparently, predicting waste generation is increasingly essential in waste collection planning, waste treatment strategies and establishing waste policies toward a sustainable waste management system ([Abbasi, Abduli, Omidvar, & Baghvand, 2012](#); [Chen & Chang, 2000](#); [Thanh & Matsui, 2011](#)). In developing world, one of the most challenges faced by local governments is the prognosis of solid waste quantities to have appropriate actions and plan ([Ghinea et al., 2016](#)). For instance, in Viet Nam, the National Technical Regulation QCVN 07:2010/BXD ([MOC, 2010](#)) provided a method to estimate waste generation for five urban types based on population and waste generation rate determined in the document. However, the results of prediction are not reliable in term of practical application for different cities because the solid waste generation is impacted not only by demographic factor but also by social, economic as well as other factors (e.g. family expense or waste prevention policies). Therefore, the later edition of this regulation, QCVN 07:2016 ([MOC, 2016](#)) uses neither this method for waste generation estimation nor any other model instead. Lack of research and method on waste generation estimation has led to a considerable challenge in municipal waste management in developing countries.

Then, the decision making process normally have been carried out by authority alone and lack of taking consideration of the opinions of involved parties such as business sectors, citizens, NGO etc. Thus, the social acceptance, which is a crucial aspects of sustainability has not been well presented in waste management plan. Different stakeholders normally require different interest from waste management system. For instance, authority might requires a low cost sytem with minimum of waste to landfill. Residents are interesting in a system with fast collection and less pollution. Meanwhile, business sectors care more about how to maximize the benefit or minimize the cost. Waste management system always has conflicts needs to be solved by all participants. Thus, a requirement of development a Decision Support System (DSS) helping a variety of decision makers from various stakeholder group participating in decision making process is essential. Especially, the decision making process needs the involvement of citizens



(people who generated waste and being directly affected from waste management system) in full-fill the meaning of sustainability.

Lastly, SWM is a significant issue in sustainable development encompassing technical, socio-economic, legal, ecological, financial, political and cultural components ([Chang & Pires, 2015a](#)). System analysis which provides unique, interdisciplinary support for strategic analysis and decision-making procedures, has been lagged behind in developing countries due to the lack of studies and knowledge of implementing system analysis in waste management. System analysis approach have been applied to analyse for SWM over the last few decades ([Pires, Martinho, & Chang, 2011](#)). Multi-Objective Decision Making approach has been developed to solve the conflict of multi-objective problems and balancing the environmental and economic goals of the system. However, previous studies in MODM models are well addressed by presenting a decision variable for the selection of technologies rather than environmental impacts. The environmental impact should consider various of pollutants emission from variety of treatment technologies, not only take into account for GHG emission or CO<sub>2</sub> emission or only emission from incinerator, landfill. Moreover, the waste cycle from generation source to final disposal was well calculated in LCA studies but not well presented in previous MODM studies. Thus, a MODM model which can fill those gaps mentioned above is crucial for developing countries.

### ***1.1.2 Current status of Municipal waste management in Viet Nam***

Vietnam is an S-shaped country located in the Center of South-East Asia which has 3,730 km mainland border with China in the North, Laos and Cambodia in the West. The total land area of 330,967 km<sup>2</sup> with a population of approximately 92 million in 2015 ([GSOVN, 2016](#)). Vietnam is developing rapidly and undergoing urbanisation with current GDP of about 193.6 billion US\$.

Solid waste generation is the result of human activities in their production and consumption cycle. Rapid urbanisation and industrialisation in Vietnam have led to thousands of tonnes of municipal solid waste (MSW) generated daily. Currently, solid waste generation is assessed to be more than 24 million tonnes per year, with a likelihood of reaching 52 million tonnes by the year 2020 ([T. K. T. Nguyen, 2014](#)). Increasing MSW generation has been becoming an emerging

environmental issue for authorities in Viet Nam ([D. L. Nguyen, Hoang, & Bui, 2013](#)). The growing waste amount causes negative impacts on the environment and human health due to the inadequate disposal of waste ([Ngoc & Schnitzer, 2009](#)). Also, 80% of MSW was disposed of in landfills without being recycled, reflecting the material and energy losses of the society ([Ghinea et al., 2016](#)). Thus, Integrated waste management has become significantly important regarding recycling material and energy from MSW as well as resource conversions ([van de Klundert, Anschütz, & Scheinberg, 2001](#); [Zurbrugg, Gfrerer, Ashadi, Brenner, & Kuper, 2012](#)).

### 1.1.2.1 . Waste Management in Vietnam

#### *Waste generation and composition*

Table 1.1 presents the significant increase in waste generation rate and the total quantity of MSW during the period of 2007-2010 and prediction for 2020 and 2025. Annually, the average increasing rate of MSW in urban areas is 10-16% per year, and the waste generation per capita rate is much higher in the major cities such as Ha Noi, Ho Chi Minh, Da Nang. The rapid of urbanization and economic growth, as well as the increase in living standards and the changing life styles, has led to the increase in municipal waste generation, especially in urban areas.

The per capita waste generation levels generally increase, in correlation to the improvement in the standard of living. According to the data reported by provinces, the average daily generation rates in kg/person/day range from 0.8 to 1.2 kg/person.day in the major cities and from 0.35 to 0.5 kg/person.day in small towns ([T. K. T. Nguyen, 2014](#)). On average, the consumed amounts of energy, goods, and food of urban residents are about 2-3 times higher than those of rural residents in Vietnam. Thus, urban dwellers produce about twice as much waste as their rural counterparts.

**Table 1.1.** Waste generation in urban area

Content	Unit	Year					
		2007	2008	2009	2010	2020	2025
Urban Population	million	23.8	27.7	25.5	26.22	44	52
Percentage of urban citizens	%	28.2	28.99	29.74	30.2	45	50

Waste generation rate in urban	kg/capita.day	0.75	0.85	0.95	1.0	1.4	1.6
Total MSW generation	ton/day	17.68	20.85	24.22	26.22	61.6	83.2

Source: ([MONRE, 2011](#))

The composition of MSW in Viet Nam is diverse. It mainly consists of a large organic fraction (56-77%), followed by recyclable waste (10-14%) and paper (2-7%). The MSW contains recyclable materials (paper, plastic, glass, metals, etc.), hazardous waste (paints, pesticides, used batteries), and degradable materials (fruit and vegetable peels, food waste). Table 1.2 shows the composition and waste characteristics in some cities in Viet Nam. This suggests that there is a tremendous potential for the implementation of biological processing and recycling activities for MSW in Vietnam. Presently the solid waste generation is assessed to be more than 15 million tons per year with approximately 80 % from municipal sources, 17 % from industrial sources and the remaining 3 % from other sources. By the year 2010, the expected solid waste generation is 24 million tons per year, with a likelihood of reaching 52 million tons by the year 2020 ([D. L. Nguyen et al., 2013](#)).

Table 1.2. Waste composition and characteristics

Composition	Unit	City			
		Hanoi	Da Nang	Hue	Pleiku
Organic	%	53.8	66	55	60.49
Plastic	%	3.42	4	5.2	12.7
Paper, carton	%	4.2	3.1	4.4	9.65
Metal	%	1.4	4.9	7	1.16
Glass	%	1	0.9	1.8	0.13
Inert	%	28.18	16.4	23	12.6
Rubber	%	4.9	1.6	1.5	2.8
Textile	%	1.7	2.3	3	0
Hazardous	%	1.4	0.8	0.8	0.4
Moisture content	%	43.04	51.2	50	50.5
Ash content	%	13.7	16	15.5	13.9
Bulk density	ton/m <sup>3</sup>	0.41	0.4	0.4	0.38

Recyclable material	%	16.62	16.8	22.9	26.51
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Source: ([T. K. T. Nguyen, 2014](#))

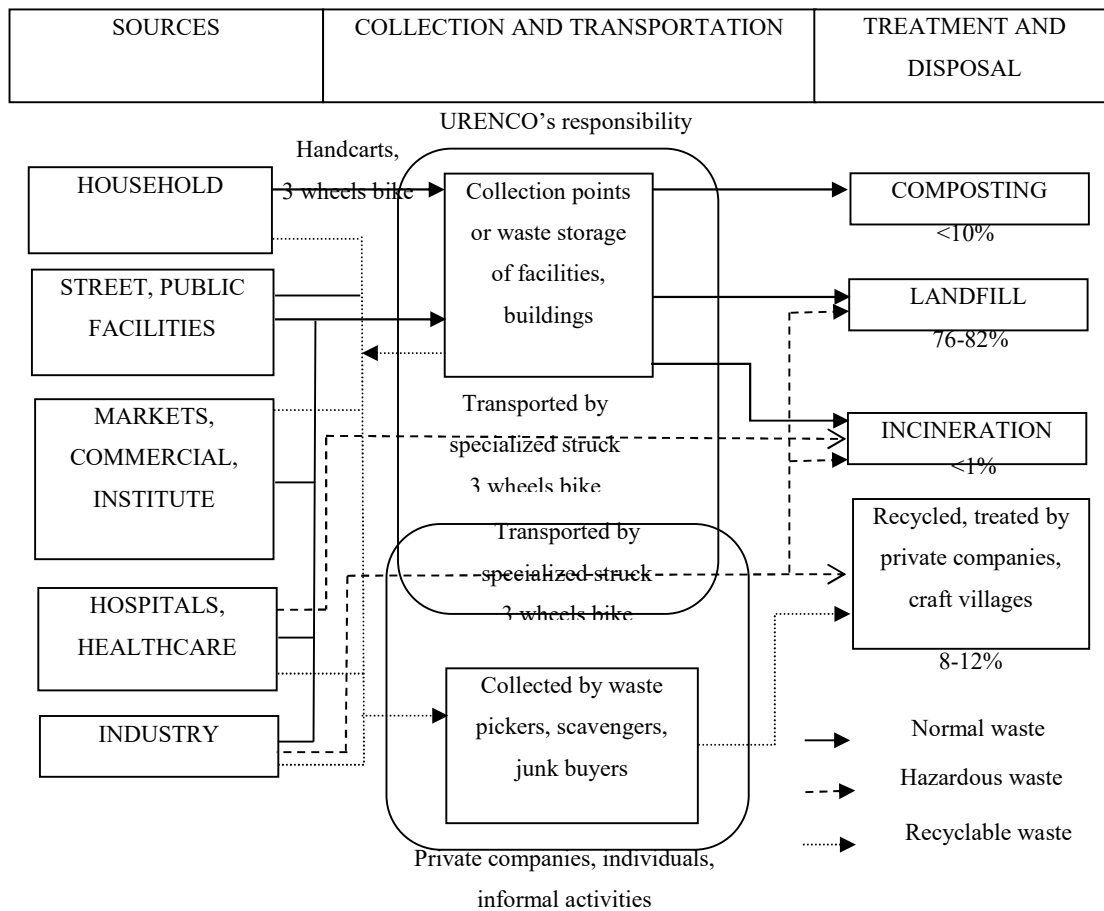
### *Waste collection and transportation*

In Viet Nam, private companies and informal recyclers participate partly in MSW management. On the other hand, the Urban Environment Company (URENCO) of the city has the highest responsibility to collect, transport and disposal the waste generated in the areas including residential waste, street waste, and waste from commercial areas, offices, markets, industrial zones, hospital, etc. MSW generation from different sources are normally collected to be stored temporarily in collection points. Then, it will be transported to disposal sites by transportation vehicles such as compression truck. The systematic diagram of waste collection and transportation is presented in Figure 1.2.

The average percentage of solid waste collection is about 72 % for the whole country, of which the collection rate in urban areas is increasing from 80–82 % (2008) to 83–85 % (2010) and in the countryside about 40–45 % ([MONRE, 2011](#); [T. K. T. Nguyen, 2014](#)). The rates of collection efficiency in some Vietnamese cities are presented in Table 1.3. Open burning and illegal dumping are popular, especially in the out-of-service areas. Waste generated is dumped in garden area, by the roadside, in ditch or lake also is burnt in the area adjacent to properties or at roadside by resident and commercial waste generator. Solid waste from households is collected by handcart or waste collection vehicle running through streets according to a planned schedule, then gathering to planned collection points. In the area where the waste collection service is provided, waste is dumped in the street without any containment. It can be blown by wind or washed into the drain or ditch of the city drainage system by rainfall, thereby contributing to littering in the city and surface water pollution, respectively.

The collection time is from 10.00 p.m. to 6.00 am in order to avoid working at the high temperatures in daytime, public complaint and traffic congestion. The inappropriate collection causes odor, air, water pollution due to waste on the streets, being blown by wind, washed into the drainage system by rainfall.

Landfill is the most popular method for MSW disposal in Vietnam at present. There are totally 98 landfills in operation in the whole country with 16 sanitary landfill sites, and the remaining are open dumping sites and unsanitary landfills. Thus, 76-82% of the total collected MSW quantity is disposed at open-dumped sites and landfills ([MONRE, 2011](#)). MSW is directly disposed of in uncontrolled and poorly managed manners such as no leachate collection system, poor design of bottom layer, no daily cover layer, and no landfill gas collection equipment, those of which lead to serious environmental problems and public health threat. In addition, illegal dumping and disposal of waste to rivers, lakes, oceans, drainage channels, empty lots and roadsides due to inefficient collection and transportation system is also a serious problem in Viet Nam.



Sources: ([T. K. T. Nguyen, 2014](#); [Thanh, 2010](#))

Figure 1.1. Common flow of solid waste and collection stakeholders in Vietnam

Composting is a useful recycling form of organic waste to produce a clean soil conditioner. It can increase the rate of material recovery, and it is known as a cost-effective means for treatment of MSW. However, the proportion of MSW to be composted is not really high in Vietnam. The summary of the capacity of all MSW composting plants is still less than 2,500 tonnes/day which is about 10% total quantity of MSW generated ([MONRE, 2011](#)). In reality, due to the difficulty in the selling of composting products, most of composting plants are not operating at full capacity. That may be as the result of following reasons: no market survey before construction of the facilities, inadequate control of the quality and quantity of the compost, technical constraints, waste not separated at sources, etc.

Table 1.3. Collection rate in different urban in Vietnam

Type of Urban	Name	Collection Rate (%)	Type of Urban	Name	Collection Rate (%)
Special Urban	Hanoi	90 – 95	Type 3	Bac Giang	80
	Ho Chi Minh	90 – 97		Bao Loc	70
Type 1	Hai Phong	80-90	Type 4	Bac Lieu	52
	Da Nang	90		Vinh Long	75
	Hue	90		Song Cong	80
Type 2	Quy Nhon	61	Type 5	Tu Son	51
	Thai Nguyen	80		Go Cong	60
	Viet Tri	95		Cam Ranh	90
	Nam Dinh	78		Tua Chua	75
	Thanh Hoa	84		Tien Hai	74

Source: ([MONRE, 2011](#))

#### *Waste treatment and disposal*

Municipal solid waste of Vietnam is usually of high moisture, and low calories (900–1,100 kcal/kg). Incineration requires substantial investment, operation and maintenance cost. Therefore the application of incineration for MSW treatment is not very much practised. However, it is applied more for treatment of the hazardous waste and the medical waste generated from hospitals in Viet Nam. Ministry of Health estimated that incinerators treated only 37 % of total health care waste and the remain was treated in inappropriate ways ([T. K. T. Nguyen, 2014](#)).

There is only one large-scale MSW incinerator with a capacity of 300 tonnes/day installed in Son Tay town and one medium scale waste-to-energy incinerator for industrial waste in Nam Son complex, Hanoi city.

*Legal documents related to waste management*

Decision No.2149/2009/QD-TTg dated December 17, 2009 by the Prime Minister on approving the national strategy for integrated management of solid waste up to 2025, with a vision to 2025 –

Decision No.1440/QD-TTg dated October 06, 2008 of the Prime Minister approving the Planning on construction of solid waste treatment facilities in three northern, central Vietnam and Southern key economic regions up to 2020; –

Decision 1216/QD-TTg dated 05 September, 2012 on the National Strategy on Environment Protection to 2020, with Visions to 2030

*For Landfills Management:*

Joint Circular No. 01/2001/ TTLT-BKHCMNT-BXD dated January 18, 2001 by the Ministry of Construction and the Ministry of Science, Technology and Environment on guiding the regulations on environmental protection for the selection of location for, the construction and operation of, solid waste burial sites

*For Power production from MSW:*

Decision No. 1030/QD-TTg dated 20 July 2009 approving “Proposal for the Development of Vietnam Environmental Industry up to the year of 2015, vision to 2025”.

*For Power generation from MSW:*

– Decision No. 249/QD-TTg dated 10 Feb, 2010 by the Prime Minister on approving the "service project development environment 2020"

– Decision No. 18/2008/QD-BCT dated July 18, 2008 of the Ministry of Industry and Trade on promulgation of regulation on avoided cost tariff and standardized electric power purchase agreement for small renewable energy power plants

– Decision No. 31/2014/QĐ-TTg dated May 05, 2014, on supporting mechanism for development of electric power generation projects using solid waste in Vietnam

*Climate change:*

– Decision No.2139/QĐ-TTg dated 5 Dec, 2011 by the Prime Minister on approving the national strategy for climate change

– Decision No.130/2007/QĐ-TTg dated 02 Aug, 2007 by the Prime Minister on several financial mechanism and policies applied to investment projects on clean development mechanism

– Decision No.1775/QĐ-TTg dated 21 Nov, 2012 by the Prime Minister on several financial mechanism and policies applied to investment projects on clean development mechanism

*1.1.2.2 . MSW management problem identification and solutions*

One of important problems that lead to inappropriate waste management in Viet Nam is that the local government are not adequately equipped to provide proper waste treatment and collection service. It is due to various reasons such as lack of resources, managerial capacity as well as financial issues. The main problems will be list as following:

**Technical constraints:** Waste treatment technologies such as composting, incineration, anaerobic digestion is not applied successfully in Viet Nam due to lack of technical attention. For instance, waste treatment technologies developed domestically are cheap but the technologies tend to have low-quality elements or lack of technical, environmental attention. Thus they sometimes get failed or generates much pollution in operation. The imported technologies, on the other hand, are much more expensive, but getting no attention about the feasibility for local waste and conditions such as waste characteristics, technical levels of operators, managerial capacity, economic affordability, etc. As a result, many facilities have stopped working or are working inefficiently with emitting pollution. Low implementation of waste separation at source is also a cause of ineffective treatment. Thus, improvement of waste separation activities as well as evaluating an adequate levels of waste separation rate is essential for sustainable waste management planning.



**Institutional constraints:** There seems to be a consensus that weak institutions are a major issue in Viet Nam as well as other developing countries ([Wilson, 2007](#)). Strengthening and capacity building should be important to develop the more efficient waste management system. Waste policy and legal framework are required so that they should be able to set up sustainable objectives and targets in certain time. Moreover, scientific research and applied studies which can overcome the lack of attention should be encouraged to enhance the efficiency and capacity of decision makers. For example, the lack of reliable waste data and information due to poor condition of standardised methods and studies leads to uncertainty of input data for waste management planning and calculation. Thus, standardised methodologies of waste characterization study is essential to get reliable data for waste management planning, and so decision making support studies will be very beneficial for creating suitable waste management initiatives as well as applied technologies studies, which will provide more affordable and technically feasible treatment solutions. Also, awareness education for residents and authorities also need to get more attention and investment and within the environmental protection policy, the “3R Initiative” of Reduce- Reuse-Recycle has been raised as an important issue in need of close attention.

**Financial constraints:** Multiple studies on waste management in developing countries have cited financial and institutional constraints as the main reasons for inadequate disposal of waste, especially where local governments is weak at performing initiative or underfinanced even though rapid population growth continues ([Zhu et al., 2008](#)). In general, solid waste managements is given a tiny priority in developing countries. The same problem occurred in Vietnam, where limited funds were provided to the solid waste management sector by government and distribution of these limited funds were mismanaged due to low managerial capacity. Thus, the level of waste treatment service that is required for protection of public health and the environment are not attained.

**Decision-making support system constraints:** In Viet Nam and many other developing countries, there is lack of decision support system being developed to help decision makers in making waste management plan, especially citizens and other stakeholders are hardly to get involve in decision-making process. On the other hand, there is no MODM model study was

conducted to optimize various conflicted objectives for sustainable waste management plan. Thus, developing a DSS using MODM model to support sustainable waste management planning is essential in Viet Nam towards sustainable development of the country.

## 1.2 Research objectives

The overall aim of this dissertation is to obtain the knowledge of methodologies to develop a sustainable solid waste management system which will include various steps such as waste characterization, modelling and simulation to get optimal results, and creating a framework of working with DM to obtain the final solution of waste management. The main objective is to achieve a waste management system associated with sustainable development in the social-economic conditions of Vietnam which ensure following targets: *environmental effectiveness*, *economic affordability* and *social acceptance*.

In this study, detail targets needed to be done as listed as follows:

(1) To obtain and analyse the waste generation and composition from various MSW sources including household, commercial, tourists to get the reliable input data for waste management modelling. In addition, a waste characterization method including sampling procedures and appropriate statistical analysis will be developed and suggested as a reference that is readily applicable to medium and small cities in Vietnam for waste characterization study.

(2) To analyse the influence of correlated factors to household waste generation by linear regression analysis and a multivariate linear regression model is developed to estimate household waste produced.

(4) To analyse the Waste management strategies of waste-to-landfill control and efficiency of waste separation at source, a single objective optimization (minimizing Cost) is proposed to compare costs, GHG emission and pollutants emission of 12 different scenarios.

(3) Optimisation models to identify the optimal solutions for the sustainable waste management system is simulated to support the decision-making process. Decision variables of the optimisation model will show the efficient waste flows, and appropriate treatment technologies to reach the objectives.

(5) To find a optimal solution in minimizing Cost, minimizing Emission and minimizing Waste to landfill, an mutiple objective optimization models which uses DM's references as input-parameter is proposed in order to achieve the best solution of waste flow allocation and treatment options and agreement of all DMs.

(6) To create a framework of decision making process based on Reference points method by experiencing meeting as well as working with related decision makers (MD) including authorities, stakeholders, and citizens representatives.

### **1.3 Scope of study**

The study will focus on MSW management in Viet Nam, the case study is conducted in Hoi An city ,a city on the coast of the East Sea in the South Central Coast region of Vietnam, located in Quang Nam province and it is recognized as a World Heritage Site by UNESCO. The city has natural land area of 6,171.25 ha with the total population of the city in 2013 is around 93 thousands and the number population density of 1,508 people km<sup>2</sup> ([HASD, 2013](#)). It comprises 13 administrative wards including an island ward. The city is a unique urban in Vietnam which consists many types of urban including: urban and rural places and especially it is a famous touristic city (Hoi An ancient town), that can lead to great differences of waste generation from different places ([Abu Qdais et al., 1997](#)).

Tourism is the most dynamic industry and the biggest economic contributor of the city. In 2013, the total income of tourist service and retail sales (from restaurants only) was 1,500 and 1,100 billion VND respectively. Meanwhile, the total industrial production value of the city was only 212 billion VND ([HASD, 2013](#)). Also, the MSW generation increases associated with the growth of the number of tourists. Thus, tourist industry might has affected strongly to the variation of waste generation and composition.

In general, MSW in Hoi An is currently disposed of at an open dumping landfills without taking any operational and engineering control. Besides, one composting plant with a capacity of 55 tons per day has been operating inefficiently. The opened dump landfill and the composting plant have caused huge adverse effects on the environment and public health. Hence, MSW management is one of the most important issues of Hoi An and developing a sustainable municipal solid waste management system has become a necessity in the City.

## 1.4 Outline of Research

To obtain the proposed objective of the study, the dissertation contents including 6 chapters as followed:

**Chapter 1**, General Introduction to the study

**Chapter 2**, a literature review of methods and results of previous studies related to this work is reviewed. The method of MSW characterization, such as monitoring of waste generation, classification of waste composition, relevant factors of waste generation, statistical analysis, modelling is mentioned. Moreover, the optimisation model and application of MCDM is also reviewed in the literature review.

**Chapter 3**, explain the case study and methodologies applied in the research. After introduction of the case study, the section describes the method for waste sampling, waste characterization and statistical analysis. Then, modelling technique of optimisation model implemented in this work is presented. Lastly, the method of the multi-objective decision-making process to the optimal solution for waste management is explained.

**Chapter 4** deals with the analysis of MSW characterization. It will account for the detail of household waste, hotel waste, restaurant waste and street waste generation as well as composition. Differences in waste generation and composition from different areas in the city is also examined.

**Chapter 5**, this chapter describes the development of a prognosis model for solid waste generation from households in Hoi An city, a famous tourism city in Vietnam. Bayesian model average method (BMA) was applied to evaluate impacts of various factors on household waste generation. Then, multivariate linear regression model is proposed for estimating waste generation.

In **Chapter 6**, a single optimisation model to minimise cost of waste management is proposed to evaluate the impacts of landfill target initiatives and separation efficiency. Then, it presents the results of consensus analysis model of the local expert opinion for choosing objectives and potential treatment alternatives of the system. Lastly, a multi-objective model is

proposed and an optimal solution is determined by an interactive method for discussion of decision makers. The result propose a sustainable waste management plan for the city,

**Chapter 7** summarizes the main findings of this dissertation. Drawbacks of this study and recommendations for further study is also presented in this chapter.

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## 2. LITERATURE REVIEW

### 2.1 Sustainable waste management planning

#### 2.1.1 Sustainable waste management system

Integrated waste management is defined as a combination of ~~combines~~ waste stream, waste collection, recycling, treatment and disposal, in addition, other monitoring activities, risk and pollution prevention, with the objective of achieving human health and environmental protection. Generally, functional elements of waste management are generation source, storage at source and separation, collection, transfer and transport, recycling and treatment; final disposal.

The conventional waste management approach is that waste generation, collection and disposal systems are planned as independent operations. However, all elements are very closely interlinked and have interaction with each other. There are also interaction between the physical components of the system and the conceptual components that include the social and environmental spheres.

The traditional reductionist approaches of “flame, flush or fling” to waste management is unsustainable as it lacks flexibility and long term thinking ([Jeffrey K, 2010](#)). The shift to more sustainable society requires greater sophistication to manage waste. Solid waste management systems need to ensure human health and safety. According to [F.R. McDougall et al. \(2001\)](#), a sustainable system for solid waste management must be *environmentally effective, economically affordable* and *socially acceptable*.

*Environmental effectiveness* the waste management system must reduce as much as possible the environmental burdens of waste management (emissions to land, air and water, such as CO<sub>2</sub>, CH<sub>4</sub>, SO<sub>x</sub>, NO<sub>x</sub>, BOD, COD and heavy metals).

*Economic affordability*: the waste management system must also operate at a cost acceptable to the community, which includes all private citizens, businesses and government. The costs of operating an effective solid waste system will depend on existing local infrastructure, but ideally should be little or no more than existing waste management costs.



***Social acceptance:*** the waste management system must operate in a manner that is acceptable for the majority of people in the community. This is likely to require an extensive dialogue with many different groups to inform and educate, develop trust and gain support.

Achieving sustainable goals involves balancing social, economic and environmental perspectives is difficult, and possible conflicts of objectives related to the three pillars of sustainability would be inevitable. There will always need a trade-off. It is necessary to acknowledge and deal with these conflicting objectives across domain boundaries in the diverse spectrum of project with system thinking.

### ***2.1.2 System analysis approach to Waste Management***

Sustainable waste management is a complex tasks that requires appropriate technical solutions, sufficient organizational capacity, managerial capacity of government as well as agreement and cooperation of various stakeholders ([Zarate et al., 2008](#)). According to [Marshall et al.](#) SWM in developing countries requires an approach that can handle complexity due to the interaction and complexity between the physical components of the system and the conceptual components that include the social and environmental spheres ([Jeffrey K, 2010](#)). Moreover, the conventional reductionist approach divides interacting system and their elements into smaller parts that could not tailor to handle complexity.

The system approach developed out of an attempt to unify science. A system approach handles the complexity more efficiently, particularly at the nexus of eco-social systems, could contribute substantially to solid waste management research and decision making in developing countries ([Jeffrey K, 2010](#)).

System analysis has provided unique, interdisciplinary support for SWM policy analysis and decision making over the last few decades. [N.-B. Chang et al. \(2011\)](#) highlighted 14 of classified tools and methods, in two domains including system engineering methods and system assessment tools to illustrate the SWM challenges, trends and perspectives.

***(1) The system engineering methods*** includes cost-benefit analysis (CBA) or benefit-cost analysis (BCA), forecasting model (FM), simulation model (SM), optimization model (OM), Multi-criterion decision making (MCDM) and intergrated modeling system (IMS).

***(2) The system assessment tools*** consist management information system (MIS), decision support systems (DSS), expert system (ES), scenario development (SD), material

flow analysis (MFA), life cycle assessment (LCA) or life cycle inventory (LCI), risk assessment (RA), environmental impact assessment (EIA), and strategic environmental assessment (SEA), socio-economic assessment (SoEA), and sustainable assessment (SA).

The integration of these systems analysis techniques plays an important role in SWM system because these alternatives help to tackle challenges for cost-benefit-risks trade-offs through a wide range of comparative analysis ([N.-B. Chang et al., 2015](#)).

### **2.1.3 Multi criteria decision making models**

MCDM was a discipline aimed at supporting decision makers and stakeholders deal with numerous conflicting objectives and contradictory impact factors. The method was used to reach optimal and compromise solutions and improve the quality of made decision by satisfying multiple criteria. MCDM include multi attributes and multiple objectives, which are known as multi attributes decision making (MADM) and multi objective decision making (MODM) in decision science. MADM issues are based on classical decision analysis to conduct trade-offs among a finite number of alternatives with respect to a set of attributes of the system such as cost, risks or emission. MADM is applied as a caliber for decision makers to choose among different alternatives, meanwhile, MODM is applied to problems with multi conflicting objectives to identify a feasible alternative that yields the most satisfactory set of values for the objective functions ([N.-B. Chang et al., 2015](#)). MODM is not applied to problems with predetermined alternatives, rather than selects the feasible space of solution by considering the various interactions between constraints and objectives, which then used to determine a compromised and optimal solution.

Previous studies applied MODM model in waste management, [N.-B. Chang et al. \(1996\)](#) developed a MODM model for reasoning the potential conflict between environmental and economic goals and for evaluating sustainable strategies for waste management in a metropolitan region; [Costi et al. \(2004\)](#) proposed a MODM model that aims at presenting the structure and the application of a decision support system (DSS) designed to help decision makers of a municipality in the development of incineration, disposal, treatment and recycling integrated programs; and [Harijani et al. \(2017\)](#) develop a multi-objective mixed integer linear programming model in which the economic, environmental and social dimensions of sustainability are concurrently balanced for sustainable recycling of MSW.

However, most of the MCDM models developed for SWM have serve drawbacks as pointed out by [Morrissey et al. \(2004\)](#) and [N.-B. Chang et al. \(2011\)](#). Firstly, the models have limitations in consideration the complete waste management cycle, from the generation of waste through to final disposal. Most are only concerned with refining the actual multi-criteria technique itself. In addition, most of models considered economic and environmental aspects, but very few of them considered social aspects for a sustainable SWM which requires all three aspects. The non-involvement of the people who generate the waste, (i.e. the general public) in a meaningful way in the decision making process is a major shortcoming of these models and as a result, it is contended that none of the models can be considered to be fully sustainable. Another identified weakness of the current models, is that no model identified considers the involvement of all relevant stakeholders, namely the government, the local authorities, the technical experts and the community.

## 2.2 MSW characterization

### 2.2.1 Waste composition analysis

Data describing the actual waste flow is basic input in discussions on any of waste management aspects such as technical design of collection system, environmental objectives, operating costs, types of recycling material economic incentives, information strategies, etc. Therefore, reliable waste generation and composition data are useful ([Dahlén et al., 2008](#)). The quality of waste composition data are highly affected by the sampling procedure and method applied ([Petersen et al., 2004](#)). Therefore, the absence of international standards for solid waste characterization has led to a variety of sampling and sorting approaches, making a comparison of results between studies challenging ([Dahlén et al., 2008](#); [Edjabou et al., 2015](#)).

There are basically two approaches for analyzing waste stream composition: *The material flow approach* and *the output approach*. *The material flow approach* looks at the production and the life cycle of the product to estimate the composition of the solid waste stream. It more applicable to large scale study and geographical area like the entire country, rather than local studies ([McCauley-Bell et al., 1997](#)). An advantage of the material flow is the broad geographical scope for which the solid waste stream can be estimated. However, a fact of this method is that the focus is on product categories, which is not waste stream categories and it can exclude some significant waste components because its generation is out of product sector.

*The output approach*, on the other hand, focus on components of the waste stream and can provide information regarding the waste composition, generation prior to separation or disposal. *Direct sampling at the source* and *Vehicle load sampling* are the most popular waste composition sampling method of *the output approach* for determining the composition of the MSW ([McCauley-Bell et al., 1997](#); [Tchobanoglous et al., 1993](#)). The former method can provide the waste information related to specific waste producers or waste data to be associated with the specific area, while the latter is more about giving the general data of waste composition and hardly to attribute accurately to the geographical areas or types of generation sources.

*Vehicle load sampling method* is often carried out by sampling the waste received at transfer stations, landfill sites or at treatment facilities ([N.-B. Chang et al., 2008](#); [Wagland et al., 2012](#)). The most advantage of this method is to be enable to reduce the amount of samples and less efforts for samples collection. Nevertheless, beside the drawback of not presenting the generation source’s characteristics, the variation of waste composition and generation is significant. Weight, fraction and characteristic of waste could be changed due to the compaction mechanism on most of modern collection vehicles. For instance, waste fractions sampled from such compact vehicles have been considerably difficult in distinguishing individual material fractions during manual due to the effect of mechanical stress and blending. Water lost and cross-contamination between individual fractions may occur, leading to further inaccuracies, error or variation of the study’s results.

Table 2. 1. Method for waste composition analysis

Method description	No. Categories recommendation	Reference	Applied
<b>Vehicle load sampling</b>			
The American Society for Testing and Materials (ASTM D5231 – 92): Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste	At least 13	( <a href="#">ASTM, 2003</a> )	( <a href="#">N.-B. Chang et al., 2008</a> ; <a href="#">Gidarakos et al., 2006</a> )
A methodology was modeled into a knowledge-based system to guide users and	12 – 52 with median of 28	( <a href="#">McCauley-Bell et al.,</a>	( <a href="#">Sharma et al., 2007</a> )

promote consistency in MSW composition studies in the state of Florida.	categories	<a href="#">1997</a> )	
The Nordic Innovation Center provided a standard method for sampling and characterization of municipal solid waste.	11 main categories	<a href="#">(Nordtest, 1995)</a>	In Sweden <a href="#">(Dahlén et al., 2008)</a>
<b>At source sampling</b>			
The Nordtest method also provide a guideline for sampling waste from household	11 main categories	<a href="#">(Nordtest, 1995)</a>	-
A method for stratified sampling of household waste based on socio-economic conditions	8 categories	<a href="#">(Mbande, 2003)</a>	<a href="#">(Mbande, 2003)</a>
A method for selecting sampling areas that takes account of geographical, waste management and socio-demographic factors to ensure that the individual samples taken are representative of their local area and the aggregated samples are representative of an entire region.	6 categories	<a href="#">(Burnley et al., 2007)</a>	<a href="#">(Burnley et al., 2007)</a>

*Collecting waste directly from individual households* or sources of waste generation has many advantages, it allows for the collection of personal data from each of the participating household or it allow the waste data to be associated with the specific source ([Dahlén et al., 2008](#)). Some previous studies conducted collecting waste from household sampling to compare the characteristics of waste from different types of sources such as single/multi-family ([S. Lebersorger et al., 2011](#); [S Lebersorger et al., 2003](#)), family incomes ([Bolaane et al., 2004](#)), etc. In addition, waste analysis at source can reduce the difficulties in degradable waste charaterisation analysis such as food and vegetable wastes, which may decompose quickly, contaminating the entire waste stream and making it difficult to characterize ([Dangi et al., 2008](#)). To ensure uniform coverage of the geographical area, stratified sampling which divide the study area into non-overlapping sub-areas with similar characteristics is often applied ([Dangi et al., 2011](#); [Philippe et al., 2009](#); [Sharma et al., 2007](#)). Table 2.1 describes some method for solid waste composition analysis applied for vehicle load sampling and at source sampling.

The limited studies conducted at the source of generation have faced difficulties using the correct statistical tools ([Dangi et al., 2008](#)). One of the common errors that can occur is the situation in which researchers equate the number of physical samples collected to the number of statistical samples, or samples required to obtain statistically meaningful results ([Bolaane et al., 2004](#)). On the other hand, the advantage of statistical tool was ignore in the study in Dublin, [Dennison et al. \(1996\)](#) reported a simple random sampling formula with post-stratification that gave 384.2 as the required statistical sample size and yet the authors utilized a large initial sample with 1500 total households. Moreover, the examination of normal distribution of collected data was also ignored in some studies. To apply appropriate statistical analysis technique, the type of data distribution is relatively important.

For number of waste categories, recommendation of various methods are varied widely. Most of methods suggest a small number of primary categories (main compositions) and a bigger number of secondary categories (sub-compositions) ([N. P. Thanh, 2010](#)). However, the number of waste categories applied in a study is often depended on the purpose of the particular study. For instance, a study for MSW management planning often use 9-12 primary categories but a Life Cycle Analysis (LCA) or Material Flow Analysis (MFA) study, will separate waste to more (up to 100) categories ([N. Thanh et al., 2012](#)). According to [Dahlén et al. \(2008\)](#), a number of waste composition of about 10, as far as possible based on the physical characteristics would limit the misunderstanding and reduce errors in sampling process. Also, limited waste categories will facilitate comparisons among studies, over temporal and spatial conditions.

### ***2.2.2 Prognosis waste generation modelling***

One of the challenges faced by local governments is the prognosis of solid waste quantities to have appropriate actions and plan ([Ghinea et al., 2016](#)). Apparently, Predicting waste generation is increasingly essential in waste collection planning, waste treatment strategies and establishing waste policies toward a sustainable waste management system ([Abbasi et al., 2012](#); [Chen et al., 2000](#); [N. P. Thanh et al., 2011](#)). Lack of research and method on waste generation estimation has led to a considerable challenge in municipal waste management in Viet Nam.

Various modelling techniques were applied to the development of solid waste generation predictive models. According to [Peter Beigl et al. \(2008\)](#), multivariate methods, such as

system dynamics and input-output analyses, are very complex due to the numerous interactions between parameters and the main problem of these methods is difficult to achieve model validations. Linear regression analysis, on the other hand, was more popular in the application of waste generation estimation ([Bach et al., 2004](#); [Peter Beigl et al., 2008](#); [Buenrostro et al., 2001](#); [Ghinea et al., 2016](#); [N. P. Thanh et al., 2010](#)). The term linear can give the casual observer the impression that linear models can only handle simple datasets. In fact, linear models can easily be expanded and modified to handle complex datasets in reality. Linear regression analysis is useful in empirical investigations and prediction rather than studying on the theoretical relationship between variables, which are better done by nonlinear regression analysis ([Faraway, 2005](#)).

Previous studies had modelled the total municipal waste generation using various variables and reported that municipal waste generation rate significantly correlated with economic factors. At regions and country level, [Hockett et al. \(1995\)](#) created a model of the demographic, economic and structural determinants of per capita waste generation. The study found that the per capita retail sales and tipping fees are the significant determinants of waste generation, and demographic variables were not significant as correlates of waste products. [Thøgersen \(1996\)](#), studied on data of 18 OECD countries, showed that GDP per capita (Gross Domestic Products) explained 50% variations of per capita waste generation ( $R^2 = 0.5$ ) based on simple linear regression analysis. Exponential and polynomial linear regression analysis in this research proved that there was a significant correlation between GDP per capita and waste produced per capital, and the coefficient of determination was slightly higher than simple linear regression. [Daskalopoulos et al. \(1998\)](#) provided predictive models for EU and USA for the total amount of waste arising annually with GDP and population acted as predictor variables in polynomial equations. Another research estimated MSW generation by multivariate linear regression model in consideration of the national gross domestic product per capita (GDP), the infant of mortality rate per 1000 births, the percentage of the population aged 15 to 59 years, the average household size and the life expectancy at birth as predictor variables ([P Beigl et al., 2004](#)).

In consideration of factors affecting to household waste generation, [Dennison et al. \(1996\)](#) and [Abu Qdais et al. \(1997\)](#) estimated waste generation rate per capita based on household size. [Abu Qdais et al. \(1997\)](#) reported that the correlation between waste

generation rate and the number of people in the family was weak ( $r=0.33$ ), but there was a strong relationship between the waste amount and annual rental rate ( $r=0.83$ ) which attributed to household income. As [Thøgersen \(1996\)](#), Abu Qadis and Dennison did not give any models to estimate per capita waste generation rate based on related factors. [S Lebersorger et al. \(2003\)](#) found that the correlation between the quantities of residual waste with the household type and age was significant in multi-family dwellings. A significant positive correlation was also found between the number of rooms and solid-waste generation in a study of [Monavari et al. \(2012\)](#).

Multivariate linear regression analysis was applied widely in waste generation forecasting research ([Grazhdani, 2016](#)). Also, the stepwise analysis normally is utilised to ensure that the final regression model provides the best fit ([Bdour et al., 2007](#); [Y. F. Chang et al., 2007](#); [Hamby, 1994](#); [S. Lebersorger et al., 2011](#); [Shamshiry et al., 2014](#)). However, the stepwise regression analysis was recommended not to use because it may not correctly determine the best variable set and tend to yield results that are not replicable ([Derksen et al., 1992](#); [Hamby, 1994](#); [Thompson, 1995](#)). In addition, the diagnostic checking to verify the statistical adequacy of the model was not carried out ([Bdour et al., 2007](#); [Karpūšenkaitė et al., 2016](#); [Shamshiry et al., 2014](#)) and model validation with a new dataset also got lack of attention ([Buenrostro et al., 2001](#); [Ghinea et al., 2016](#); [S. Lebersorger et al., 2011](#)). The two analysis above was essential to evaluate the reliability and performance of a linear regression model.

[Benítez et al. \(2008\)](#) developed a mathematical model to predict residential solid waste generation using simple linear and multivariate linear regression with continuous variables (household income) and discrete variables (education, household size). The result of this study showed that the model selected could explain 51% of the variation of waste generation rate, but used all predictor variables in the analysis. Apparently in multivariate linear regression models, the higher number of independent variables, the higher value of the coefficient of determination. Therefore, choosing the model based on the maximum coefficient of determination is not feasible options when dealing with a lot of independent variables.



Thus, providing a reliable model with appropriate diagnostic tests for the hypothesis of linear assumptions and a validation method is crucial for helping the decision and policy makers and related stakeholders in forecasting the quantity of waste from households.

## **2.3 MSW Optimization modeling**

### **2.3.1 Optimization models**

Optimization models are the core of the systems engineering modeling approach. Single objective models aim to seek for the optimal solution associated with a single objective and numerous technical, environmental, financial and managerial constraints. Normally, single objective model helps to solve the economic issues such as the cost minimization, maximizing total benefits and formulated by deterministic methods including linear programming ([Huang et al., 1992](#)), non-linear programming ([Costi et al., 2004](#); [Wu et al., 2006](#)), mixed-integer programming ([Badran et al., 2006](#); [Das et al., 2015](#)) or combination of them ([Fiorucci et al., 2003](#)).

Multi-objective programming (MOP) models were developed and widely applied to deal with the need of multiple objectives such as the minimization of total cost and maximization of recycled waste, or minimization of pollution emission at the same time in waste management studies. [N.-B. Chang et al. \(1996\)](#) developed a multi objective mixed integer programming model for reasoning the potential conflict between environmental and economic goals. [Minciardi et al. \(2008\)](#) developed a multi-objective optimization model for waste flows management based on the model proposed by [Costi et al. \(2004\)](#) to minimize cost, minimize emission, unrecycled waste and amount of waste to landfill with an interactive method to get decision makers involved in various step of decision process. [Cucchiella et al. \(2014\)](#) constructed a model to evaluate and quantify the effect of initiatives for diversion of current waste from landfill in Italy. Economics and financial indicators were used to define the profitability of waste facilities. The study proposed efficient waste to energy plant and regional strategies of waste management for optimizing financial and environmental benefit of the sector. [Vadenbo et al. \(2014\)](#) applied a sequential approach to estimate the minimum heat requirement for the diverse solutions obtained in the Pareto front using mixed integer linear programming formulation of the heat exchange problem.

### 2.3.2 Solving approaches

Variety of multi-objectives optimization model solving approaches were applied for searching optimal solution. Some well-known and most used methods are mentioned as following:

*Weight method* is a scalarization method and the most basic technique for solving multi-objective problems. It combines multiple objectives into one single objective scalar function by using weights for each single objectives. Mathematically, the method corresponds to minimizing (or maximizing) the weighted sum of all objective functions over the set of feasible decisions. The weighted sum will result in Pareto-optimal decision and to identify the weights of objectives, this technique needs an experienced people who know the problem, experts or a decision makers. Therefore, using weighted sum and experts, we can sometimes generated all Pareto-optimal solution and out-comes by changing weighting coefficients. Thus, it require a certain performance level from an optimization model, to set the weight for the objectives ([Lyeme et al., 2017](#)). Moreover, if the model is non-convex, the full Pareto front cannot be generated, thus limiting the advantage of the weighting method. Since, every problem has different settings and every model behaves in a different way, weighted method is not an appropriate method for solving the multi-objective problems. However, it is most common multi-objective optimization method implemented in waste management researches ([Ahluwalia et al., 2006](#); [Alumur et al., 2007](#); [Galante et al., 2010](#); [Zhang et al., 2005](#)).

*Goal programming method* help to specify what objective outcomes we would like to achieve. This method might work in a much more general setting than the method using of weighting coefficients, but it is more complicated mathematically. This approach is using the target levels or goals to form the feasible point, where a solution is considered as feasible if the deviations from that reference point is minimal. Apparently, a goal setting by the decision maker is a more intuitive approach since it correlates to the behavior of the problem under study. It is appropriate for the decision maker to capture the necessary elements of a problems and formulate there into goals and constraints. However, finding the optimal set of solutions can be tricky, since the distance from the goal can mislead the decision maker and can produce decisions that are not Pareto-optimal. Hence, additional assumption are necessary to have good results from the goal programming. For example, the target levels or goals are pessimistic to limiting the use of goals to objective values that are not highly

unrealistic ([Wierzbicki et al., 2000](#)) and restricting the area of optimal solutions ([Lyeme et al., 2017](#)).

Another approach for prioritization of the objectives is *Lexicographic method*, where the decision maker make an order of objective functions to be minimized. After the first objective is optimized, its value should be preserved and used as a constraint in the following objective function minimization. The process is terminated as soon as one of the programming problems results in a single solution. Not many studies use this solution method. A study of [Sudhir et al. \(1996\)](#) used lexicographic method to seek for the optimal solution of six objectives by comparing different priority order of the objectives.

### **2.3.3 Gaps in sustainable waste management optimization models**

Various optimization models for optimal solution in waste management were developed over the last decade. However, the environmental consideration in models still need to be improved. Single objective models is addressing the environmental issues in cost or as constraints. These are not sustainable for managing the environmental factors since they are not directly focused on the minimization of waste emission. Thus, the narrow scope of environmental factors as constraints in the current models mean that there is a need to go further and include new environmental metrics. Also, multi-objective optimization models are well addressed by presenting a decision variable for the selection of technologies rather than environmental impacts. Because environmental impact cannot only be considered only in incinerator emission ([Minciardi et al., 2008](#)) or only taking to account for GHG emission ([Govindan et al., 2014](#); [Mavrotas et al., 2015](#)) or CO<sub>2</sub> emission ([Wang et al., 2011](#)) but also should consider other technologies such as recycling, composting, AD, landfill, etc. and more pollutants emission. Moreover, the environmental issue should not be considered in the economic cost for sustainable SWM, it should be considered as independent entity in the modeling formulation and taking the holistic approach.

In addition, the social factors should be improved up since they are not well presented in previous models. Thus, the implementation of the objective function with social factors, or as parameters of DM in sustainable multi-objective optimization models is inevitable. The decision making process needs the involvement of waste generator (people who generated waste) in fullfill the meaning of sustainability. This issue should go together with upgrading

the environmental issues in the objective function to include new methods of solving multi-objective models.

## 2.4 Conclusions

One of difficulties in application of optimization model in SWM is to reflex the complexity of real system which requires a reliable database of waste characterization and intensive information as input data and parameters of the models. Waste generation and characterization analysis plays an important role for collecting input data in waste management modeling. However, within the literatures, there is still the lack of appropriate statistical analysis and test might affect the results of waste characterization studies. Moreover, the relevant factors of waste generation as well as the prognosis model expected to be useful for decision makers, researchers, stakeholders, recyclers for planning and improving the current status of waste collection and management. Nevertheless, studies is still lagged behind in Vietnam and the models' reliability and performance evaluation has gotten lack of attention.

System analysis approach and MOP model is a useful tool in decision science to support decision making in solid waste management. Most of models applied in waste management did not considered the waste management cycle, from waste generation to final disposal, except the LCA. Thus, the combination of LCA and LCI in optimization modeling of sustainable waste management can help to solve the weakness in analysis of waste cycle in OM models. In addition, it also enable the model to consider more kind of pollutants emission from all process and treatment facilities of waste management system. However, in this dissertation, the exact calculation of LCA or LCI is not the purpose of this work. Thus, in order to consider the environmental aspects and waste stream in the system, available data in the existing researches and the reliable scientific reports in LCI and LCA will be used as references for model parameters.

Lastly, few previous studies have considered public participation in the decision-making process. The public is only apprised or takes part in discussion, and has little effect on decision making in most research efforts ([Hung et al., 2007](#)). Especially, the non-involvement of the people who generate the waste, (i.e. the general public) in a meaningful way in the decision making process is a major shortcoming of these models. Thus, a method of modeling which can take into account the participation of all relevant stakeholders, authorities and

citizens is crucial for supporting decision making of a sustainable waste management system. This doctoral dissertation will develop optimization models with an appropriate approach that fully considering the environmental, economic and social factors to provide optimal solution of sustainable waste management in a case study in Viet Nam.

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### 3. METHODOLOGY AND PROPOSED CASE STUDY

#### 3.1 Methodology

##### 3.1.1 Waste generation and composition study

###### 3.1.1.1 Stratified random sampling method

The purpose of sample survey design is to maximize the amount of information for a given cost. Simple random sampling, the core sampling design, often provides useful estimates of population quantities at low cost. According to [Scheaffer et al. \(2011\)](#) stratified random sampling, which in many instances increases the amount of information for a given cost.

“A *stratified random sample* is one obtained by separating the population elements into nonoverlapping groups, called *strata*, and then selecting a simple random sample from each stratum” ([Scheaffer et al., 2011](#)).

The procedure of stratified random sampling method is presented as follows:

The first step in the selection of a stratified random sample is to specify the strata clearly, then each sampling unit of the population is placed into its appropriate stratum. For example, we suppose to stratify the sampling for household waste which is different between rural and urban areas. Hence, to specify what is meant by urban and rural is essential so that each sampling unit falls into only one stratum.

After the sampling areas have been divided into strata, we select a simple random sample from each stratum and the statistical sample size will be calculated based on the guideline in ([Nordtest, 1995](#)). We must be certain that the samples selected from the strata are independent. That is, different random sampling schemes should be used within each stratum so that the observations chosen in one stratum do not depend on those selected in another.

###### 3.1.1.2 Waste sample collection

To collect waste samples for waste generation and composition analysis, we applied door-to-door waste collecting method from every single household which was chosen as survey sample. The detailed procedure will be explained in section 4.

###### 3.1.1.3 Classification categories of solid waste

Most methods suggest a limited number of primary categories (also called principal components), and a large number of secondary, tertiary, etc. categories (subcomponents), which

are more or less applied depending on the purpose of a particular study. In addition, the statistical significance will decrease when the number of components increases, which is described above in the discussion about the number of sub-samples needed. The aim of this study is to provide detailed information on waste composition to support the development of sustainable waste management plan. Thus, in this study author will choose the number of main categories is 10 and the number of secondary categories is 18 according to the guideline in [Nordtest \(1995\)](#), based on physical appearance characteristics and usage purpose. The detailed information of categories will be described in the next chapter.

For component analyses, author chose the mother sample (the lot) from each stratum to cover consecutively 14 days, and the size of each analysed sample is more than 90 kg ([Sfeir et al., 1999](#)).

#### *3.1.1.4 Questionnaire survey*

A questionnaire survey was carried out with the face-to-face interview at the house of families involved to waste sampling program to obtain data reflecting to socioeconomic factors and demographic information of the household. This information will be used to evaluate the correlation of household waste generation with related factors and modelling prognosis waste generation model.

#### *3.1.1.5 Laboratory analysis*

In this study, physical characteristics of waste including specific weight, the moisture content will be analysed by [ASTM-E1109 \(2009\)](#) and [ASTM-E949 \(2004\)](#), respectively. The chemical elements and features such as volatile matter and ash content and energy content are analysed by ([ASTM-E897-88, 2004](#)) and ([E711-87, 2004](#)) standard. We used CHN analyser for analyzing the C, H and N content in waste samples. For each category such as Food, Garden, Plastic, Cardboard, Paper, Combustible and Hazardous waste several samples were collected randomly for analysis.

### **3.1.2 Mathematical modelling of waste generation**

The data obtained in the previous part of this study were interpreted to independent and dependent variables to modelling the waste generation model. A Bayesian Model Averaging is applied to identify the significant predictor variables for estimating waste generation. This

solution provides optimal predictive ability by involving averaging over all possible models ([Madigan et al., 1994](#)). Quantities of interest and parameter estimates are provided via direct application of the principles described as follows:

The posterior distribution given data  $Z$  of the quantity of interest  $\Delta$ , such as a model parameter or a future observable, is defined by Eq. 3.1.

$$p(\Delta | Z) = \sum_{k=1}^K pr(\Delta | M_k, Z)pr(M_k | Z) \quad (3.1)$$

Where,  $M_1, M_2, \dots, M_k$  are the models under consideration. Eqs. 3.2 and 3.3 give the posterior probability for model  $M_k$  and the integrated likelihood of  $M_k$  respectively.

$$pr(M_k | Z) = \frac{pr(Z | M_k)pr(M_k)}{\sum_{k=1}^K pr(Z | M_k)pr(M_k)} \quad (3.2)$$

$$pr(Z | M_k) = \int pr(Z | \theta_k, M_k)pr(\theta_k | M_k)d\theta_k \quad (3.3)$$

Where,  $\theta_k$  is the vector of parameters of model  $M_k$ ,  $pr(\theta_k | M_k)$  is the prior density of the parameters under the model,  $pr(D | \theta_k, M_k)$  is the likelihood, and  $pr(M_k)$  is the prior probability that  $M_k$  is the actual model. The BMA estimates a parameter  $\theta$  using Eq. 3.4.

$$\hat{\theta}_{BMA} = \sum_{k=1}^K \theta_k pr(M_k | Z) \quad (3.4)$$

The Bayesian information criterion (BIC) approximation is formally defined in Eq. 3.5. The BIC is used as a criterion for model selection from the set of models, and the model with the lowest BIC approximation is preferred.

$$BIC = -2. \log (RSS_p) + p.\log n \quad (3.5)$$

Where,

BIC: is Bayesian information criterion

$RSS_p$ : is square sum of residuals in fitting sample data to the model with  $p$  independent variables

$p$ : is the number of regressors including the intercept

$n$ : is the number of observation or equivalently, the sample size

Then, Multivariate linear regression analysis will be applied to develop the prognosis model of waste generation. The multivariate linear regression model is described as equation followed:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \varepsilon \quad (3.6)$$

Where  $\alpha$  is the intercept term which indicates the mean of the response variable  $Y$  when all predictor variable  $X$  is equal to 0;  $\beta$ , a vector of  $\beta_i$ , is the slope of the model, and it explains the average change in the dependent variable. The residual  $\varepsilon$  represents the difference between estimated values and observed values.  $\varepsilon$  may include measurement error although it is often due to the effect of unincluded or unmeasured variables ([Faraway, 2005](#); [Longnecker et al., 2001](#)).

### ***3.1.3 Single optimization model for evaluation of alternative waste management initiatives***

#### ***3.1.3.1 Single optimization model***

The most basic technique for solving OMs is a set of “mathematical programming”, a representative technique in the field of operational research. Each mathematical programming is based on a different mathematical structure that can only be applied to optimize a specific problem with unique properties. Solving these models should rely on well-defined algorithms designed to obtain the optimal solution in the problem domain. Four useful and popular methods in mathematical programming are Linear Programming (LP), Integer Programming (IP), Non-Linear Programming (NLP) and Dynamic Programming (DP).

The purpose of this study is proposed a model to describe the waste flow and cycle from the generation source to final disposal with the objective of minimizing total cost. Thus, the NLP is applied because there are nonlinear functions in the model for describing the waste flow. In general, a nonlinear OM can be written as follows:

$$\text{Min (Max): } Z = C.X$$

$$\text{Subject to: } A.X \geq, =, \leq B$$

$$X \geq 0$$

Where,

X: is a  $n \times 1$  column vector of decision variables including  $n$  elements  $X_1, X_2, \dots, X_n$

A: is a  $m \times n$  matrix of constants  $a_{11}, a_{12}, \dots, a_{1n}, \dots, a_{mn}$ , which can be negative or positive

B: is a  $m \times 1$  column vector of nonnegative constraints

C: is a  $1 \times n$  row vector of constants  $c_1, c_2, \dots, c_n$ , which can be negative or positive

The first equation is called objective function and the second and the third equation are called constraints. When the objective function and/or the constraints are a nonlinear function, the mathematical programming model is defined as a nonlinear programming model.

### *3.1.3.2 Analysis of waste management strategies alternatives*

To analyse the feasibility of alternative waste management strategies toward to economic concern, GHG emission reduction as well as pollution emission reduction. Classification scenarios categorized by waste-to-landfill reduction target and waste separation efficiency alternatives toward to minimizing total cost of the system. Thus, 12 single optimization model based on 12 scenarios chosen were solved for comparing total cost, total pollutant emission and GHG emission. The detailed of scenarios description is mentioned in section 6.

## **3.1.4 Multi-objective optimization model for MODM**

### *3.1.4.1 . Questionnaire survey*

Another simple questionnaire survey of local experts who play as authorities, waste managers, stakeholders, environmental scientists, citizen representatives is also conducted to obtain the idea of potential treatment technologies suitable for the socio-economic conditions of the city as well as the important objectives and requirements of different decision makers. The results of this survey will contribute to optimization model modelling. In this study, 20 local experts were interviewed for the analysis.

### *3.1.4.2 . Multi-objective optimization model*

The use of a single objective optimization approach has been recently recognized to limit the applicability of mathematical programming models, and many multi-objective situations exist in real-world systems. Thus, multi-objective is developed to fulfil the complicated problem in

reality. The complexity in MODM, some objectives permit a precise performance measurement, such as economics, but others do not, such as aesthetics and convenience. To solve these problems, information gathering, identification of achievable objectives, and the model building should be addressed as a whole to bridge the gaps between real world problems and mathematical programming models. The challenge is to adequately identify the actual objectives by choosing not only the appropriate criteria but also the fair number of targets.

A MODM with  $k$  objective  $Z(x)$  and  $n$  decision variables  $x_j$  ( $j \in [1;n]$ ) and  $m$  constraints  $g_i(x)$  can be defined mathematically in a vector notation as

$$\text{Maximize (Minimize) } Z(x) = [Z_1(x), Z_2(x), Z_3(x), \dots, Z_k(x)],$$

$$\text{Subjects to: } g(x) \leq 0$$

$$x \geq 0.$$

However, determining the set of alternatives may require considerable effort, MODM problems normally reflect the following needs to identify the best policy for the public ([Chang et al., 2015](#)):

Multiple objectives with or without priority: much efforts have been made for the last decade to develop the model with objectives other than only economic considerations.

Multiple decision makers in a participatory process: The majority of the optimization methods presented in earlier times deal with a single decision maker, but real-world decision making frequently involves multiple decision makers, such as a variety of stakeholders. Behavioral and analytical models need to be developed that reflect different thinking and preferences at the various stages of decision making associated with MODM.

When more than one objective function is used in a system engineering problem, they often conflict. An increase in one may cause a decrease in the other and vice versa. Therefore, the optimum solution no longer remains unique, and simultaneously maximizing together all the conflict objectives is impossible. Optimality is thus replaced by the satisfying solution or compromise solution. Methodologies need to systematically guide the selection of a “compromise” or “satisficing” solution rather than a “best” solution.



The concept of Pareto optimality was first introduced within the framework of welfare economics by the Italian economist Vilfredo Prato. The decision is Pareto-optimal if we cannot improve one of the criteria outcomes without deteriorating other criteria outcomes. In more general cases, when we minimize some criteria, maximize others, or even do different things with other criteria (e.g., keep them close to prescribed values), we speak about efficient decisions and outcomes. Thus, the concept of efficiency just generalizes the concept of Pareto-optimality. Pareto-optimality is an essentially weaker concept than single criterion optimality. Pareto-optimality does not tell us which decisions to choose; it tells us only which decisions to avoid ([A. Wierzbicki et al., 2000](#)).

#### *3.1.4.3 Reference Point method for decision making*

The Reference Point Method and its interactive technique were firstly proposed by [A. P. Wierzbicki \(1982\)](#) and later successfully applied in engineering design, solving environmental management problems as well as other fields of decision support ([A. Wierzbicki et al., 2000](#)). Reference point methodology could be considered as a generalization of goal programming, aiming at using arbitrary (not only unrealistic) goals or reference objectives and obtaining only efficient outcomes, at the cost of avoiding norm minimization and replacing it by optimization of a more complicated function.

The main advantages of goal programming are related to the psychologically appealing idea that we can set a goal in objective space and try to come close to it. The basic disadvantage refers to the fact that this idea is mathematically inconsistent with the concept of Pareto-optimality or efficiency.

The RPM has been known as the most interactive analysis method of multiple criteria optimisation problems. The basic concept of the interactive scheme in RPM is as follows. The DM define their requirements regarding aspiration levels by giving a target value of each objective outcome. Based on the reference levels provided by the DM, a special scalarizing achievement function will be constructed, which tends to be maximised to generate an efficient solution to the multiple criteria problem. The DM will evaluate the computed efficient solution and compare with their aspiration level as well as the previous solution; the process allows the modification of reference points of the DM to have a new efficient solution if he/she does not

satisfy with the current ones. The advantage of The RPM over other interactive methods such as goal programming, weighted sum method is that the RPM always corresponds to a non-dominated point of the multi-objective problem and create a chance for many DMs can come to a good “compromise solution”. Meanwhile, the goal programming method can generate non-efficient solutions to the multiple objective problems. On the other hand, the weighted sum method and lexicographical method both are not proper procedures for reaching compromise solutions as the weighted sum is fully compensatory operator that does not encode the idea of balanced solutions ([Perny et al., 2010](#)).

### ***3.1.5 Statistical analysis and computer software***

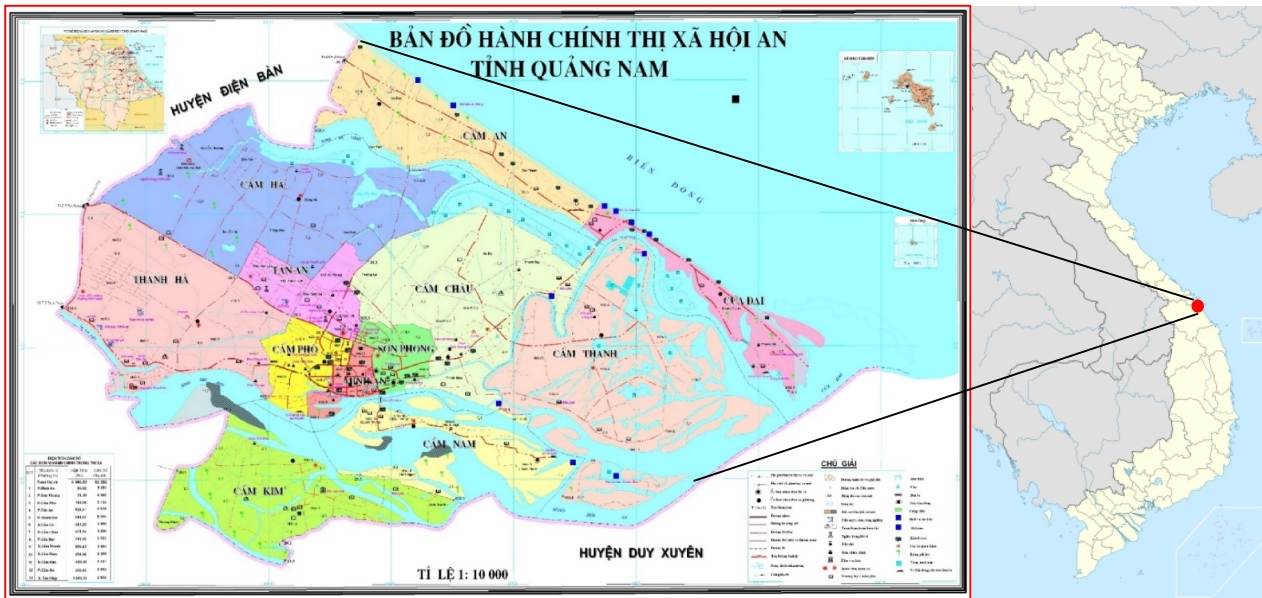
The author calculated key statistics of waste generation and composition and also used a variety of statistical analysis such as ANOVA analysis, linear regression, etc. The statistical software was applied is R software (ver 3.2.0) for statistical analysis and modelling waste generation, Microsoft Excel was used for manipulating input data.

The author also constructed and solved the optimization model by GAMS (General Algebraic Modeling System) software (version Win 64 24.7.4).

## **3.2 Case study in Hoi An, Viet Nam**

### ***3.2.1 General Introduction***

Hoi An is a city of Viet Nam, on the coast of the East Sea in the South Central Coast region of Vietnam. It is located in Quang Nam Province, and it is recognized as a World Heritage Site by UNESCO. Hoi An city has a natural land area of 6,171.25 ha with the total population of the city in 2013 is around 93 thousand and the number population density of 1,508 people/km<sup>2</sup>. Hoi An city comprises 13 administrative wards including an island ward is Tan Hiep island). Therefore, Hoi An city is a unique urban in Vietnam which including many types of urban including urban, suburban and rural places especially it is a famous touristic city (Hoi An ancient town), that can lead to great differences in waste generation from different locations. Also, there are around 1,5 million of tourists coming annually to Hoi An, so the amount of commercial and tourist waste generated is enormous and increase gradually.



(source: Hoi An People committee)

Figure 3.1. The location and general map of Hoi An city

The number of tourists visiting Hoi An city (HAC) has increased over the last decade, and its economy has developed tremendously. Rapid urbanisation and tourism development in Hoi An have led to a considerable increase in municipal solid waste. Like many other cities in Vietnam, the social, economic and environmental impacts of this rising waste generation are acquiring significant attention from the society. In general, MSW in Hoi An is currently disposed of at an open dumping landfills without taking any precautions or any operational control. Besides, one composting plant with a capacity of 55 tonnes per day has been operating inefficiently, and the product was not well sold in the market. The opened dump landfill and the composting plant have caused huge adverse effects on the environment and public health.

Tourism is the most dynamic industry and the biggest economic contributor of the city. In 2013, the total income of tourist service and retail sales (from restaurants only) was 1.500 and 1.100 billion VND respectively. Meanwhile, the total industrial production value of the city was only 212 billion VND ([HASD, 2013](#)). Also, the MSW generation increases associated with the growth of the number of tourists (Figure 1). Thus, tourist industry might be the greatest contributor of municipal waste generation in HAC, and it has affected strongly by the variation of waste generation and composition. Hence, MSW management is one of the most important

issues of Hoi An and developing a sustainable municipal solid waste management system has become a necessity in the City.

There was a lack of previous studies on integrated municipal waste management of the city. [Chu \(2014\)](#) investigated on the co-operative model of waste management based on the cooperation of local residences, authorities, waste managers and stakeholders in two communities, Cam Ha and Cam Pho. The result of the study indicated that the awareness of residence and the efficiency of waste separation at source program had been increasing. However, the study also showed that 30% of communities had been affected by environmental pollution related to solid waste treatment and recycling activities; 13/44 communities reported that residences often complain about the collection system.

### 3.2.2 Current status of MSW management

#### 3.2.2.1 Waste generation

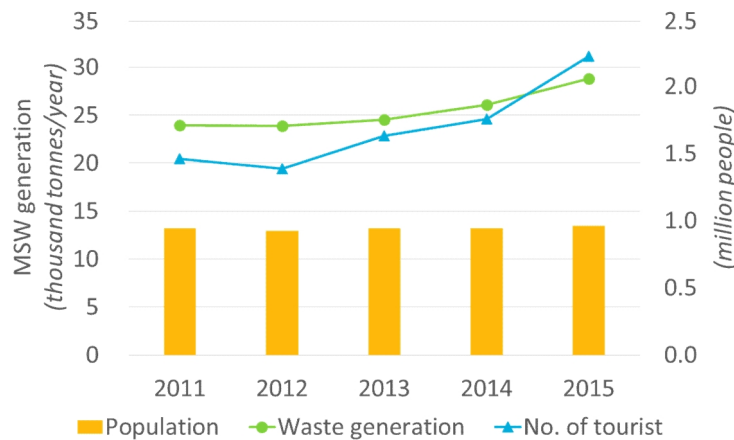


Figure 3.2. MSW generation in Hoi An

MSW generation in Hoi An has increased rapidly in the past few years from 24 thousand tonnes in 2011 to 29 thousand tonnes in 2015 ([HAPWS, 2014, 2015](#)). Besides, the tourist industry is considered one of the most dynamic industries and the greatest contributor to the economic development of the city ([Hoang, Fujiwara, et al., 2016b](#)). Tourist development has led to significant influences to the environment with respects to resource consumption as well as pollution generation including solid waste generation ([Denafas et al., 2014](#); [Espinosa Lloréns et al., 2008](#); [Shamshiry et al., 2011](#); [Teh et al., 2007](#)).

In Hoi An city, one of the major impacts of tourism is the changing in generation rate and composition of MSW. Figure 3.2 presented the amount of municipal waste generation associated with population and tourism development of the city from 2011 to 2015. There was a sharp increase in MSW generation in the last two years from 26 to 29 thousand tonnes, accounted for approximately 13% of rising rate. This might be due to the steep increase in the number of tourists came to the city from 1.75 million in 2014 to 2.25 million tourists in 2015.

Hoi A public work service Co. Ltd (HAPWSC) recently has been carrying out a waste monitoring program to investigate the waste composition of the city. The program used sampling from a vehicles method to analyse waste of collection trucks from each ward. According to HAPWSC, in 2014 the average daily waste generated is 0.481 kg per capita, the total average amount of waste generated is about 43,4 tons daily (Figure 3.3).

Minh An and Tan An ward are the two wards have the highest daily waste generation per capita at above 0.7 kg per capita. On the other hand, Cam Thanh and Cam Kim was the lowest source at around 0.1 kg per capita daily. Other wards are generating about 0.5 kg per capita daily.

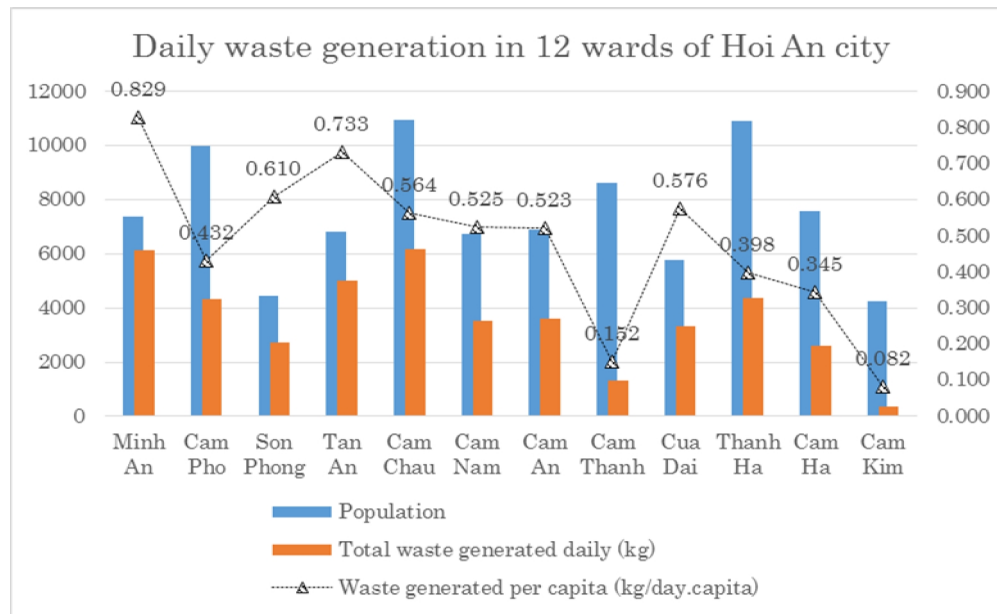


Figure 3.3. Daily waste generation rate in Hoi An city (recorded in 2014)

### 3.2.2.2 Waste collection and transportation

MSW collection in Hoi An city is operated by Hoi An public work service JSC. MSW collection in Hoi An is similar to the most of the cities in Vietnam, which is carried out as a two-

tier system: primary and secondary collection. In the primary collection, waste is stored and transported from home to drop-off points, and the secondary collection involving storage and transporting waste from collection points to treatment and disposal facilities.

Kerbside collection has been used in Hoi An MSW collection system based on the location. The centre neighbourhoods are collected daily (Minh An, Cam Pho and Son Phong) or 6 days per week (Tan An). Meanwhile, in the suburban and rural areas, MSW was collected three times (Cua Dai, Cam An, Cam Nam, Thanh Ha, Cam Ha, Cam Chau, two times (Cam Thanh) and one time a week (Cam Kim) ([HAPWS, 2015](#)).

In the city centre, residences are reminded by the collection truck with music and voice to explain what kind of waste will be collected that day. This type of operation is not very popular in Vietnam. Using handcart to gather waste from houses is more popular in Vietnam, and it is applied in other areas of Hoi An city. The handcarts transport waste from household to collection points and waste will be transported to the disposal site by trucks.



Figure 3.4. Kerbside collection in the centre of Hoi An

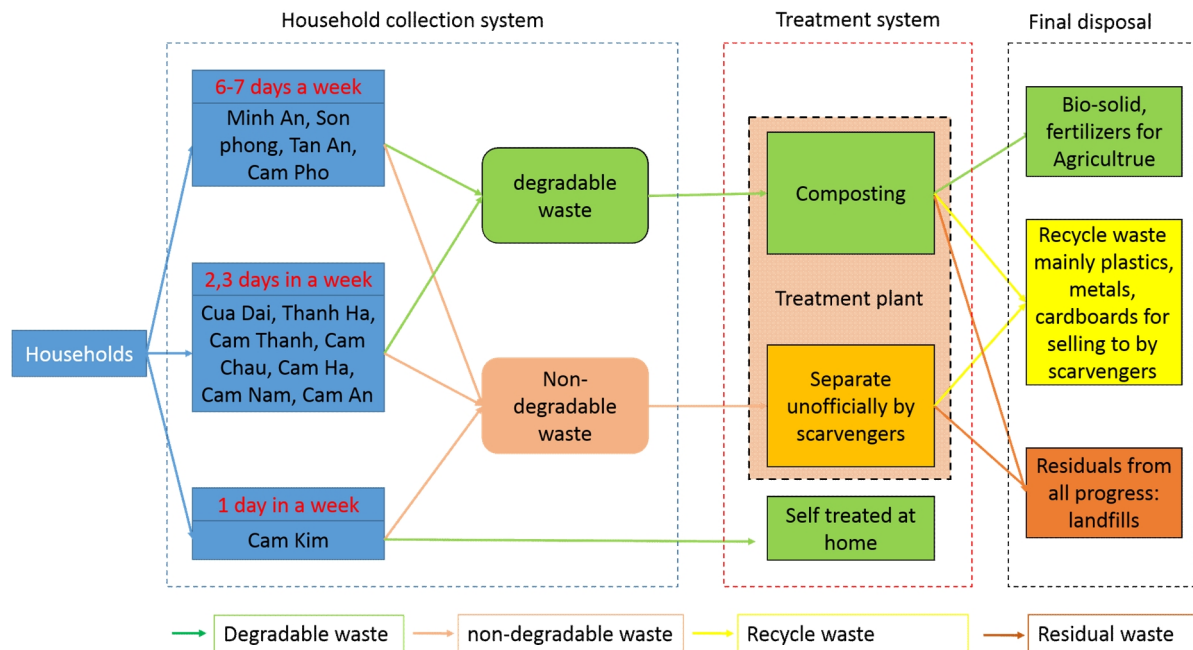


Figure 3.5. Current MSW management in Hoi An

Table 3.1. Waste collection schedule for Hoi An city

Wards	Frequency of Collection	Notes
Minh An	<b>7 days per week</b>	
Cam Pho	4 days for degradable	
Son Phong	3 days for non-degradable	
Cam Chau		
Tan An	<b>6 days per week</b> and 3 days each	
Cua Dai	<b>3 days a week</b>	
Cam An	2 days for degradable	
Cam Nam	1 day for nondegradable	
Thanh Ha		
Cam Ha		
Cam Chau		
Cam Thanh	<b>Twice a week</b> , 1 for each	
Cam Kim	<b>Once week</b> , only non-degradable	Degradable waste treated at home by household

### 3.2.2.3 *Waste separation and recycling:*

MSW in the city is composed of two groups of materials: Degradable (kitchen waste, garden waste, etc), and nondegradable (paper, plastic, metal, dust, textile, leather, etc) waste. At present, Hoi An is the first city in Vietnam successfully carried out waste separation at source. Degradable and nondegradable waste is separated and collected on different days in a week. A major difference in waste recycling activities between Vietnam and developed countries are collecting the recyclable materials.

In developed countries, such as Japan, recyclable waste is collected and transported separately by collecting company like other types of waste. On the other hand, in Hoi An, recyclables were not collected officially by the waste collectors but separated and collected by informal sectors such as scavengers and scrap collectors. Recyclable materials might be collected at the source via buying at the households or picking up at drop-off point by scavengers. Besides, there are many waste pickers, and scavengers work at the waste treatment plant to collect recyclable materials; that will be sold to a bigger buyer or recyclable centre afterwards, where waste will be separated and sold to factories as manufactured input materials.

There is few in the way of recycling initiatives of Hoi An waste managers and authorities; thus, recycling activities are carried out by “informal” sectors such as private companies, handicraft villages, and scavengers in all stages. The informal sectors have a significant contribution in recycling activities and provide a livelihood to many immigrants and marginalised people. Also, the free collection by scavengers is also expected to provide excellent segregation of MSW as they collect the recyclable materials from the streets, bins and disposal sites for their livelihood as well as avoid environmental costs and reduce capacity problems at dumping and landfill sites. In Hoi An, there are currently 17 private companies household buying of approximately 3.2 tonnes recyclable materials from scavengers per day ([Chu, 2014](#)).

However, Recycling technologies used by private companies and handicraft villages are still traditional and backwards, thus causing serious environmental pollution problems. Especially, some private businesses recycling waste is located inside the urban areas and thus potentially cause serious health impact problems.



#### 3.2.2.4 *Waste treatments and disposals*

In Vietnam, MSW is disposed of in landfills and 85% of which either without or with insufficient engineering standards. More than a half of MSW in Hoi An (approximately 40 tonnes per day) has dumped to an open-dumped landfill (Cam Ha landfill) in 2015. The landfill is not engineered and no way to meet required national standards with liners, drainage system, landfill gas control systems, leachate management system, and environmental monitoring system. Besides the official disposal sites, the city is also being suffered from the illegal disposal of waste in rivers, lakes, oceans, drainage channels, empty lots and roadsides.

Although there are many environmental pollution and operation problems associated with the disposal of MSW at open dumping sites, however, it appears that landfill might continue to be the most widely adopted practice in Hoi An in the coming few years. The reason for this problem is caused by ineffective operation of other treatment facilities such as a composting plant and an incinerator.

The composting plant with designed capacity of 55 tonnes per day has started operating since 2012. According to a report of Hoi An public work service Jsc The actual amount of degradable waste treated was average 35 tonnes with an average 4.1 tonnes (approximately 1500 tonnes per year) compost product per day ([HAPWS, 2014](#)). However, only 30% of fertiliser could be sold and given to forestry and agriculture. As a result., there was an accumulative amount of approximately 1.500 tonnes of fertiliser has been in stock in 2014.

Being known as a useful and cost-effective means for treatment of MSW in Vietnam but, the product value of MSW composting in Hoi An is not high at present. Although MSW is separated at source, there are reasons of unsuccessful composting plant in Hoi An such as inappropriate pre-treatment technology, inadequate monitoring of the quality and quantity of the compost being produced, and lack of attention to the market demand and to consumer feedback ([D. L. Nguyen et al., 2013](#); [T. K. T. Nguyen, 2014](#)). Moreover, the mix of food waste and garden waste in waste separation program also might be a reduce the quality of compost input materials due to the presence of dust, sands, twigs and inert materials, which contribute a major portion in garden waste in Hoi An.

The incinerator invested by the city committee has stopped operating since completely constructed and failed the operational test in 2015. The problem was not identified; it might be a result of the low quality of local technology or inappropriate study on MSW characteristics as well as cost-benefit of new technology.

### ***3.2.3 Challenges of current solid waste management***

During the last few years, the MSW quantity in Hoi An has been increasing significantly due to tourism development activities. As a consequence, the capacity of collection, transportation, treatment and disposal have become to be not sufficient. In addition, there is a significant increase in the expense required for the collection, treatment disposal and treating environmental pollution associated with MSW.

For instance, the investment for construction of transferring areas and the number of transport vehicles, as well as storage equipment in public locations, has not met the increasing demand for MSW. This leads to the less effectiveness of collection, separation at source as well as accumulation of MSW in residential areas causing the odour problem. Moreover, collection facilities and equipment has not met the technical standard and has not ensured the requirement for environmental sanitation. Although the expenses used for collection, transportation has been increasing but still not meet the requirement of the city development.

The recycle material activities have been contributing about 5% of MSW recycled ([Chu, 2014](#)), is carried out by informal sectors such as scavengers, recyclers and craft villages. Due to lack of recycling technology, incentive policies and legal enforcements, the efficiency of recycling activities is low, and it consists risks of pollution emission, disease exposures to the community.

Moreover, inappropriate management of MSW also caused the negative community health impacts. People living near the open dumping sites and unsanitary landfills are being exposed to the adverse impacts with the symptoms of the dermatological disease, respiratory diseases, and diarrhoea. The most vulnerable groups are scavengers on the site in which most of them are women ([D. L. Nguyen et al., 2013](#)).

The open-dumped landfill has been a serious problem in the city not only in term of environmental and community health impacts. Directly disposing of in an open site and poorly

managed manner have also caused social conflicts arisen between affected residence community, waste management company and city authorities. Due to the failure of new treatment plants such as composting and incinerators, residents have lost faith in waste managers and authorities. The resident's belief in waste separation at source programme might be lost since they could not see any improvement of the waste treatment practices and the environment. Lack of faith of citizens could lead to the other failures in authorities efforts to improve waste management system in the future.

Tourism has accounted for a significant amount of waste generation and has a strong effect on MSW generation in Hoi An city ([Hoang, Fujiwara, et al., 2016a](#); [Hoang, Nguyen, et al., 2016](#)). Furthermore, environmental pollution associated with MSW management have resulted in adverse effects on the tourism industry. Visibility of “mountain of waste” (open landfill), odour pollution from waste collection and treatment site, waste left over on the tourist street due to the weak of the collection system could leave the negative impression on tourists. The number of tourists visiting the city could decline due to environmental problems, impact on economic development.

The environment driver should be a major driver of waste management and disposal in Hoi An city due to following reasons:

- 1) a clean environment can preserve human health, which is the first objective as well as the indicator of the success of a waste management system;
- 2) environmental protection priority requires strong decisions from authorities, which might motivate other drivers such as institutional, economic and human drivers.

For instance, decline the amount of waste landfilled by having an appropriate treatment technology (such as incinerator) is essential to reduce contamination and environmental pollution. That requires significant investment in terms technology and equipment (economic drivers). Also, it encourages scientific research (institutional drivers) to develop local technology or tailor the technology transferred from developed countries according to local conditions. Lack of involvement of scientific research might be a reason for the failure of the current composting plant and incinerator in Hoi An. Residents might have lost faith in authorities and the local legislation due to the worsening of environmental conditions and vice versa (human drivers).

Another driver should be considered as a significant driver for Hoi An is institutional drivers including scientific research and legislation. Sustainable waste management is a long-term target which can balance the three targets: environmental effectiveness, economic affordability and social acceptance. Deciding the point of balance requires a comprehensive and precise research based on natural, geographical and socio-economic conditions of target city.

In addition, local legislation can change the way waste materials are managed or disposed of ([P. Agamuthu et al., 2009](#)). For example, in Hoi An, appropriate legislation to control waste from tourism sectors (from hotels, restaurants, tourist places, etc.) could encourage MSW reduction because of a significant contribution of waste from this area.

A decentralised treatment approach could benefit for degradable waste due to the failure of the centralised treatment facility and the small amount of waste generation in further areas. However, the approach needs to be studied carefully to have the applicable implications and appropriate legislation to encourage decentralised waste treatment. Education and awareness were implemented successfully in Hoi An and should be maintained and improved.

### **3.3 Research proposed for the case study**

Persistent increase in waste generation coupled with highly varied waste composition due to the impact of tourism has required a sustainable waste management in Hoi An city. It is not only to ensure environmental protection and public health risk prevention but also the incentive of tourism promotion and economic development. Several essential drivers being responsible for a sustainable waste management in developing countries were discussed in previous studies ([P. Agamuthu et al., 2007](#); [P. Agamuthu et al., 2009](#); [Wilson, 2007](#)). However, the groups of drivers work in different degrees in different times to affect the efficiency of a waste management, and sustainable waste management is a long-term objective. Therefore, choosing balance point of three factors: economic, environment and society in the first period of establishing a sustainable waste management system is increasingly important.

Therefore, in this dissertation, a systematic approach which includes critical stages of waste management planning is proposed to develop a sustainable waste management system.

The main objective of this study is to provide detailed information related to waste flow management and appropriate treatment technologies options based on optimization analysis to

support decision makers in the decision-making process to establish a sustainable waste management system for the city. To achieve this important purpose, the author also conducts various analysis which is crucial for waste management modelling and planning such as sampling and surveying, waste characterization analysis, waste generation modelling, optimization modelling, creating a framework for discussion of decision makers.

The reliable data of MSW generation and composition is necessary for developing waste management model as well as developing a 3R approach. Thus, the author will present the procedure of waste data collection and analysis thoroughly to obtain reliable information about waste generation rate and detailed composition which will be used as the input parameter of the waste management model. Figure 3.6 presents the objectives and content of waste data sampling and survey proposed

The author will evaluate the correlation between socioeconomic and demographic factors with waste generation to provide supporting information for improvement of waste collection and management system. The study will also develop a mathematical model for estimating household waste generation. Also, various theoretical tests, as well as validation technique, will be carried out for evaluating the performance of the model and choosing the “best” model for predicting waste generation.

In addition, the aim of this study will describe and assess the current status of waste management system, and identify the problems as well as discussing the solution. Thus, a single objective model of waste management system will be developed to minimizing cost and evaluating the initiatives of sustainable waste management. A comparative analysis of 12 scenarios with different waste to landfill target and waste separation efficiency initiatives will be conducted to assess the waste stream management strategies and treatment alternatives based on various aspects, such as GHG emission, energy generation/consumption, economic cost/benefit, and land use burden.

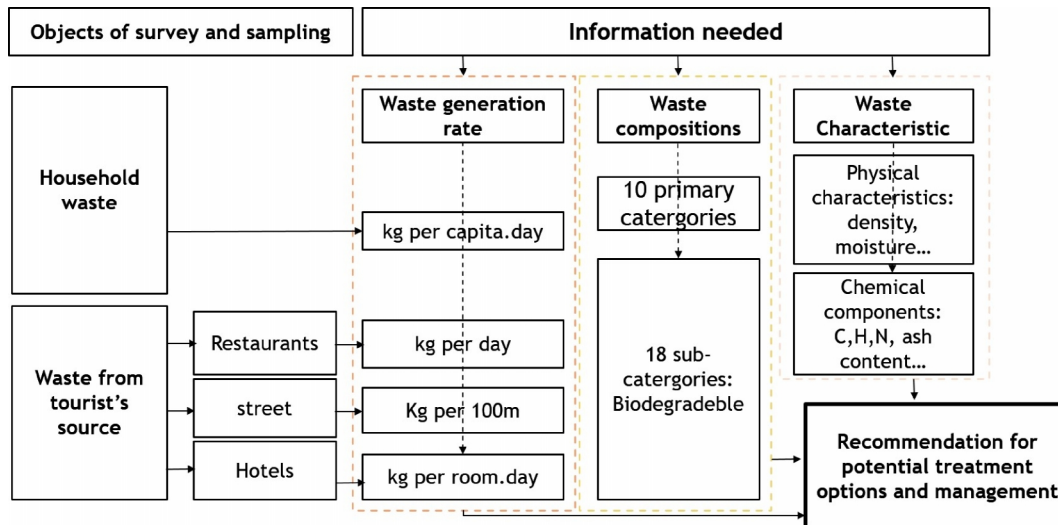


Figure 3.6. Targets and contents of waste data collection

It is a heavy task to identify the balance point of three aspects of sustainable waste management for decision makers. A multi-objective optimization model which considers minimizing pollutants emission, minimizing cost and waste-to-landfill will be developed for seeking a feasible optimal solution of waste stream management and treatment alternatives of sustainable waste management. The model proposed will overcome the limitation of previous models by directly calculate various pollutants emission and considering all technologies' emission such as composting, AD, landfill, etc.

Lastly, the social factors of sustainable management in the waste model will be improved in this study by the involvement of waste generators and stakeholders in the decision-making process. The reference point method is applied for solving the optimization model to get the optimal solution for sustainable waste management. A framework of procedures for different DMs work and discuss to get an agreement on a compromised solution for waste management is introduced.

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## 4. MUNICIPAL SOLID WASTE CHARACTERIZATION

### 4.1 Introduction

Rapid urbanisation and tourism development have led to significant increase in municipal solid waste (MSW) generation in Hoi An City (HAC), a famous tourism city the centre of Vietnam. Currently, improper disposal (an open-dumped landfill) and not effective treatment method (a composting plant) in the city have caused adverse impacts on all components of the environment and human health. Therefore, MSW management is one of the most significant environmental problems in Hoi An and developing a solid waste management system with material and energy recovery capabilities has become a necessity in the City.

It is clear that understanding the features of the waste stream is crucial for planning, design, and operation of a solid waste management (SWM) system ([Abu Qdais et al., 1997](#); [Chang et al., 2015](#)). To develop a waste management system and choose appropriate treatment technologies, accurate and reliable data on the waste composition and generation are needed ([Edjabou et al., 2015](#)). Also, understanding physical properties and chemical composition of MSW components is crucial in evaluating treatment options. However, physical, geographical, sociocultural, economic, and political factors may have influences on the composition and generation of municipal solid waste (MSW) ([Gallardo et al., 2014](#); [Gidaracos et al., 2006](#)). Especially, the tourism industry may lead to significant influences to the environment with respect to resource consumption as well as pollution generation. One of the major impacts of tourism is the change in generation rate and composition of MSW as well as household waste. Some previous studies have reported the increase in MSW in the tourist areas resulting from the high number of tourists during the tourism season ([Denafas et al., 2014](#); [Espinosa Lloréns et al., 2008](#); [Shamshiry et al., 2011](#); [Teh et al., 2007](#)). Thus, waste composition and waste generation rates can be different in places influenced by, and in those not influenced by tourism. Study on variations of waste characterization among various regions in a tourist city may be beneficial in planning a sustainable system.

Study on waste has still lagged behind where it concerns waste arising from tourism operations due to the near absence of reliable data on MSW management related to this sector

([Ezeah et al., 2015](#)). In HAC, there are no studies on waste characterization in the city; a waste composition monitoring program has been carried out recently, but there has been no information on waste generation and waste composition from different sectors. The tourism industry in HAC now is considered one of the most dynamic industries and the greatest contributor to the development of the city; hence, a study on waste characterization of household and tourism sectors from various geographical areas would have a great contribution to a sustainable MSW management system planning.

The aim of this study was to provide detail waste generation and composition to evaluate differences in waste characterization among different types of urban areas as well as between household and tourism, the two biggest sources of municipal solid waste in the city. Results of the study would play a major role in developing a sustainable system such as choosing appropriate treatment options, designing collection system, or operating solid waste management system in the city. We also provided an advantageous framework including sampling procedures and appropriate statistical analysis, as a reference that is readily applicable to small-scale cities in Vietnam.

## **4.2 Methodology**

### ***4.2.1 Research target areas and number of samples***

HAC comprises 13 administrative wards including an island ward that has its old waste management system. Thus, in this study, we focus on 12 neighbourhoods in the mainland. The City is a unique urban area in Vietnam, which consists of many types of areas including urban, rural places, and a famous tourist quarter (Hoi An ancient town). Therefore, in consideration of tourist factors affecting household waste generation, we divided the city into three strata (ST). ST1 is the Hoi An ancient town area including Minh An ward and part of Cam Pho Ward; ST2 comprises eight urban and suburban wards, and ST3 is a group of the other countryside wards (Tan Hiep island is excluded in this study). Figure 4.1 describes the three strata in this study; the ST1, ST2, and ST3 areas are represented by red, green, and blue, respectively.

The sampling strategy adopted in this study is stratified random sampling to reduce variations in household waste. We can apply the graph of Van der Broek and Kirov ([Van der Broek et al., 1971](#)) (Figure 4.2), which showed that the sampling ratio should be about 13

households per 1000 households to obtain a standard of error of 5% (Nordtest, 1995). The number of statistical samples was estimated based on the data of households number in each

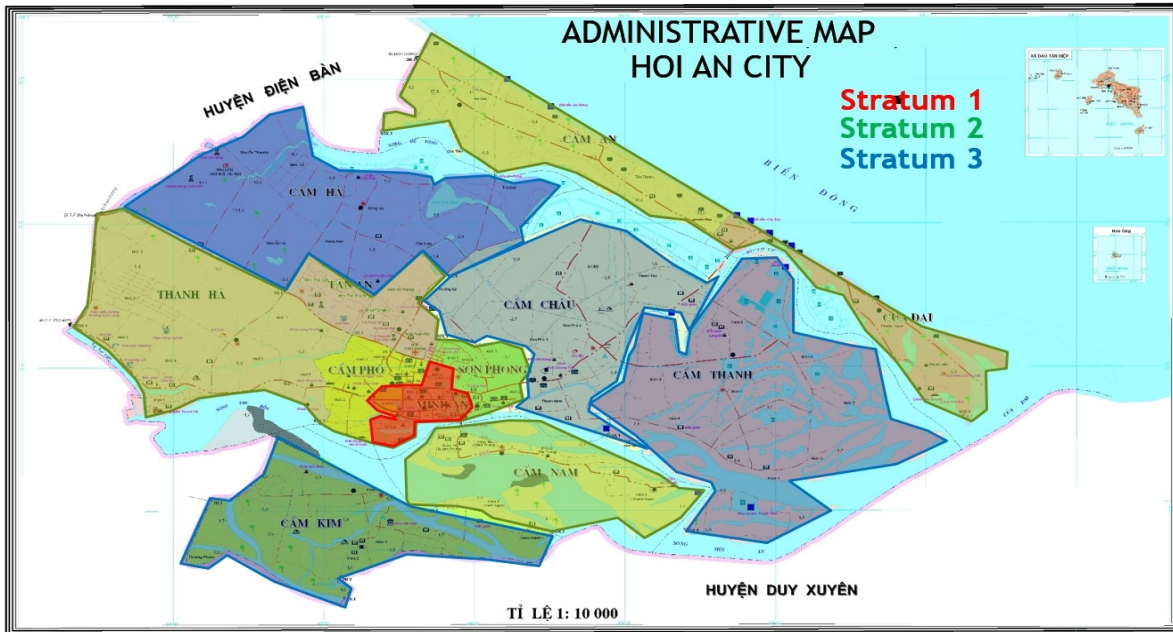
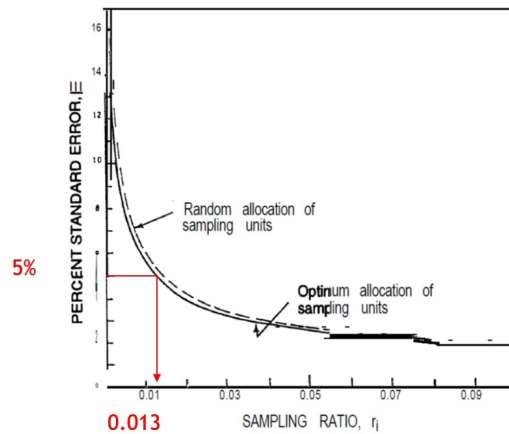


Figure 4.1. Target research areas.

ward from the Hoi An statistical yearbook 2013 (HASD, 2013). Households participating in the survey program were randomly chosen from each stratum by R software from the lists of households in three strata, gathered from the Hoi An Center for Population and Family Planning.



Source: (Nordtest, 1995)

Figure 4.2. Sampling ratio

To determine the waste characterization from various sources of the city, not only waste from households but also waste from tourist sources including hotels (HT), restaurants (RBC), and streets (STR) of tourist corners was chosen as targets of the study. The Hoi An Statistical Yearbook (2013) was used to identify and shortlist hotels and restaurants in the city, which would be chosen randomly as samples for waste quantity sampling. In Hoi An, there are several kinds of accommodations such as hotels, homestays, and guesthouses. Totally, nine types of accommodations for tourists including five hotels, three homestays and one guesthouse were selected randomly.

Table 4.1. Numbers of statistical samples adopted in the survey program.

Code	Type of Sources	No. of households ( <a href="#">HASD, 2013</a> )	Number of samples (n)	
			Statistic required	Number of samples
ST1	Stratum 1	2.752	36	50
ST2	Stratum 2	14.394	185	187
ST3	Stratum 3	4.904	64	84
ST	Total households	22.530	285	321
HT	Hotels		-	9
RBC	Restaurants		-	6
STR	Streets		-	3

For selecting restaurants, as suggested by independent local experts and authorities, restaurants in Hoi An were sorted into two types based on their locations: in the city center and along the beach. Thus, three of each type were randomly chosen for the survey. Likewise, three walking streets in the Hoi An ancient quarter were selected to identify the amount of street waste generation and composition. In this study, we randomly chose nine hotels, six restaurants, and three walking streets in tourist corners for samples collection. The number of households, hotels, restaurants, and streets in the survey is described in Table 4.1.

#### **4.2.2 Sampling procedures**

The period of sampling was three weeks from August 2 to August 20, 2015. On the first week, we focused on training both students engaging in the sampling program and families selected as donors of household waste. The actual sampling time was 14 days from August 7 to August 20. Every day, we collected wastes in the morning from households, hotels, restaurants

and streets, then transported them to the waste treatment plant and separated them for composition analysis.

There were 25 students recruited from Danang College of Technology (DCT) in Vietnam. These students were trained and provided technical, safety guidelines, as well as personal protecting equipment such as rubber gloves, safety glasses, masks, and other equipment including plastic buckets, handkerchiefs, and record paper sheets. In the first stage, all groups went to visit every single household invited to participate in the program and collected basic information (e.g., number of household members). As a result, a total of 321 households agreed to participate in the survey of waste sampling collection. Total households for each stratum were 50 for Stratum 1, 187 for Stratum 2, and 84 for Stratum 3.

Each family had a single identified code including two parts: the first part consisted of three digits presenting the name of the stratum (ST1, ST2, ST3) and the second part was the number of household by numerical order starting from 1 in each stratum. Every single household participating in the program was assigned a code marker in front of the door to avoid collection mistakes. The procedures of collecting, marking and analysis waste samples is presented in the figure 4.3.



Figure 4.3. Waste sampling procedure

Waste sample collection was carried out from each selected household daily for two weeks from August 7th to August 20th. On the first day, not all waste samples were collected, while the second-day waste was collected completely but was later discarded to ensure that the waste to be analyzed had been generated in the last 24 hours. Every morning, collecting team members brought black plastic bags with the sample identification codes and transported the waste bags with household waste to the treatment plant to measure and record the weight.

Samples were separated few hours after being collected to minimize variations due to biological and chemical processes. On the first day of waste composition analysis, bags of household waste were randomly selected from those collected so that the total weight of the bags may be around 120 kg. Thus, 70 waste bags from 70 households were selected randomly as samples for composition analysis including 13 from Stratum 1, 36 from Stratum 2, and 21 of Stratum 3. Samples of household waste that had been chosen on the first day would be kept as samples for the whole survey period.

On the other hand, bags of hotels and restaurants waste were selected randomly for composition analysis every day due to the huge amount of waste collected daily from these two sources. There was an average of around 105 kg of household waste and 145 kg of waste from restaurants, hotels, and streets separated daily. Waste samples were separated into ten primary components presented in Table 4.2. In this study, the effects of seasonal variations in waste characteristics were not investigated.

Table 4.2 Categories of waste separation in samples

Primary components	Material
Food waste	Degradable food remnants
Yard waste	Leaves, residual from gardens, etc.
Plastic	Plastic bags, plastic bottles, PET bottles, or plastic packages, etc.
Cardboard	Cardboard, packing cardboard, cartons, milk and juice package
Paper	Newsprint, magazines, office paper, mixed paper, tickets
Metal	Metal packaging, non-packaging metal, aluminum, iron, ferrous metals, non-ferrous metals, etc.
Glass	Glass bottles, all kinds of glasses, etc.
Combustible	Textiles and leather, healthcare textiles, carpeting and mats, wood, bamboo, rubber, napkins, sanitary napkins, etc.
Incombustible	Inert materials and non-combustible materials, etc.
Hazardous waste	Battery, medical waste, electrical devices, etc.

### 4.2.3 Physical and chemical analysis

In this research, we analysed the waste characteristics including specific weight ([ASTM-E1109, 2009](#)), moisture content ([ASTM-E949, 2004](#)), volatile matter and ash content ([ASTM-E897-88, 2004](#)), energy content ([E711-87, 2004](#)) and chemical elements (C, H, N) (using CHN analyser). We collected 37 samples after composition analysis for laboratory analysis; the samples selected did not include non-combustible materials. For each category such as Food, Garden, Plastic, Cardboard, Paper, Combustible and Hazardous waste several samples were collected randomly for analysis.

Waste density was analysed right after waste composition analysis; waste samples were dried in the dryer for 48 hours (for moisture content analysis) then were taken to the laboratory for further analysis.

The energy content of municipal solid waste and C:N ratio of Food waste is measured, we assumed inorganic carbon of Food waste equals zero. The statistic calculation for the mean of the component and analysed values is calculated as ([ASTM-D5231-92, 2016](#)).

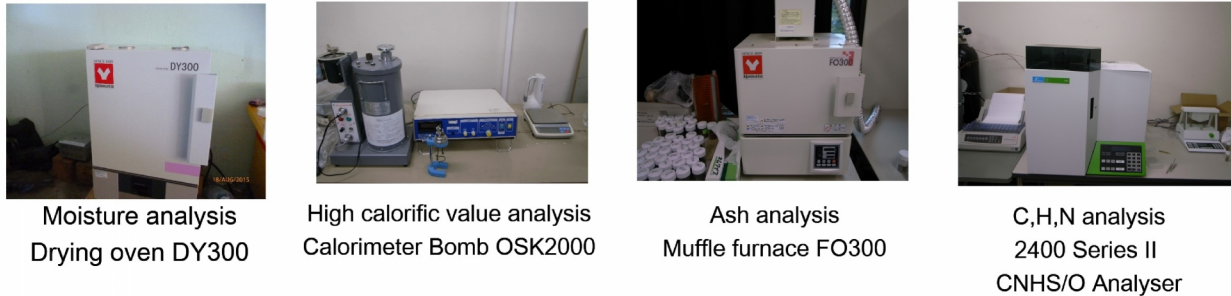


Figure 4.4 Physical and Chemical analysis

### 4.2.4 Statistical analysis

Daily waste generation of household  $j$  in strata  $i$  is expressed as  $w_{i,j}$ . Waste generation rate and its average in strata  $i$  are expressed in Eq (4.1) and Eq (4.2), respectively.

$$y_{i,j} = \frac{w_{i,j}}{h_{i,j}} \quad (4.1)$$

$$\bar{y}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} y_{i,j} \quad (4.2)$$

Where  $h_{i,j}$  is the number of people of the household  $j$  in stratum  $i$ ;  $y_{i,j}$  is the daily waste generation per capita of household  $j$  in stratum  $i$ ; and  $n_i$  is the number of sample households in stratum  $i$ .

In this study, we used geometric and standard deviation ([Tchobanoglous et al., 1993](#)) for statistical measures to describe the mean of waste generation and percentages of waste components. For stratified random sampling, population mean of waste generation and composition was unbiasedly estimated by a weighted average of means of strata ([Bolaane et al., 2004](#); [Scheaffer et al., 2011](#)), described by the following equation:

$$\bar{y}_{st} = \frac{1}{N} \sum_{i=1}^L n_i \bar{y}_i \quad (4.3)$$

$N$ ,  $L$  is the total number of households being surveyed and the number of strata, respectively.

Distribution of waste generation rate for each stratum is examined by using skewness and kurtosis. Skewness, expressed by Eq (4.4), is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. The skewness value can be positive or negative, or even undefined. Kurtosis, expressed by Eq (4.5), is a measure of whether the data are heavy-tailed or light-tailed about to a normal distribution.

$$S_i = \frac{1}{N_i} \sum_{j=1}^{N_i} \frac{(y_{i,j} - \bar{y}_i)^3}{s_i^3} \quad (4.4)$$

$$K_i = \frac{1}{N_i} \sum_{j=1}^{N_i} \frac{(y_{i,j} - \bar{y}_i)^4}{s_i^4} \quad (4.5)$$

Where  $s_i$  is a standard deviation of  $y_{i,j}$ .

An analysis of variance (ANOVA) was carried out to analyze the significant differences in mean waste generation rate and waste compositions among sources and geographical areas. The total waste generation data and quantity of waste types were entered into Microsoft Excel 2013 to estimate means of waste generation per capita (for households), per room (for hotels), and 100



meters (for street) and percentage of waste components. Results were transformed by taking the logarithm of their original values ([Bernache-Pérez et al., 2001](#); [Brown et al., 2002](#)) to approximately close to a Normal distribution. Then, they were used as input data for R software (ver 3.2.0) where ANOVA was tested. To compare between strata, a post-hoc analysis was applied with Turkey's Honest Significance Difference method ([Longnecker et al., 2001](#); [Tuán, 2014](#)) for pair comparisons.

During the time of survey program, waste collection from 30 households was not consistent. Therefore, we disregarded the data gathered from those families in the statistical analysis. As a consequence, data of 291 statistical samples for households were selected for analysis.

### 4.3 Result and discussion

#### 4.3.1 Municipal waste generation

##### 4.3.1.1 Household waste generation

The waste generation rate of each household was calculated by dividing the amount of waste produced in a day with the number of family members ([Dangi et al., 2011](#)). Figure 4.5 shows the results of statistical estimates and the boxplot of waste generation rate; red dots present the mean of waste generation rate of each stratum, and small black dots are outlier observations.

Waste generation of ST1 and ST2 ranged from 0.00 to 0.70 kg capita<sup>-1</sup> day<sup>-1</sup>, but ST3 took a lower range of 0.00 - 0.30 kg capita<sup>-1</sup> day<sup>-1</sup>. These results showed that waste generation of households from rural areas (ST3) varied less than from urban areas (ST1 and ST2).

Table 4.3 Means of waste generation and 95% confident interval.

Stratum	Waste generation rate (kg capita <sup>-1</sup> day <sup>-1</sup> )		
	Mean	Upper limit	Lower limit
ST1	0.203	0.046	0.900
ST2	0.264	0.085	0.823
ST3	0.120	0.024	0.604

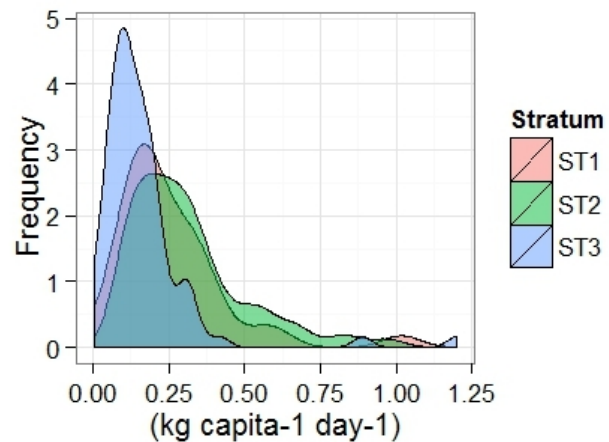
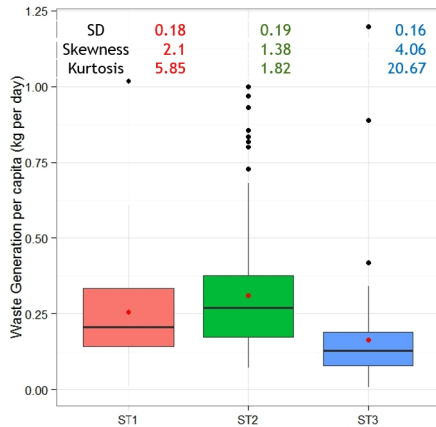


Figure 4.5 Boxplot of waste generation rate    Figure 4.6 Density of waste generation rate

Figure 4.6 shows the density of waste generation rate of each stratum. It was found that each waste generation distribution of the three strata positively skewed like a normal bell-shaped curve distorted to the left. According to [Tchobanoglous et al. \(1993\)](#), some degree of positive skewness is common in solid waste generation data. The ST3's distribution peaked because the coefficient of kurtosis was higher than the coefficient of kurtosis of the normal distribution, which was equal to 3 ([Bolaane et al., 2004](#); [Dangi et al., 2008](#); [Tchobanoglous et al., 1993](#)). Previous studies used mean estimates and standard deviation (SD) ([Bolaane et al., 2004](#); [Gomez et al., 2008](#); [Philippe et al., 2009](#); [Qu et al., 2009](#); [Thanh et al., 2010](#)) to describe the confidence interval of waste generation rate by tolerating the small amount of skewness to have Normal distribution ([Dangi et al., 2008](#)). However, in this study we used geometric mean and standard deviation for statistical estimates of waste generation rate ([Tchobanoglous et al., 1993](#)). The geometric mean of waste generation rate and 95% confidence interval are shown in Table 4.3. A person living in the countryside (ST3) generated half the amount of waste produced by a person living in the urban area. Among different waste generation studies at household level in Vietnam, the rate was estimated at 0.285 kg capita<sup>-1</sup> day<sup>-1</sup> in Can Tho City ([Thanh et al., 2010](#)) and 0.6 in Ho Chi My City, as reported by Tran et al. ([Tran et al., 2014](#)). Both cities mentioned above are bigger and more developed than Hoi An. Thanh et al. ([Thanh et al., 2010](#)) sampled from 100 households for both rainy and dry seasons then estimated the mean of two results. Tran et al. ([Tran et al., 2014](#)) meanwhile, combined the amount waste after household separation to estimate

the daily waste generation per household. This study assumed the average number of a family member was four to calculate waste generation per capita. Results of this study showed that the household waste generation rate in Hoi An was slightly lower compared to those in Can Tho city and Ho Chi Minh City. The overall mean of household waste generation rate was 0.223 kg capita<sup>-1</sup> day<sup>-1</sup> with average varying between 0.207 and 0.240 kg capita<sup>-1</sup> day<sup>-1</sup>. Thus, total household waste generation of the city was estimated at 20.75 tonnes per day.

Table 4.4 Results of variance analysis

Source	DOF <sup>1</sup>	SOS <sup>2</sup>	MS <sup>3</sup>	F <sup>4</sup>	P <sup>5</sup>
Between Strata	2	34.7	17.35	37.5	3.4.10 <sup>-15</sup>
Within Strata	288	133.3	0.46		

<sup>1</sup> Degree of freedom; <sup>2</sup> Sum of square; <sup>3</sup> Mean square; <sup>4</sup> F-value; <sup>5</sup> P-value

Figure 4.7 presents the post-hoc analysis results. Horizontal lines indicate the 95% confidence interval of differences of average waste generation between strata. If the 95% confidence interval line is not crossing the zero line, it meant waste generation rate was significantly different between two strata. The result showed that waste generation rate in ST3 was significantly different from those in ST1 and ST2. Thus, the waste generation rate from urban areas was double that from rural places, and the difference was statistically significant. The result of the study would be useful in the prediction of waste generation for a waste management planning program.

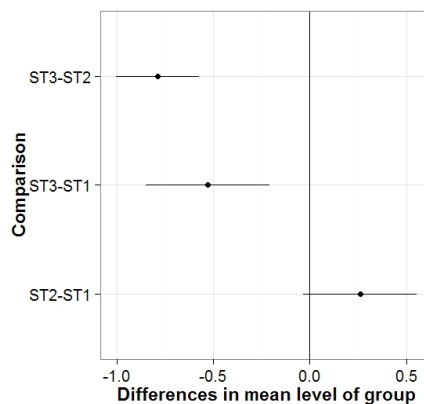


Figure 4.7 95% family-wise confidence level

Tourist area (ST1) produced less waste per capita than did the urban and suburban areas (ST2) as a result of this survey. Family business and involvement in tourism services of people living in the center (ST1) had significant impact on family lifestyle, such as reduced time at home, eating outside, or less time spent together with family members could be a reason for less waste produced. However, this difference was not statistically significant as shown in Figure 4.7.

According to the data of Hoi An Public Works Service Co. Ltd. (HAPWC) report regarding the daily waste amount, we estimated the average amount of city municipal waste transported to a treatment facility, which was about 70.13 tonnes day<sup>-1</sup>. Therefore, daily household waste generation accounted for approximately 30% of total municipal waste in Hoi An City. The results of ANOVA (Table 4) indicated that there were differences between waste generation rates among the three Strata (signals were much higher than noises), and the differences were statistically significant (p-value<0.05).

#### 4.3.1.2 Waste generation from tourism sectors

The estimated average waste generation from hotels was 1.22 kg room<sup>-1</sup> day<sup>-1</sup>. However, there was a significant difference between hotels with large capacity (four stars hotels in this study) and hotels with small capacity (three stars and two stars hotels and homestays).

As can be seen from Figure 5, high standards hotels generated about 4 kg room<sup>-1</sup> day<sup>-1</sup>; meanwhile, three stars and lower standard hotels produced about 0.35 kg room<sup>-1</sup> day<sup>-1</sup>. Chan and Lam([Chan et al., 2001](#)) reported that mean of waste generation from a room in midscale hotels (which included three and four stars hotels) in Hong Kong was 2.76 kg room<sup>-1</sup> day<sup>-1</sup> and from hotel restaurants were 0.75 kg per meal cover in 1996. The hotel waste generation rate tended to decrease as a result of Chan and Lam([Chan et al., 2001](#)) estimated model. However, waste from guest rooms and restaurants of hotels were studied separately in the research mentioned above.

The results of this study were significantly lower than those of [Trung et al. \(2005\)](#), who estimated waste generation rate by a questionnaire survey of 50 hotels in Vietnam. [Trung et al. \(2005\)](#) reported that two and three stars hotels generated 0.7 – 5.6 and 8.2 – 17.9 kg guest<sup>-1</sup> day<sup>-1</sup>, respectively while four stars hotels produced 13.5 – 32.3 kg guest<sup>-1</sup> day<sup>-1</sup>. [Byer et al. \(2006\)](#) meanwhile, indicated that the waste generation rate of two, three, and four stars hotels appeared identical from 0.4-0.5 kg guest<sup>-1</sup> day<sup>-1</sup>.

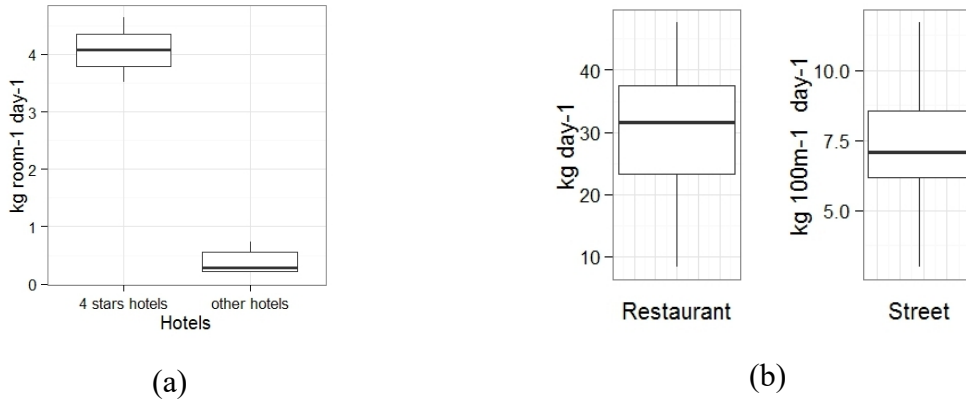


Figure 4.8 Boxplot of waste generation from tourism sector

Figure 4.9 describes the correlation between the number of hotel rooms and waste generation rate. The results of correlation analysis showed that the coefficient of correlation ( $r$ ) was 0.95, and it was statistically significant ( $p < 0.05$ ). The coefficient of determination was 0.91, which meant that 91% variations in waste generation rate could be explained by the number of hotel rooms.

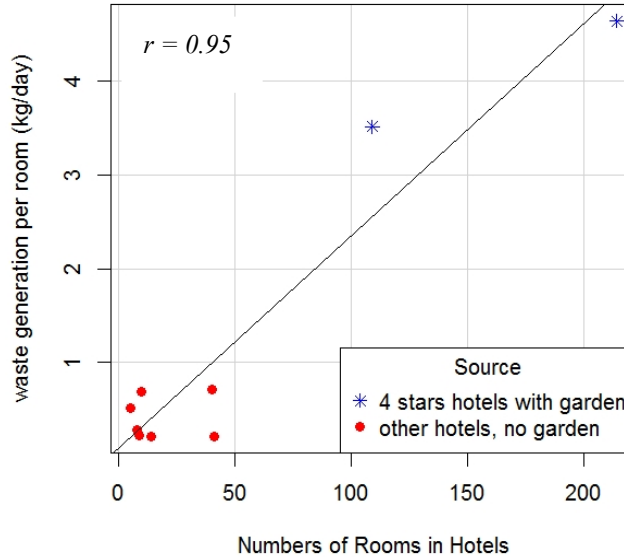


Figure 4.9 Correlation of mean of waste generation and number of hotel room

The average waste generation measured was 28.85 kg day<sup>-1</sup> from restaurants and 7.35 kg 100m<sup>-1</sup> day<sup>-1</sup> from street litter. On 95% Confidence interval, the means of waste generation rate from tourism sources were estimated as follows:

Hotels: 0.6 kg room<sup>-1</sup> day<sup>-1</sup>, range from 0.05 to 6.07.

Restaurants: 26.18 kg day<sup>-1</sup>, range from 7.68 to 89.30.

Streets: 6.99 kg 100m<sup>-1</sup> day<sup>-1</sup>, range from 3.56 to 13.67.

### **4.3.2 Municipal waste composition**

#### *4.3.2.1 Household waste composition*

The composition of household waste was made up of 38% food waste, 19% yard waste, 14% plastic, 15% combustible waste, and others including cardboards, paper, metals, glass, incombustible waste, and hazardous waste constituted less than 5% (Figure 4.10). The major components of household waste in Hoi An were food waste and yard trimmings (19%), which together constituted 57% of the total household waste. Metal and hazardous material were the smallest contributors to household waste stream.

Figure 4.11 provides the waste compositions of households from the individual stratum. In comparison between strata, the portion of food waste in ST1 was higher (at about 43.3% on average) but less garden waste (7.54%) than the other two strata. ST2 and ST3 had nearly similar percentages of food and garden waste of around 35% and 19%, respectively. The percentages for most of the categories of ST2, ST3 (Fig.8), and total household (Fig.7) were apparently identical. Meanwhile, ST1 (Fig.8) and Tourist (Fig.7) waste were similar in shape to a higher percentage of food and glass waste, though a lower proportion of garden waste. Thus, the household waste characterization was different between an area affected by tourism (ST1), and two areas less affected by tourism activities (ST2 and ST3). However, the results from ANOVA indicated that differences in waste composition were not statistically significant ( $p < 0.05$ ).

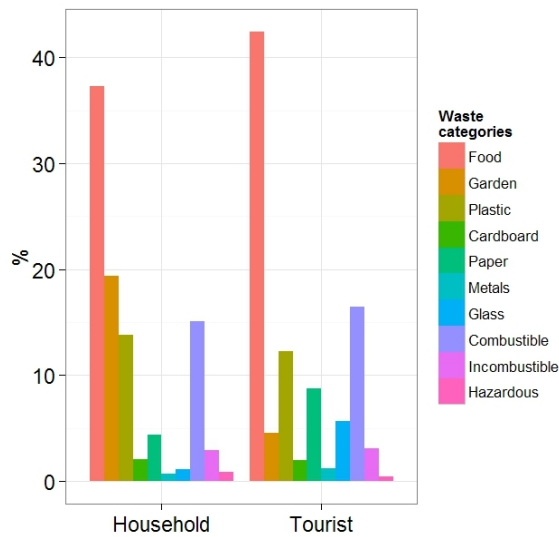


Figure 4.10 Waste composition of household and tourism sector.

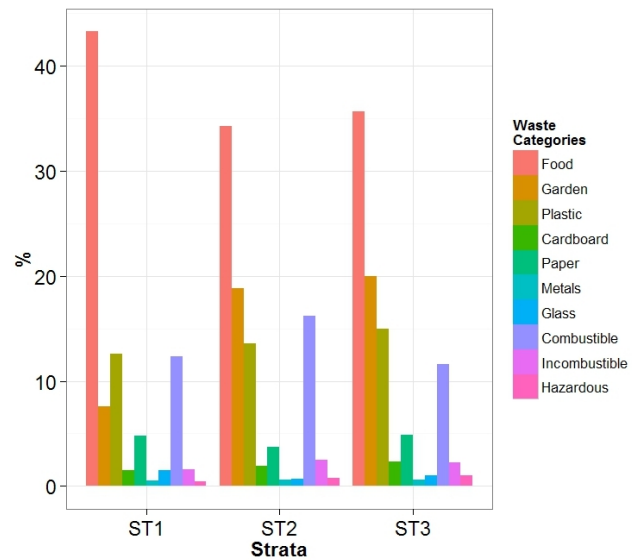


Figure 4.11 Household waste compositions of three strata.

#### 4.3.2.2 Tourism waste composition

The waste stream of tourism sources (including hotels, restaurants, and streets) was different compared to that of the household waste stream (Figure 4.10 and Table 4.5). The portion of food waste of tourism was slightly higher (42%) but the garden waste was significantly lower (4.5%) than that of household. Glass materials released from the tourism industry were far greater than those from households. It was understandable because tourism service activities produced huge amounts of glass, especially beverage bottles. Both household and tourism wastes had high portions of plastic and combustible materials (as explained in Table 4.2).

Table 4.5. shows the percentage of waste compositions from hotels, restaurants, and streets separately. All three sources of waste had a high portion of food waste. Activities of restaurants on streets and leftovers discharged by walking tourists could explain the high amount of food waste in street litter bins. Naturally, we found higher amount of glass waste such as discarded beer and wine bottles during the sampling period.

Table 4.5 Waste composition of different sources regarding tourism waste

Waste Compositions (%)	Hotel waste	Restaurant waste	Street waste
Food	49.0	39.5	39.4
Garden	7.2	6.4	1.4
Plastic	16.4	8.4	13.8
Cardboard	3.2	1.9	1.0
Paper	9.7	9.6	6.7
Metals	0.7	2.2	0.4
Glass	3.4	9.4	4.5
Combustible	8.6	15.3	31.8
Incombustible	0.7	7.0	0.8
Hazardous	1.0	0.3	0.2

Chan and Lam ([Chan et al., 2001](#)) declared that plastic toiletries constituted the highest portion (above 50%) of waste from hotel guest rooms. Byer et al.,([Byer et al., 2006](#)) indicated that compostable material (including food waste and yard waste) formed the largest portion of the hotel waste stream, accounting for approximately 60%-70%. It was slightly higher than the compostable material portion in this study.

#### 4.3.2.3 Municipal waste composition

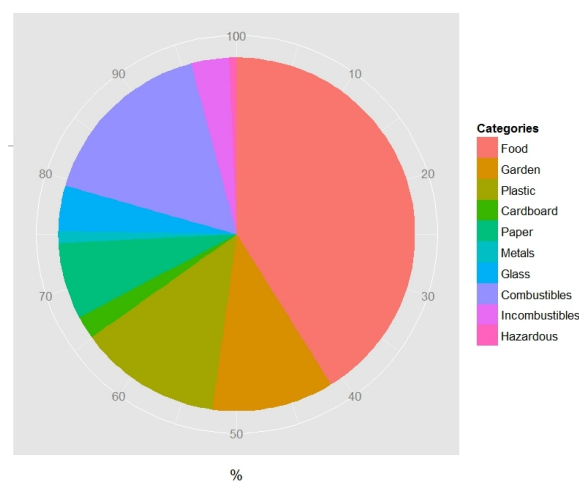


Figure 4.12 Municipal waste compositions



Figure 4.12 shows the municipal waste composition of the city, in which the largest proportion was food wastes (42%) and hazardous waste was the least portion (less than 1%). Garden waste, plastic, and combustible materials were significant contributors ranging from 12% to 16%. Other components were less than 10% of total waste. Similar values of total degradable waste were reported by Hoi An Public Works Service Co. Ltd. (HAPWC) in September 2015. However, the report indicated that the percentage of yard waste was much higher than that of food waste. Figure 4.12 presents the percentage of waste sub-categories

Studies for solid waste composition analysis implemented various approaches without common international standards. Therefore, it was difficult to compare results of different sampling and sorting methodologies (Dahlén et al., 2008; Edjabou et al., 2015). The portion of biodegradable waste (food waste and garden waste) was slightly lower than those in developing cities such as Beijing, China (69.3%) (Qu et al., 2009), Cape Haitian, Haiti (66.6%) (Philippe et al., 2009), Kathmandu, Nepal (71%), Can Tho, Vietnam (80%)(Thanh et al., 2010) and Da Nang City, Vietnam (68,5%)(MONRE, 2011). However, recyclable waste components such as plastics, cardboards, papers, and metals were approximately alike compared to the above studies. The difference could be caused by different lifestyles and dietary habits as well as differences in the effects of tourism industry between Hoi An and other cities. Combustible waste, on the other hand, was not investigated in the studies mentioned above, but it was one of the major components in municipal waste in HAC.

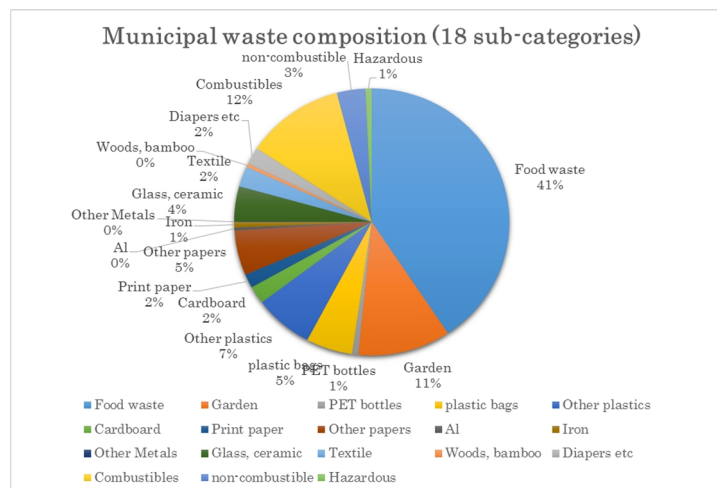


Figure 4.13 Hoi An MSW composition 18 sub-categories

### 4.3.3 Waste characteristics

The results of MSW density analysis are shown in Table 3. The mean specific weight of Hoi An MSW is 263 kg/m<sup>3</sup>. Household waste density is about 226 kg/m<sup>3</sup>, lower than Hotel, restaurant waste and street waste. Density of street waste is higher (317 kg/m<sup>3</sup>) than waste from other sources.

Table 4.6 Waste characterization in Hoi An city

Sources	Waste density (kg/m <sup>3</sup> )											Total
	Foo	Gar	Pla	Plb	Car	Pap	Met	Gla	Com	Int	Haz	
Household	343	118	29	55	712	88	231	208	154	527	176	226
Hotel, Restaurant	388	116	34	49	672	114	250	363	245	325	327	281
Street	377	91	31	57	613	99	600	811	315	921	1,050	317
<b>MSW</b>	<b>368</b>	<b>113</b>	<b>32</b>	<b>53</b>	<b>680</b>	<b>101</b>	<b>294</b>	<b>366</b>	<b>218</b>	<b>495</b>	<b>372</b>	<b>263</b>
<b>C:N ratio</b>	<b>21.5</b>	-	-	-	-	-	-	-	-	-	-	-

Foo: Food; Gar: Garden; Pla: Plastic; Plb: Plastic bag; Car: Cardboard; Pap: Mixed paper; Gla: Glas and Ceramic; Int: Inert material; Haz: Hazardous material

Figure 4.14 and Figure 4.15 present the results of MSW physical, chemical characteristics analysis and LHV measurement. The moisture of MSW is about 50%, Ash and Carbon content is approximately 10% and 40% approximately.

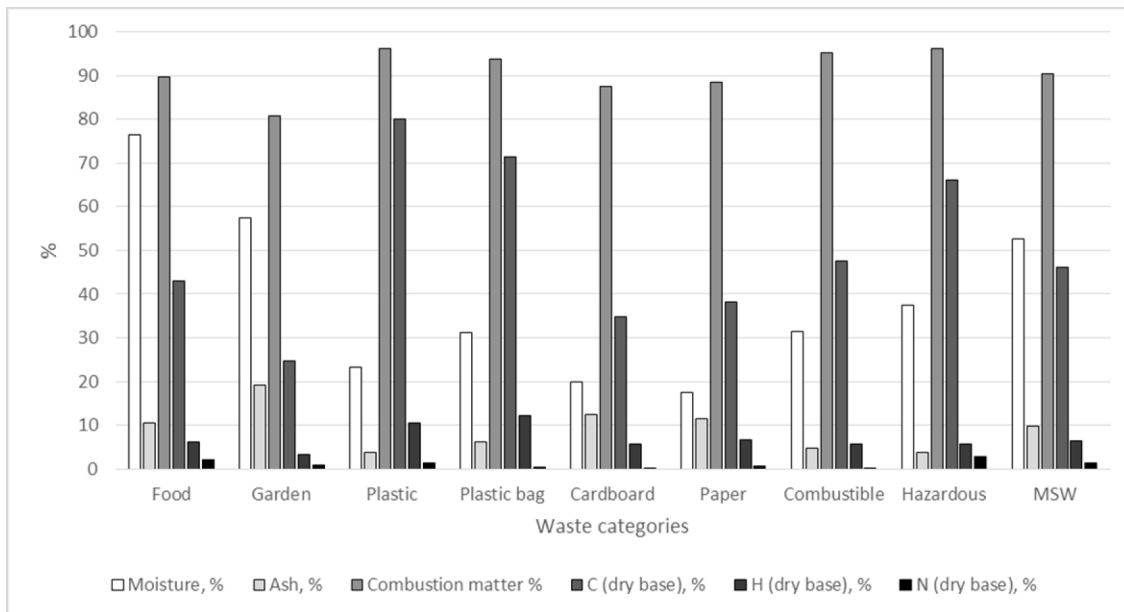


Figure 4.14 Physical and chemical characteristics of MSW in Hoi An city

The moisture content of MSW in Hoi An is about 53%. The high moisture content is caused by Food and Garden waste, which accounted for 40% and 10% in composition and the moisture content is 75% and 57% respectively. The high moisture will affect the thermal treatment of MSW but is essential for biological treatment technology. Also, the C:N ratio of biodegradable waste (Food and Garden waste) is 22.1, which is a good ratio for composting. However, since the composting plant in Hoi An has been operating ineffectively, a deeper study in socio-economical and technical efficient assessment might be needed to improve the treatment efficiency.

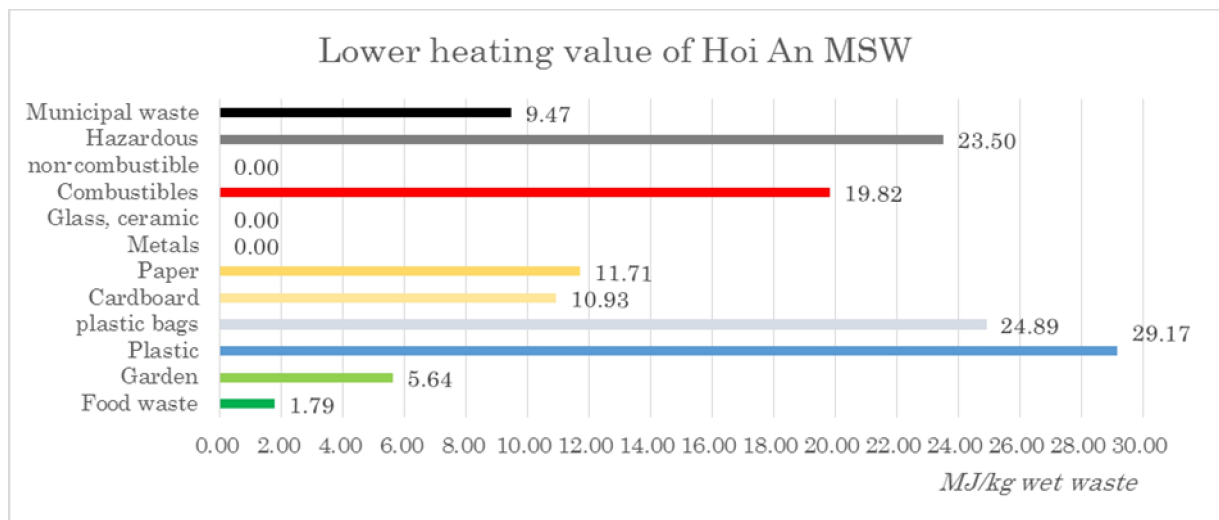


Figure 4.15 Calorific value of MSW in Hoi An city

The heating value of MSW is about 9.4 MJ/kg waste. In the waste management hierarchy, waste incineration has been considered as a mode for energy recovery. As indicated above, the average calorific value of Hoi An MSW is about 9.4 MJ/kg (ranged from 2 – 30 MJ/kg). As a result of comparing the moisture, ash and carbon content to the Tanner triangle (WB, 1999), incineration technology is a feasible option in term of waste combustibility. An incineration could be a potential technology to reduce the waste amount quickly in the city. Especially, the landfill of the city have been operating improperly and have been out of capacity.

WTE have been one of the best technology in term of energy recovery in MSW management ([Kathirvale et al., 2004](#)). The result from energy content of MSW in Hoi An indicated that a WTE system might be a potential option for the city waste treatment system. However, the total amount of waste produced is about 70 tonnes per day, the capacity of waste incineration will be not high. Thus, cost-benefit study for incineration without energy recovery facilities should be carried out.

Significant quantities of food waste, garden waste, and combustible waste proved that we might consider introducing biological and thermal treatment technologies as potential treatment options for municipal solid waste. However, the composting plant in Hoi An currently has been operating unsuccessfully like most of the other composting plants in Vietnam. Failure in composting technologies are caused by various factors such as inappropriate pre-treatment techniques, not enough attention to the biological process requirements; poor quality of the fertilizers, and poor marketing experiences ([Nguyen, 2014](#)). Centralized composting plant with high capacity might be improper for the Hoi An condition due to lack of management skills, operating funds, and low technology application. Thus, decentralized biological treatment (small-scale plants, home composting) seem advisable to apply in these conditions, especially with households in rural and suburban areas that have gardens and engaged in agriculture. However, socio and economic incentives should be studied to encourage decentralized organic waste treatment.

Thermal treatment, on the other hand, has been considered one of the best technologies in term of energy recovery and reducing waste to landfill in MSW management ([Kathirvale et al., 2004](#)). Waste incineration has been getting more attraction from the city authorities. The high portion of combustible waste in Hoi An indicated that incineration technology might be a potential option for the city waste treatment system. Nevertheless, the total amount of waste produced is about 70 tonnes per day, and the capacity of waste incineration will be not high. Thus, a study on the characteristics of waste such as heating value, moisture content, and chemical elements (C, N, H) is required to determine the potential of incineration. A cost-benefit study for incineration without energy recovery facilities also should be carried out.

Recyclable waste (plastic, cardboard, paper, and metal) accounted for a large percentage of around 20% giving a good chance for material recovery. However, informal recycling activities for plastics, cardboard, and some other materials by organized waste pickers at treatment plants are currently adequate. Also, current recycling activities employ residents living nearby Hoi An waste treatment plant and are supported by local people. A material recovery program, therefore, may not be warranted for now because of social and technological constraints, but should be taken into account in the future.

#### **4.4 Conclusion**

Detailed survey and analysis of waste generation and composition in a tourism city, Hoi An, Vietnam, were conducted to evaluate differences among types of urban as well as between household waste and tourism waste. The findings are as follows:

Daily per capita household waste generation was  $0.223 \text{ kg capita}^{-1} \text{ day}^{-1}$ . Total household waste generation rate in Hoi An City was 20.75 tonnes per day, which accounted for about 30% of total municipal waste generation.

People living in rural areas generated about half of the amount of daily waste compared to people living in urban areas. On the other hand, residents in the urban areas highly affected by tourism activities produced less waste than in areas not affected by such activities.

Hotels generated about  $0.6 \text{ kg room}^{-1} \text{ day}^{-1}$  and one restaurant in HAC produced an average of  $26.18 \text{ kg day}^{-1}$ . The mean of waste generation from tourist streets was  $6.99 \text{ kg } 100\text{m}^{-1} \text{ day}^{-1}$ . The study found that hotels with garden and higher standard (four stars) created more waste than lower-standard hotels. Regarding the correlations between the waste generation rate and the number of hotel rooms, the result indicated a statistically significant correlation between the number of rooms and total waste generation of hotels. The coefficient of correlation ( $r$ ) was 0.95, and the coefficient of determination was 0.91.

The municipal waste composition of the city had food waste as the largest proportion (42%) and hazardous waste as the smallest contributor (less than 1%). Total biodegradable waste (food and yard trimmings) was approximately 53%. Combustible waste was the second significant

component of about 16% while other recyclable contributed about 20% of the municipal waste composition.

Waste composition in the city center was affected by tourism services because it was different from other areas and likely alike with the waste composition of the tourism sector in food, garden, and some other components.

Results from this study suggested a methodology of waste characterization survey based on characteristics of urban areas. The results and methodology are accepted to be informative for authorities, decision makers, stakeholders, and planners in developing a waste management plan.

Regarding the potential treatment technologies, we suggested that biological and thermal treatment technology should be considered as highly potential options for municipal solid waste to reduce waste to landfill. A recyclable material program should be developed in the future toward sustainable waste management.

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## 5. MODELLING WASTE GENERATION PROGNOSIS MODEL

### 5.1 Introduction

An understanding of relationships between the quantity and quality of waste outputs from human processes and local characteristics is essential in municipal solid waste management (MSWM). To develop an adequate planning of sustainable waste management system, the appropriate forecast of waste generation plays an important role. One of the challenges faced by local governments is the prognosis of solid waste quantities to have appropriate actions and plan ([Ghinea et al., 2016](#)). In Viet Nam, The National Technical Regulation QCVN 07:2010/BXD ([MOC, 2010](#)) provided a method to estimate waste generation for five urban types based on population and waste generation rate determined in the document. However, the results of prediction are not reliable in term of practical application for different cities because the solid waste generation is impacted not only by demographic factor but also by social, economic as well as other factors (e.g. family expense or waste prevention policies). Therefore, the later edition of this regulation, QCVN 07:2016 ([MOC, 2016](#)) uses neither this method for waste generation estimation nor any other model instead. Lack of research and method on waste generation estimation has led to a considerable challenge in municipal waste management in Viet Nam.

Various modelling techniques were applied to develop solid waste generation, predictive models. According to [Beigl et al. \(2008\)](#) and linear regression analysis, on the other hand, was more popular in the application of waste generation estimation ([Bach et al., 2004](#); [Beigl et al., 2008](#); [Buenrostro et al., 2001](#); [Ghinea et al., 2016](#); [Thanh et al., 2010](#)) due to the capacity of expendability and modification to handle complexity of the real world, and it's more useful in empirical investigations and data prediction [J. J. Faraway \(2005\)](#).

Previous studies had modelled the total municipal waste generation using various variables and reported that municipal waste generation rate significantly correlated with economic factors ([Hockett et al., 1995](#); [Thøgersen, 1996](#)), or household size ([Abu Qdais et al., 1997](#); [Dennison et al., 1996](#)), types of house ([S Lebersorger et al., 2003](#)) and the number of rooms in house ([Monavari et al., 2012](#)). However, the diagnostic checking to verify the statistical adequacy of

the model was not carried out ([Bdour et al., 2007](#); [Karpušenkaitė et al., 2016](#); [Shamshiry et al., 2014](#)) and model validation with a new dataset also got lack of attention ([Buenrostro et al., 2001](#); [Ghinea et al., 2016](#); [S. Lebersorger et al., 2011](#)). The two analysis above was essential to evaluate the reliability and performance of a linear regression model. In addition, [Benítez et al. \(2008\)](#) chose the model based on the maximum R-square but in reality it is not a feasible option when dealing with a lot of independent variables.

This study aims at to provide a reliable model to help the decision makers and related stakeholders in forecasting the quantity of waste from households. The Bayesian Model Average (BMA) method will be used instead of stepwise regression to avoid the noise variables from gaining entry to the model in selecting predictor variables ([Derksen et al., 1992](#)). Multiple linear regression models are developed with significant determinant variables chosen by BMA. Diagnostic tests for the hypothesis of linear assumptions and a conventional validation method were conducted to evaluate the performance of the model. The software R (v3.2.0) was used for linear regression modelling and statistical analysis in this study ([Julian J Faraway, 2005](#); [J. J. Faraway, 2005](#); [Tuán, 2014](#)).

## **5.2 Mathematical modelling of Waste generation**

The general procedure of the methodology applied is briefly described as follows. Firstly, a household waste sampling and a questionnaire survey were carried out to gather the data of waste generation and explanatory variables. Next, the BMA method was used to select the significant predictor variables for the regression model. Then, the regression coefficients of the model would be identified. Finally, the test for linear hypothetical assumptions and validation was performed to evaluate the model's performance.

### **5.2.1 Data collection**

The waste generated was assessed from families in the whole town through a door-to-door sampling method in 2015. To reduce variations in household waste generation, stratified random sampling method was applied. The city was divided into two strata based on the Rural-Urban topology of households. The number of samples was estimated from the number of households in each stratum with a sampling ratio of 13 households per 1000 households ([Hoang et al., 2017](#)). The needed statistical samples size should be 280 families; 321 households were gathered to

participate in the sampling program. Waste generated from households was sampled in 14 days consecutively by 25 students of Da Nang University and two authors. Every household taking part in the program was assigned with a code marker in front of the door to avoid collection mistakes. The procedures for sample collecting and analysing are presented in Figure 4.3.

Then, a survey was conducted by face-to-face interview questionnaire to all households in the project. The study is to obtain information of personal and socioeconomic background of the family such as house area, with garden or not, family size, member ages, and monthly income, etc. The results obtained from this survey were interpreted to identify the explanatory variables for the mathematical models of household waste generation estimation.

### **5.2.2 *Variables used in modelling***

Regression analysis was used for explaining the relationship between dependent variable Y (or response or output variable), and one or more independent variables (or predictor variables) X. Thus, analysis of data gathered from the questionnaire survey was followed by identifying the variables involved. The database comprised ten independent variables presenting demographic, geographic and economic influencing factors to household waste generation. The response variable is mean of the per capita waste generation ( $\text{kg capita}^{-1} \text{day}^{-1}$ ) gathered from the sampling of household waste. Three types of independent variables including categories, discrete and continuous variables were employed. Table 5.1 explains the variables included and symbols assigned. A variable matrix consisting the information of household-family participating in the sampling was constructed and used as the input dataset for the analysis.

Table 5.1 Types of variables in linear regression

Type of variable	Variable	Symbol	Unit/value/types	Determination of variables
Dependent continuous	Per capita waste generation per day	$Y_{hhw}$	kg per capita per day	Average of daily waste generated from each family member in each household
Predictor variables				
Independent category	Household location	$X_{plc}$	Urban (=1) Countryside (=0)	If the house located in urban area If the house located in country area
Independent category	House garden	$X_{gar}$	Yes (=1) No (=0)	The house has garden The house does not have garden
Independent category	Home business	$X_{bus}$	Yes (=1) No (=0)	Family members do business at home such as a convenience store, restaurant, café bar, shop, mini hotel, vehicle rent Do not have any business at home
Independent discrete	Family income	$X_{inc}$	1 2 3 4 5 6	Very low: less than 500.000 VND per person per month Low: From 500.000 - 1.200.000 VND per person per month Lower-middle: From 1.200.000 – 2.500.000 VND per person per month Upper-middle: From 2.500.000- 4.000.000 VND per person per month High: From 4.000.000- 6.000.000 VND per person per month Very high: more than 6.000.000 VND per person per month
Independent discrete	Household size	$X_{siz}$	Number	The number of individuals in the family
Independent discrete	Number of room	$X_{rom}$	Number	Number of rooms in the house
Independent continuous	House area	$X_{are}$	$m^2$	The total area of the house
Independent continuous	House area per person	$X_{pa}$	$m^2$ per person	The household area divided by the number of family members
Independent continuous	% of children	$X_{chi}$	Percentage	The percentage of people less than 20 years old in the family
Independent continuous	% of adults	$X_{adu}$	Percentage	The percentage of people from 20 - 59 years old in the family
Independent continuous	% of old people	$X_{old}$	Percentage	The percentage of people older than 59 years old in the family

### 5.2.3 Selection of determinant variables

The dataset was divided randomly into two sets: 70% of the data as training set and other 30% is testing set. The training sample set would be used to determine the predictor variables and identify the coefficient of the model. Meanwhile, the testing sample set will be used for

validating the model. The Bayes model average method ([Raftery et al., 1997](#), [Hoeting et al., 1998](#)) will be utilised to identify the combination of significant independent variables to explain MSW generation best. The “best” model can provide the most precise prediction with a reasonable number of variables or accurate estimations for new cases exchangeable ([Raftery et al., 1997](#)). BMA provides a consistent mechanism of accounting for this model uncertainty which is often ignored in model selection, leading to overfitting models and might cause over-confident inferences ([Hoeting et al., 1999](#); [Fernández et al., 2001](#)). According to [Hoeting et al. \(1999\)](#), BMA also provides improved the out-of-sample predictive performance of the linear model. A Bayesian Model Averaging solution to this problem provides optimal predictive ability by involving averaging over all possible models ([Madigan and Raftery, 1994](#)). Quantities of interest and parameters estimates are provided via direct application of the principles described as follows:

The posterior distribution given data  $Z$  of the quantity of interest  $\Delta$ , such as a model parameter or a future observable is defined by Eq.5.1.

$$pr(\Delta | Z) = \sum_{k=1}^K pr(\Delta | M_k, Z) pr(M_k | Z) \quad (5.1)$$

Where,  $M_1, M_2, \dots, M_K$  are the models under consideration. Eqs.5.2 and 5.3 give the posterior probability for model  $M_k$  and the integrated likelihood of  $M_k$

$$pr(M_k | Z) = \frac{pr(Z | M_k) pr(M_k)}{\sum_{k=1}^K pr(Z | M_k) pr(M_k)} \quad (5.2)$$

$$pr(Z | M_k) = \int pr(Z | \theta_k, M_k) pr(\theta_k | M_k) d\theta_k \quad (5.3)$$

Where,  $\theta_k$  is the vector of parameters of model  $M_k$  and  $pr(\theta_k | M_k)$  is the prior density of the parameters under the model,  $pr(Z | \theta_k, M_k)$  is the likelihood and  $pr(M_k)$  is the prior probability that  $M_k$  is the actual model. The BMA estimates a parameter  $\theta$  by Eq. 5.4.

$$\hat{\theta}_{BMA} = \sum_{k=1}^K \theta_k pr(M_k | Z) \quad (5.4)$$

The Bayesian information criterion called BIC approximation which is formally defined as Eq.5.5. BIC is used as a criterion for models selection from the set of model, the model with the lowest BIC approximation is preferred.

$$BIC = -2. \log (RSS_p) + p.\log n \quad (5.5)$$

Where,

BIC: is Bayesian information criterion

$RSS_p$ : is square sum of residuals in fitting sample data to the model with  $p$  independent variables

$p$ : is the number of regressors including the intercept

$n$ : is the number of observation or equivalently, the sample size

#### 5.2.4 *Multivariate linear regression model*

A multivariate linear regression model is described as Eq. 5.6.

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \varepsilon \quad (5.6)$$

Where,  $\alpha$  is the intercept term which indicates the mean of the dependent variable  $Y$  in the case that all predictor variable  $X$  is equal to 0;  $\beta$ , a vector of  $\beta_i$ , is the slope of the model, and it explains the average change in the dependent variable. The residual  $\varepsilon$  represents the difference between estimated values and observed values.  $\varepsilon$  may include measurement error although it is often due to the effect of unincluded or unmeasured variables (Faraway, 2005). In linear regression, it is assumed that the errors are normally distributed, independent and have equal variance  $\sigma^2$  ( $\varepsilon \sim N(0, \sigma^2 I)$ ). The correlation of residuals is vital for time series data because time series regression accounts for the autocorrelation between time. Meanwhile, in non-time series regression, the independence of errors is presumed or at least minimised. Theoretically, the residuals from the model should not be correlated with either independent or dependent variables.

### 5.2.5 *Testing model assumptions*

The validity of the assumptions underlying the chosen model should be checked. The residuals  $\varepsilon$  was used to test the linear model assumptions. Formal diagnostic tests can ensure the exactitude of results but may be powerless to detect problems of an unsuspected nature, especially in data related to social and human activities. Graphical techniques are usually more efficient at revealing overall structure of the data set. They tend to be more versatile and informative ([Faraway, 2005](#)). Moreover, the graphical methods may be useful for describing as well as understanding the underlying structure of the data ([Wilk and Gnanadesikan, 1968](#)). Therefore, in this study, the graphical approach was applied as diagnostic tests for the hypothesis of linear model assumptions. The normality of residual distribution is tested by normal quantile plot of the residuals ([Wang and Bushman, 1998](#)). The plot consists of plotting the ordered residuals from the fitted model (vertical axis) versus the reference line of a normal distribution having the same mean and variance (horizontal axis). The points of model residuals on such a plot should fall close to the reference line if the errors are normally distributed. Violation of normality often occurs either because the distributions of either predictor or response variable are significantly not normal. In this article, author generated the residuals versus fitted values plot and residuals versus independent variables plot to find out the way to improve the model. A useful method is that if the non-random shape occurs in only one of the plots, the predictor variable should be transformed. If it happens in more than one plots, we should transform the response variable to improve the model. “The plot of residuals versus estimated values (fitted values)” can also indicate constant variance if the scatter is symmetric vertically around zero. There is some approach to dealing with non-constant variance violation in linear regression model. Weighted least squares or transformation of the response variable can be used to have a constant variance of the outcome variable (Faraway, 2005). Likewise, to test for violations of independence, the residuals distribution should be random and symmetric around zero under all conditions. Outlier observations which do not fit the model and influential observations that have large effects on the model will be detected. The outlier test was carried out by Bonferroni



correction method (Faraway, 2005) and the Cook statistic was used for influence diagnostic (Cook, 1977).

### **5.2.6 Model evaluation and validation**

A conventional validation approach with external validation method will be applied to test the model for avoiding over-fitting (Faber and Rajkó, 2007). The requirement is that the validation samples are entirely different from the training samples which constructed the model. Thus, this approach properly necessary to assess the ability to forecast for unknown future samples (Bleeker *et al.*, 2003; Faber and Rajkó, 2007). To ensure the model can perform in a new dataset, authors divided the original data into two subsets including training set (70%) and testing set (30%). The former is used for constructing the model, whereas the latter is for validating. A combination of statistical metrics would be applied to assess the model performance, which is including coefficient of determination  $R^2$ , adjusted  $R^2$  ( $R^2_{adj}$ ), mean absolute error (MAE), root means square error (RMSE) and normalised root mean square error.  $R^2$  (R-squared) is a useful property indicating the goodness of fit of the model. The  $R^2_{adj}$  (adjusted R-squared), on the other hand, also indicates how well model fit, but adjusts for the number of independent variables in a model. MAE and RMSE are useful measures widely used in model evaluations. MAE considers the same weight to all kind of errors which is proper to describe uniformly distributed errors. Meanwhile, RMSE favours the errors with larger absolute value and is appropriate to explain normally distributed error (Chai and Draxler, 2014). In this study, RMSE was used for assessing the performance of predictive model since the residuals of the linear regression model is expected to be normally distributed. If the RMSE for the testing data set is higher significantly than that of the training data set, over-fitting occurs. The two RMSEs are close, which mean that the model is valid and enable to predict unknown data. However, the range of training data is different from testing data. Thus, to compare the RMSE of two data set, the normalised RMSE (NRMSE) was used. NRMSE is the ratio of the RMSE to the range of the data set, so NRMSE has the range of 0 to 1. Eqs. 7 and 8 explain RMSE and NRMSE, respectively. MAE will be calculated to describe the average error magnitude.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{n}} \quad (7)$$

$$NRMSE = \frac{RMSE}{y_{\max} - y_{\min}} \quad (8)$$

Where,  $\hat{y}_i$  : the estimated value of the outcome variable of observation i

$y_i$  : the observed value of the dependent variable observation i

$y_{\max}$  : the maximum observed value of the dependent variable

$y_{\min}$  : the minimum observed value of the dependent variable

n: the sample size.

A bootstrapping with 10.000 replications on the training data set is carried out to calculate the 95% confidence interval of R-square (95% ci). The coefficient of determination of the model running on testing data is also calculated. R-square of the model on testing data is expected to belong to the 95% ci.

### 5.3 Result and discussion

#### 5.3.1 Significant independent variables and selected models

The number of households responded to the face-to-face interview questionnaire survey was 286 over 321, which was more than the statistical requirement for sample sizes (281). Thus, the nonresponse samples were just neglected in later analysis. Figure 5.1 shows the results of estimation of correlation coefficients among variables. The results indicate that the correlation coefficients of outcome variables and explanatory variables are low (<0.33). In Figure 5.2, the horizontal axis names options chosen by BMA. The red colour indicated that the predictors variable correlated with the outcome variable with a positive coefficient. The blue colour presented the negative correlation, and the other colour means that the variable is not present in the model. The result of BMA method indicated that there are four independent variables including *Household location* ( $X_{plc}$ ), *Home business* ( $X_{bus}$ ), *Household size* ( $X_{siz}$ ) and *house area*

per person ( $X_{pa}$ ), proved to be significant variables for estimating daily waste generation per capita (Figure 5.2). Two variables such as  $X_{plc}$  and  $X_{siz}$  were presented in all group of significantly determinant variables selected by BMA ( $p = 100$ ) while the probability of the variable  $X_{bus}$  appearing in models chosen by BMA is 96.4% and that of  $X_{pa}$  is about 74%. Interestingly, the variables presented house income, garden, and percentages of members of different ages range in the family were not significant, indicating that those factors do not explain the variation in the waste generation rate.

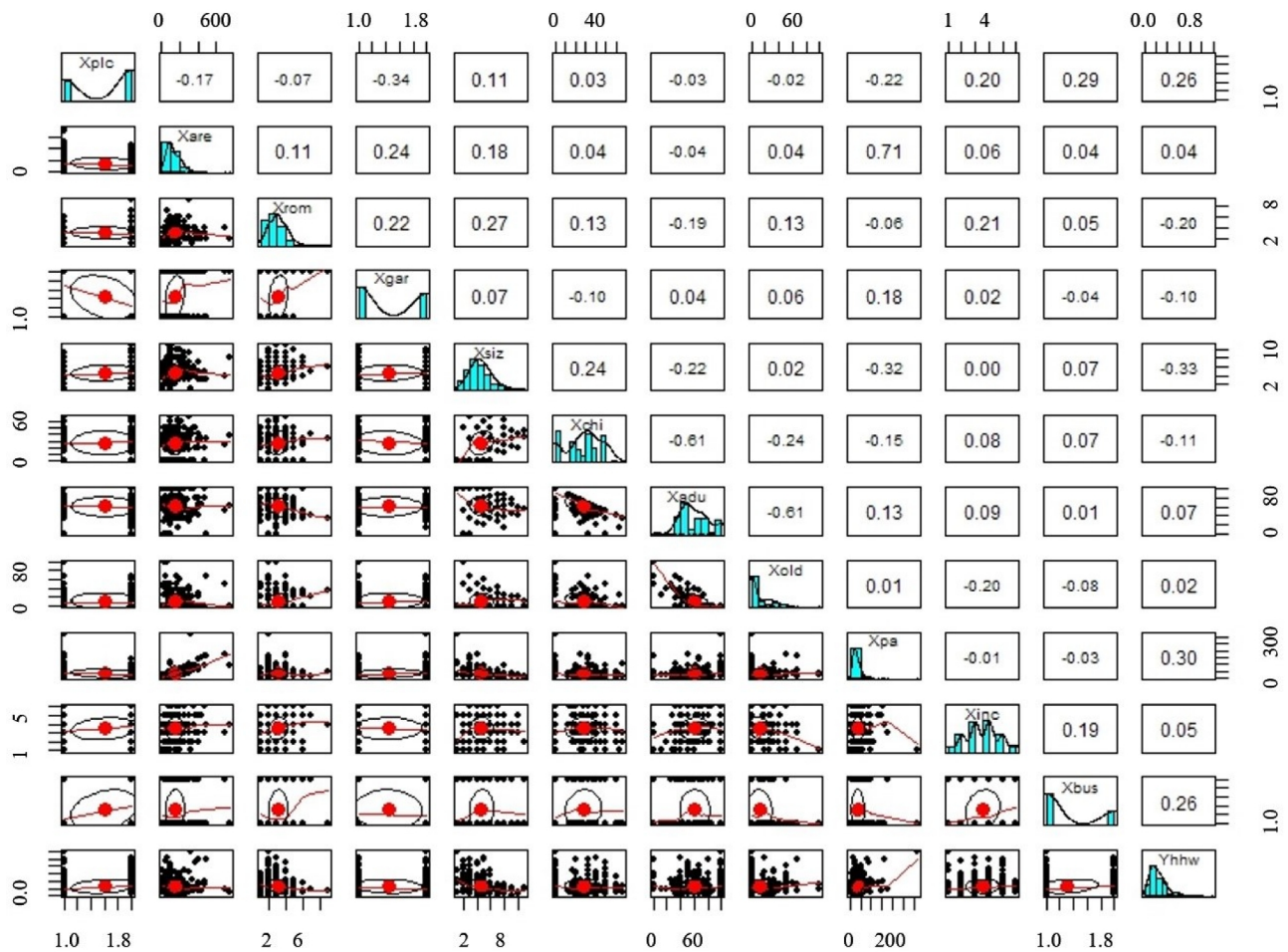


Figure 5.1 Correlation coefficients among variables

The household size ( $X_{siz}$ ) negatively correlated with daily per capita waste generation. An increase of family members will lead to a decrease of daily waste generation per capita. Previous studies were consistent with our finding of the qualitative relationship between household size

and per capita daily waste generation per capita. [Benítez et al. \(2008\)](#); [Qu et al. \(2009\)](#) and [\(Sukholthaman et al., 2015\)](#) found the same negative influence of household size on waste generation rate per capita. The positive correlation between the regressor ( $X_{plc}$ ) and the response variable indicated that the household waste generation rate associated with the area it is located. People living in urban area generated more waste than ones living in countryside area. In contrast, [Hockett et al. \(1995\)](#) found that the type of urbanisation was not a significant determinant of waste generation rate in his study. In Vietnam, the home served as a base for a business such as a convenience store, a restaurant, or a place for manufacturing goods, is quite familiar. The presence of business at home might affect to waste generation per capita quantity ([Parizeau et al., 2006](#)). Home business ( $X_{bus}$ ) was confirmed to be the significant determinant of household waste generation rate (Table 2). The variable  $X_{bus}$  correlated positively with waste generation means that family handling business at home has higher daily waste generation per person rate than one without business. Higher income leads to more goods consumption and therefore more waste production ([Buenrostro et al., 2001](#)). Nevertheless, other researchers found that the household income is not related to waste generation by different measurement of income approaches such as continuous income data ([Bernache-Pérez et al., 2001](#); [Benítez et al., 2008](#); [Grazhdani, 2016](#)), categorical income data ([Bolaane and Ali, 2004](#), [Gomez et al., 2008](#)), or proxy variables ([Mbande, 2003](#); [Gomez et al., 2008](#); [Prades et al., 2014](#)). The result of this study indicated that direct income variable ( $X_{inc}$ ) is not a significant determinant factor of waste generation. The difficulty in this relationship investigation is the accuracy of income data solicited from households, especially in developing countries ([Parizeau et al., 2006](#)). In HAC, people might consider their income to be a private matter, and business households try to conceal the real income to avoid paying more taxes. A proxy variable of the income, the total area of the house ( $X_{are}$ ) was not a significant variable to estimate the per capita waste generation. Meanwhile, the house area per capita ( $X_{pa}$ ) was proved to be a determinant variable of household waste generation rate. It meant that the amount of waste produced is correlative to the average house space for a person. The number of the room in the house was not an explanatory variable for waste generation estimation as a result of BMA. It is inconsistent with the previous study, the production of household waste was found to be positively correlated with the number of the room ([Monavari et al., 2012](#)). Other variables representing home garden and age groups were not

significantly correlated with the quantity of waste produced. The Bayesian Model Averaging method not only detected the best model but also suggested some other reliable models for predicting household waste generation based on BIC approximation. Thus, we could have some model options to identify the amount of waste. Table 2 showed the best five options of waste generation prognosis models suggested by BMA. The model 1 with four predictors has the lowest BIC approximation (-62.3), which means that the linear regression model of four variables ( $X_{plc}$ ,  $X_{bus}$ ,  $X_{siz}$ , and  $X_{pa}$ ) is the best multivariate model among all possibilities.

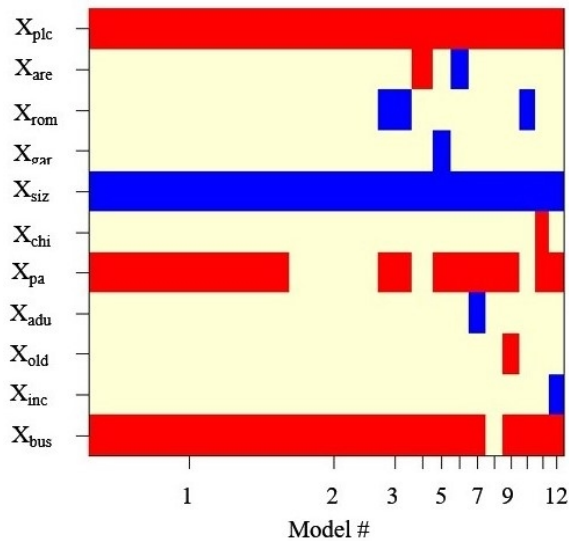


Figure 5.2 Predictors being chosen for the most reliable models by BMA

Posterior probability presents the likelihood of the model that may explain the observed data correctly. The posterior probability of models 1 and 2 is higher than other models, approximately 42% (0.422) and 19% (0.187), respectively. It indicated that models 1 and 2 are more accurate in explanation of waste generation observations than other models (around 5%). The model with three independent variables has lower  $R^2_{adj}$  (of about 30%), and models of four and five regressors have adjusted R-square of about 33%, which are similar. It means that adding more than four independent variables into the model will not improve the model fit. Table 5.2 also showed that significant level of each variable in each single model. Each of model 3,4 and 5 has more than four regressors, but not all the explanatory variables are significant determinants. The variable  $X_{rom}$  (Model 3),  $X_{gar}$  and  $X_{are}$  (Model 4 and 5) were proven negligible determinants for waste generation. Thus, we choose Model 1 and 2, whose all predictor variables are significant,

lower BIC approximations and higher posterior probability to be tested for the linear model assumption and predictive performance.

Table 5.2 Best models selected by Bayesian Model Average

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	-1.539 (***)	-1.293 (***)	-1.402 (***)	-1.894 (***)	-1.517 (***)
X <sub>plc</sub> (Urban)	0.578 (***)	0.535 (***)	0.560 (***)	0.457 (***)	0.557 (***)
X <sub>are</sub>	-	-	-	0.0005( )	-
X <sub>rom</sub>	-	-	-0.055 ( )	-	-
X <sub>gar</sub> (YES)	-	-	-	-0.08 ( )	-0.061( )
X <sub>siz</sub>	-0.128 (***)	-0.147 (***)	-0.120 (***)	-	-0.125 (***)
X <sub>pa</sub>	0.004 (**)	-	0.004 (**)	-	0.004 (**)
X <sub>inc</sub>	-	-	-	-	-
X <sub>bus</sub> (YES)	0.302 (**)	0.317 (***)	0.308 (**)	0.292 (**)	0.304 (**)
Number of variables used	4	3	5	4	5
BIC	-62.3	-60.7	-58.8	-57.8	-57.5
Posterior probability	0.422	0.187	0.071	0.043	0.038
R <sup>2</sup>	0.343	0.319	0.348	0.328	0.344
R <sup>2</sup> <sub>adj</sub>	0.329	0.309	0.332	0.318	0.327
F-statistic	25.43	30.64	20.76	10.61	20.38

*Signif. Codes: p ~ 0 (\*\*\*)*; *p < 0.001 (\*\*)*; *p < 0.05 (\*)*; *p < 0.1 (.)*; *p < 1 ( )*

### 5.3.2 Multivariate linear regression models for household waste generation

Eqs.5.8 and 5.9 show the parameter estimates for the selected model 1 and model 2, respectively:

$$\text{Log}(Y_{\text{HHW}}) = -1.539 + 0.578X_{\text{plc}}(\text{Urban}) - 0.128X_{\text{siz}} + 0.004X_{\text{pa}} + 0.302X_{\text{bus}}(\text{YES}) \quad (5.8)$$

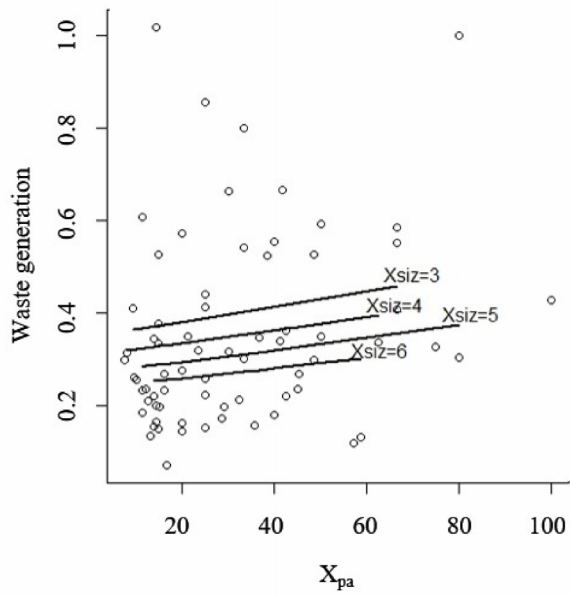
$$\text{Log}(Y_{\text{HHW}}) = -1.293 + 0.535X_{\text{plc}}(\text{Urban}) - 0.147X_{\text{siz}} + 0.317X_{\text{bus}}(\text{YES}) \quad (5.9)$$

The intercept -1.539 (in the equation 8) is the unconditional expected mean of the logarithm of waste generation rate. Therefore the exponential value of the intercept equals to 0.215 (kg/capita/day) is the geometric mean of waste generation rate. The exponential value of the coefficient for X<sub>plc</sub> is 1.78 (e<sup>0.578</sup> = 1.78), it indicates that average of the per capita waste generation of household in an urban area is 78% higher than that of household in the rural area when other independent variables are held at some fixed values. Similarly, a person in a family doing business at home generated 35% more than the one living in a family not doing business

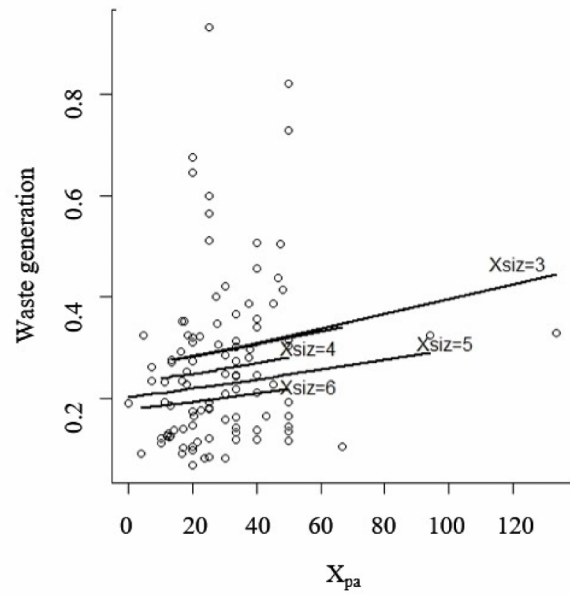
(exponential value of 0.302 equals to 1.35). The household size is the only significant predictor variable negatively correlated with waste produced, indicating that an increase in the number of family members is associated with a decrease in waste generation per capita. The coefficient of variable  $X_{siz}$  in the model is -0.128, it means that one person increase in the family leads to a decrease of 12% in waste generation rate ( $e^{-0.128} = 0.88$ ) when other variables values are unchanged. Parameter explanation is similar to model 2. Figure 5.3 describes the predicted value of waste generation per capita from the Model 1 with four predictor variables. Different lines in the plot present the estimated waste generation rate for the various values of variable household size. In this figure, we showed four value of  $X_{siz}$  ( $X_{siz} = 3, 4, 5$  and  $6$ ). Moreover, Figure 5.4 describes the predicted values of waste generation rate based on the three independent variable model chosen.

The purpose of this study is to find out a simple and reliable model to estimate waste generation, which can contribute to improving waste management. The models can provide reliable information to support current waste collection and transportation. Exact estimation of waste generation in rural and urban areas results in better design and arrangement of vehicles, labours, collection routes. That will improve the efficiency of the current collection system, which has been inefficient due to poor calculation and design. Moreover, as a result of model estimation, a decentralised management approach could benefit the waste collection due to the variation of waste generation amount in urban and countryside areas. Onsite-treatment or small scale treatment might reduce the cost of collecting the little amount of waste generated in further areas, especially degradable waste have a great potential for home-composting or recycling for feeding animals in agriculture places.

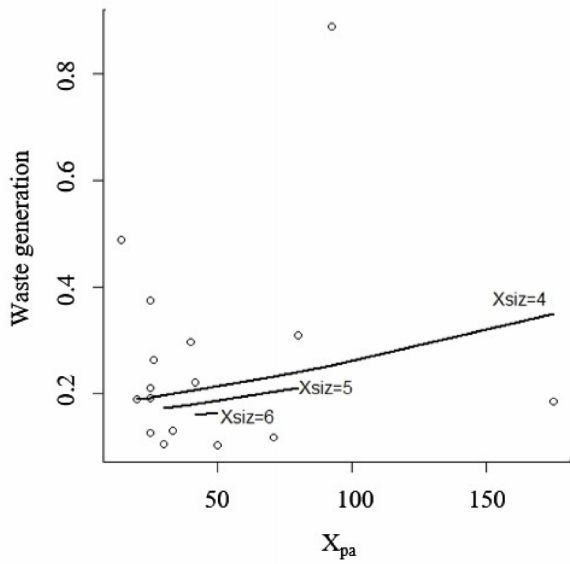
The result of the study also suggested that home businesses contributed considerable amounts of waste to the total waste requiring being collected from a household. Therefore, estimation of waste generation from houses with business could provide a basis to the decision-makers to improve the waste management system such as giving more weight to commercial and tourism sectors in the city. For instance, increasing waste collection fee for home and business sectors can support waste management since the number of households involved in this business activities are increasing quickly.



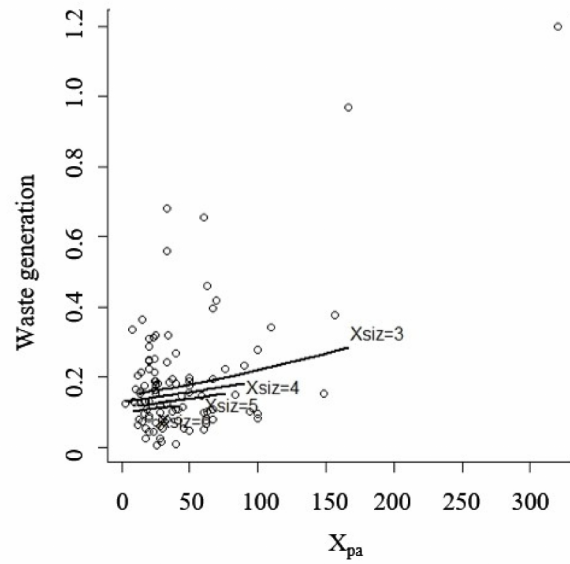
House in urban with home business



House in urban, no home business



House in urban with home business



House in countryside, no home business

Figure 5.3 Fitted line plot of model with four regressors  $X_{plc}$ ,  $X_{siz}$ ,  $X_{pa}$ ,  $X_{bus}$



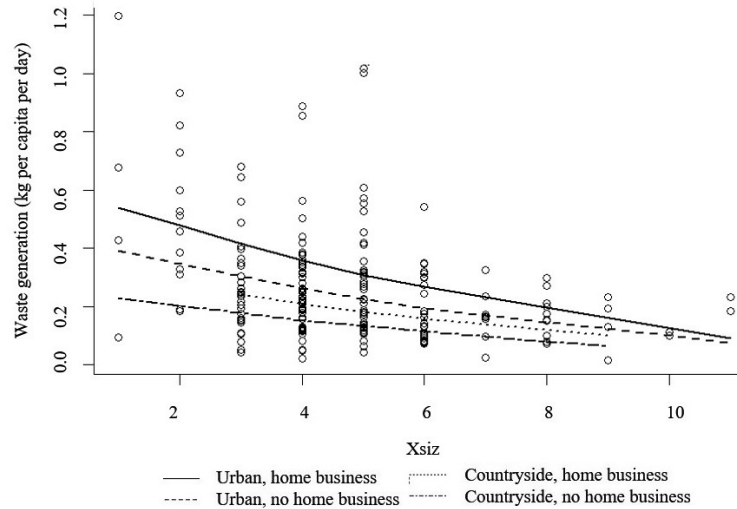


Figure 5.4 Fitted line plot of model with three regressors  $X_{plc}$ ,  $X_{siz}$ ,  $X_{bus}$

### 5.3.3 Models analysis

#### 5.3.3.1 Diagnostic test for linear model assumption

Figure 5.5 represents the test results for normality, constant variance, and autocorrelation. Two quantile-quantile plots (Figures 5.5.1 and 5.5.7) compare the residuals (all the scatters on the graph) to “ideal” normal observations (the line). The residuals follow the line approximately indicating that the errors of both models are normal. The residual versus fitted value plot (Figures 5.5.2 and 5.5.8) used for a test of nonconstant variance. The scatter is symmetric vertically around zero demonstrating that there is no evidence of nonconstant variance. Moreover, Figures 5.5.2, 5.5.3, 5.5.4, 5.5.5 and 5.5.6 (model 1) and Figures. 5.5.9, 5.5.10 and 5.5.11 (model 2) show that the scatter of residuals are symmetric approximately around zero in the plot with all the independent variables. It means that there is no problem with the correlation of the residuals. The results from graphical test indicated that all linear assumptions were satisfied.

#### 5.3.3.2 Influences of variables and observations

Figure 5.6 shows the relative importances (with 95% confidence interval) of regressors for the two models, performed by LMG method (Johnson and LeBreton; 2004, Grömping, 2006). The place of household ( $X_{plc}$ ) acts as the primary predictor variable in both models because the percentage of contribution is about 40%, followed by the household size ( $X_{siz}$ ), around 30%. The

independent variables have less contribution to waste generation (10% and 20%) was household area per person ( $X_{pa}$ ) and home business ( $X_{bus}$ ), respectively.

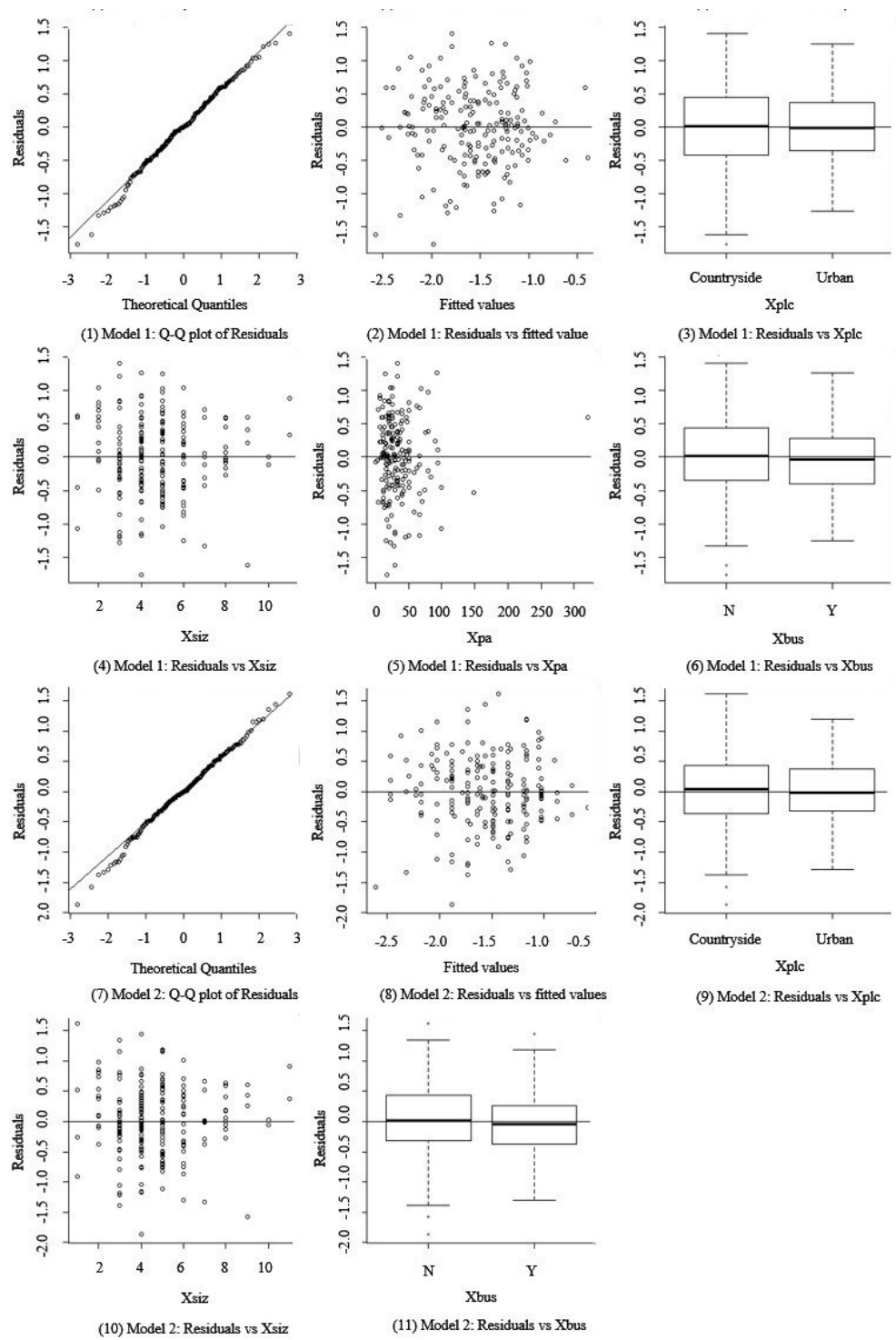


Figure 5.5 Tests for linear assumption of two models

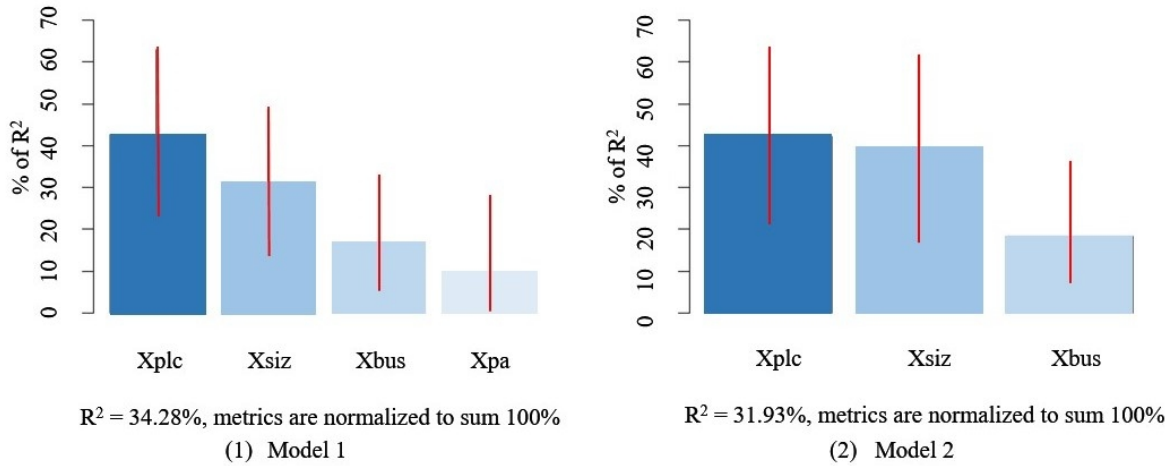


Figure 5.6 The relative importance of regressors for waste generation rate

Figure 5.7 indicated the observations have a large impact on the predicted values, measured by Cook's distance (Cook, 1977, Cook, 1979). The observations number 13, 70 and 184 have significant influences to the fit of the models than other observation, but none of them has too much influence (Cook's distance less than 1.0), (David, 2007). Outlier tests showed that there was one outlier observation in both models, which is the observation number 47.

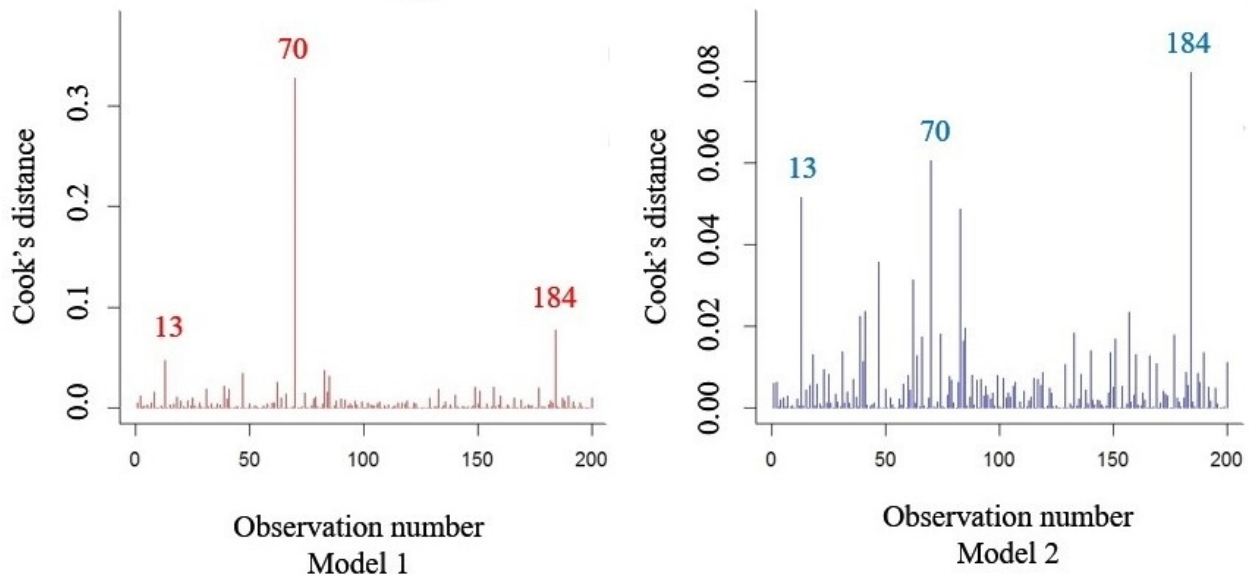


Figure 5.7 Observations have high influence to the model

### 5.3.3.3 Model validation

The  $R^2$  of the models were 0.34 (model 1) and 0.32 (model 2), it means that the models could explain about 34% and 32% the variation of daily waste generation rate per capita, respectively. Other multivariate linear regression studies had low  $R^2$  such as 51% in the study of [Benítez \*et al.\* \(2008\)](#), 36% in the research of [Grossman \*et al.\* \(1974\)](#) and 48.7% in the study by [Bach \*et al.\* \(2004\)](#). The weak coefficient of determination could be explained by the fields of study, especially in waste generation study, which attempts to predict human behaviour such as habit, lifestyle, normally has  $R^2$  values lower than 50%. Humans behaviour are simply harder to predict than physical processes. However, the goal is not to maximise the coefficient of determination because obtaining more predictor variables may cause overfitting. In other words, a low R-square does not mean the model is useless, and a significant R-square is not able to say the model is useful ([Brown and Mac Berthouex, 2002](#)). Also, a good model can maximise the percentage of variation explained but limits the ability of the results to be generalised ([Beigl \*et al.\*, 2008](#)). If the model satisfies all the linear regression assumptions, it is a proper model to estimate waste generation. Moreover, it can draw some meaningful conclusions about how changes in the predictor variables are associated with variations in the response variables.

Table 5.3 Results of model validation

Models	Datasets	Standard deviation	$R^2$	Mean $R^2$ (bootstrap)	95% ci of $R^2$	RMSE	NRMSE	MAE
Model 1	Train set	0.712	0.343	0.354	0.235 – 0.428	0.576	0.131	0.451
	Test set			0.281		0.678	0.137	0.488
Model 2	Train set	0.712	0.319	0.327	0.220 – 0.406	0.586	0.134	0.453
	Test set			0.256		0.689	0.139	0.492

Multivariate linear regression model created by training data set was run on testing data set, the statistical metrics of performance was calculated. Table 5.3 explained the model validation results. In both models, R-square of testing data set are in the 95% ci, NRMSEs and MAE of training and testing set are very close, which means two models perform well on new data. On the other hand, RMSEs are smaller than the standard deviation of the response variable (0.712), indicates that the model produces less variation than the data observations. Lastly, low NRMSEs (about 0.13 over the range of 0 to 1) demonstrate that the fitted values of both models are quite close to the observations. Thus, both models have good performance in predicting the household

per capita waste generation. Also, model 1 has performed better than model 2 because it has higher R-square, higher posterior probability and produces smaller errors (RMSE, MAE).

#### **5.4 Conclusion**

The models constructed in the current study is valuable in estimating waste generation as it provides observational evidence of the influences of multiple factors. They indicated that the impacts of socio-demographic, geographic variables and family economic activities on waste generation rate are highly significant. The model can not predict waste generation in the future, but it can provide reliable information to improve the current waste management. The location of the house is the most affected predictor for the daily amount of waste generated per capita. Both models showed that a person in an urban house produced much higher solid waste (70-80%) than one living in a countryside family. That provides an exact estimation of waste generation in rural and urban areas in better calculation and arrangement of vehicles, labours, collection routes. It also suggests that a decentralised treatment approach could benefit to reduce the collection cost for the small amount of waste generation in further areas. However, the approach needs to be studied carefully to have the applicable implications and appropriate legislation to encourage decentralised waste treatment. Education and awareness of waste generation were implemented successfully in Hoi An and should be maintained and improved. Another important factor influenced the household waste generation in HAC is family economic activities. The result of the two models showed that if a family is holding a business at home, the waste generation rate of the household will increase by about 35%. Waste fee for business sector might be an important factor to take into consideration in waste collection and management planning when the number of household opening business at home for tourism and local services such as small restaurants, homestays, shops, convenience stores and vehicle rental shops have been rising gradually in the city. The study found that household size and the area of the house are also significant determinants of per capita waste generation while other variables, particularly income per person, prove to not significant as correlates of waste production. Results from this study demonstrate that Bayesian Model Average method was a robust method to determine solid options in multiple linear regression models, especially dealing with a big number of independent variables. The result of BMA indicated that the linear regression model with four

independent variables ( $X_{plc}$ ,  $X_{siz}$ ,  $X_{pa}$ ,  $X_{bus}$ ) was the best model for estimating waste generation in HAC because of the lowest BIC approximation and reasonable model size. Meanwhile, the model with three regressors ( $X_{plc}$ ,  $X_{siz}$ ,  $X_{bus}$ ) has slightly lower performance but is very useful to predict the waste generation of household quickly because of availability information of predictor variables in census database. The study attempted to increase the understanding of waste generation to support waste management planning for the city. Thus, the two models are useful in addressing waste generation for not only analysing key factors influencing the waste generation, but they also giving waste managers a link to have a model for estimating waste generation to improve waste reduction and management efforts. The results and methodology are accepted to be informative for authorities, decision makers, stakeholders and planners to develop a waste management plan. The model developed in this paper is not reliable for predicting waste generation in the future. Lack of historical data in caused difficulties for modelling waste predictive model. Thus, modelling municipal waste generation model which can forecast the future is essential and needed to be studied.

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## 6. MODM Model

### 6.1 Introduction

Waste management is one of the most important issues concerning environmental protection and resources conservation ([Costi et al., 2004](#)). SWM in developing countries has received increasing attention from researchers and policy makers hoping to follow a sustainable approach to waste management and to integrate strategies that will produce the best practical option.

That is a difficult task, as it is essential to take into account economic, technical, and environmental aspects properly as well as the social agreement and every society has several goals for implementing SWM plans depending on some circumstances and issues. For example, the Hoi An city facing a landfill space problem may set a target to reduce the quantity of waste sent to landfill disposal or may consider source decrease, waste diversion through recycling and volume reduction alternatives such as converting waste to energy. The most sustainable choice, however, is often not clear. Important questions need to be answered is how MSW flows should be managed and what are appropriate treatment technologies for a sustainable waste management plan.

Optimization helps to find the answer that yields the most reliable solution of the problem such as the lowest cost or highest profit, lowest emission/waste or highest product; or achieves the lowest discomfort or highest happiness. In recent years, many works have presented useful and comprehensive decision-making models which are both significantly close to reality and computationally tractable in order to help planners manage solid waste treatment and disposal in urban area. However, some model does not take into account normative, environmental and technical aspects ([Y. H. Chang et al., 1998](#); [Fiorucci et al., 2003](#)).

In Vietnam, the municipal authority which has responsibility for SWM focuses primarily on organizational aspect such as improvement of municipal solid waste management quality or upgrading of waste management tools. However, in reality, waste management also consists of economic sector, comprising a variety of interlinked actors, activities and commodities ([Lyeme et al., 2017](#)). Thus, there are always conflicts exist among various stakeholders involving in waste management system. A holistic approach for modelling waste management in Viet Nam

for DSS to help decision makers is essential. Nevertheless, the application of MODM in Viet Nam has been left so far compared to other countries; there have been no studies in waste management modelling conducted in Viet Nam.

In this framework, the purpose of this chapter is that of considering a quite general model, which is comprehensive of all technical, economic, normative, and environmental aspects concerning the management of MSW. Specifically, the proposed system can help decision makers choose the solution to manage the MSW stream and the capacity of appropriate treatment plants, by a careful analysis of the waste generation and composition, physical and chemical characteristics. The problem to be solved is in a category of nonlinear mathematical programming problem. In this way, the optimal configuration of the system (from the physical and technological point of view) can be determined, as well as the optimal flows among various plants in the system. Environmental impacts are carefully represented, social acceptance is optimized due to the participation of various DMs (including citizens) in choosing the system and intensive discussion in decision-making process. The interactive approach for solving the model was applied to achieve social acceptance optimization is Reference Point Method.

## **6.2 Assessment to the desires of society**

A questionnaire survey of 18 local experts with a face-to-face interview was conducted in 2015. The purpose of the survey is to assess the requirements of different stakeholders who involved in waste management in Hoi An. The local experts who were interviewed including authorities, waste managers, stakeholders, citizens' representatives, etc. which will be explained in Table 6.1. The main focus of the survey is to find out the most important objectives for the waste management system in the city, the potential treatment technologies for the current local conditions, and how the waste stream should be managed, etc. The information provided based on the knowledge and self-evaluation of local experts who may not have comprehensive knowledge about the integrated waste management but have solid experience and profound understanding of the local system. The final results of this survey will contribute to optimization model of Hoi An waste management.

Table 6.1 Experts and stakeholder group being interviewed

Expert	Group	Explanation of the expert's role
A1 A2	Authority	People working in City Committee and Department of Environment and Natural Resource, in charge of waste management and environmental management in Hoi An
S1 S2 S3 S4	Contractor	Waste recycler works privately People working HAPSC the company in charge of solid waste collection and treatment in Hoi An city
C1 C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12	Citizen	The expert C1 to C11 are the people who live in Hoi An city, working as a monitor for waste management activities in their communities. They had a degree in environmental management. Each expert represents for one community in Hoi An including Cam Thanh, Cam Ha, Cam An, Minh An, Tan An, Cam Kim, Cam Pho, Cam Nam, Cua Dai, Son Phong, Thanh Ha. <hr/> Expert C12 is a researcher living in Hoi An city and conducting research in waste management locally and internationally.

### 6.2.1 Methodologies

The “degree of consensus” denotes the degree of similarity of preference among stakeholders and the “consensus results” signifies the average preference of all stakeholders. To calculate the consensus results and the degree of consensus, consensus analysis model (CAM) is applied ([Hung et al., 2007](#)). Fuzzy set theory is applied to deal with linguistic variables in CAM, which are employed to identify stakeholder attitudes and opinions. The CAM procedures are presented as following:

#### *Determine linguistic variable for alternative preference*

Five levels (very good, good, moderate, bad, and very bad) and (very important, important, moderate, not important, not necessary) are used as linguistic variables to assess the stakeholders' opinion ([Zimmermann, 2011](#)).

#### *Fuzzy subjective decision matrix*

The Fuzzy subjective decision matrix for each stakeholder can be established as follows:

$$\begin{aligned}\tilde{x}_{ik} &= [x_{ik}^l, x_{ik}^m, x_{ik}^r] \\ x_{ik}^l &= \min\{x_{ijk}^l\} \forall j, k \\ x_{ik}^m &= \text{geomean}\{x_{ijk}^m\} \forall j, k \\ x_{ik}^r &= \max\{x_{ijk}^r\} \forall j, k \quad (6.1)\end{aligned}$$

Where  $x_{ik}^l$  ( $x_{ik}^r$ ) denotes the left (right) value (the minimum (maximum) value in this study) of the fuzzy number of preference for alternative  $k$  judged by stakeholder  $i$ ,  $x_{ik}^m$  presents the medium value (the geometric mean value) of the fuzzy number of preference for alternative  $k$  judged by stakeholder  $i$ ;  $x_{ijk}^l$  ( $x_{ijk}^r$ ) denotes the left (right) value (min/max value) of the fuzzy number of preference for alternative  $k$  judged by expert  $j$  in the stakeholder group  $i$ .

#### *The fuzzy decision matrix*

The fuzzy decision matrix can be established by de-fuzzifying the data using the centroid method ([Solymosi et al., 1986](#)). The fuzzy decision matrix is presented in the equation 6.2, where  $f_{ik}$  is the defuzzified value of stakeholder  $i$  for alternative  $k$ .

$$\begin{bmatrix} f_{11} & \dots & \dots & \dots & f_{1n} \\ \vdots & \ddots & & \ddots & \vdots \\ \vdots & & f_{ik} & & \vdots \\ \vdots & \ddots & & \ddots & \vdots \\ f_{m1} & \dots & \dots & \dots & f_{mn} \end{bmatrix} \quad (6.2)$$

#### *Calculating the consensus results for the alternatives*

The consensus results for each option can be expressed as the mean defuzzified value of the triangle fuzzy number for stakeholders as follows:

$$CR = [\bar{f}_1, \bar{f}_2, \dots, \bar{f}_k, \dots, \bar{f}_n] \quad (6.3)$$

Where  $\bar{f}_k$  is the average of the defuzzified value of all expert in all stakeholders for alternative  $k$ .



### *Obtaining consensus degree for alternatives*

After the consensus results for the alternatives are determined, the consensus degree for these alternatives is also defined. The calculation of the degree of consensus is conducted in three steps:

Firstly, semantic standard deviation distance for each option ( $sd_k$ ) is calculated as the following equation:

$$sd_k = \sqrt{\frac{\sum_i (f_{ik} - \bar{f}_k)^2}{m-1}} \quad (6.4)$$

Then, the semantic distance is normalized. The normalized semantic distance is calculated by the following equation:

$$d_k^{norm} = \frac{sd_k}{sd^*} \quad (6.5)$$

Where  $sd^*$  is the maximum of all possible  $sd$ .

Lastly, the degree of consensus is obtained for each alternative ( $CD_k$ ). The consensus degree for each alternative is calculated using the following equation:

$$CD_k = 1 - d_k^{norm} \quad (6.6)$$

According to [Hung et al. \(2007\)](#), the degree of compromise for consensus decreases with the larger numbers of stakeholders. Therefore, as the number of possible situations is known, if the degree of consensus exceeds a certain probability, then it can be said that a compromise (or acceptable level) has been reached. Table 6.2 presents the degree of compromise for consensus with different numbers of stakeholders.

Table 6.2 Degree of compromise for consensus with various number of stakeholders

Number of stakeholders	3	4	5
Degree of compromise for consensus	0.500	0.426	0.385

## 6.2.2 Results of the expert's survey

### 6.2.2.1 The objectives of a sustainable solid waste management

Table 6.3 presents the results of the average defuzzified value of all stakeholders for the objectives of the sustainable waste management system.

Table 6.3 The CR value of general targets for sustainable waste management

Stakeholders	Objectives			Economic Objectives		Environmental Objectives		
	Economic	Environmental	Social	Cost	Benefit	Landfill	GHG	Emission
Authority	0.750	1.000	0.625	1.000	0.500	1.000	0.375	0.375
Contractor	0.875	0.75	0.625	1.000	0.000	0.938	0.188	0.542
Citizens	0.542	0.896	0.813	0.667	0.167	0.854	0.25	0.618
<b>CR value</b>	<b>0.722</b>	<b>0.882</b>	<b>0.688</b>	<b>0.889</b>	<b>0.222</b>	<b>0.931</b>	<b>0.271</b>	<b>0.512</b>

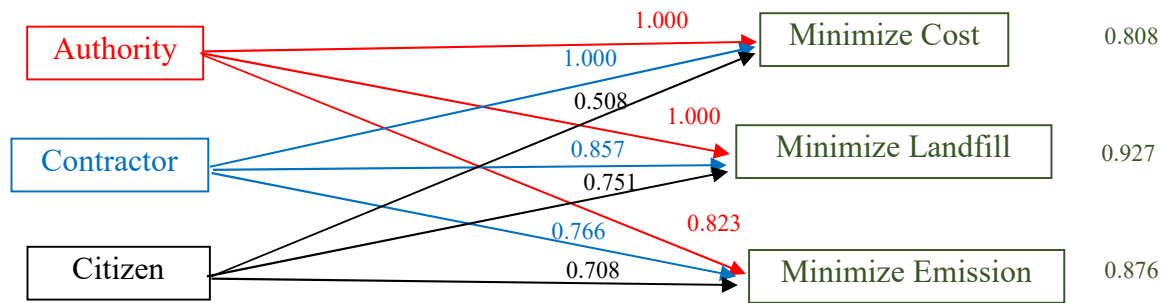
Experts agreed that three objectives including economic affordability, environmental efficiency and Social acceptance are essential for the sustainable management ( $CR > 0.500$ ). In Economic objective, minimizing cost should be focused in the model rather than benefit as the evaluation of all interviewees. Local experts understand the situation of real-world that it is hard to earn benefit from waste management in a developing city (Hoi An). GHG emission reduction got less attention according to the survey ( $CR = 0.271$ ) in environmental objectives than landfill reduction and emission reduction. This reflects correctly the real situation in Hoi An city when the land resource for landfill is limited, the current landfill has been full and caused pollution. Moreover, the global warming reduction from waste management got the lack of understanding and attention in developing countries like Viet Nam.

Figure 6.1 Present the degree of consensus for chosen objectives, it shows that there are a high level degree of consensus for chosen objectives. The consensus level of objective among stakeholders as well as in each stakeholder group for each objective. Thus, we can consider Cost, Landfill and Emission as objectives in sustainable waste management model.

### 6.2.2.2 Treatment Alternatives

The same method is applied for evaluating the stakeholder consensus of treatment options. Stakeholders will answer which treatment technology is the most suitable for the local

socioeconomic conditions, technical level conditions based on their own experience and knowledge.



Red: DC of Authority; Blue: DC of Contractor; Black: DC of Citizen; Green: Overall DC for the objective

Figure 6.1 The degree of compromise for consensus (DC value)

Table 6.4 Consensus results and Degree of consensus for treatment options

	INCE	INC	COM	ADE	AD	HT	LF	REC
Authority	1.000	0.625	0.750	0.750	0.375	0.750	0.500	0.875
Contractor	0.813	0.875	0.625	0.313	0.188	0.563	0.688	0.938
Citizens	0.813	0.438	0.688	0.729	0.375	0.729	0.583	0.896
<b>CR value</b>	<b>0.875</b>	<b>0.646</b>	<b>0.688</b>	<b>0.597</b>	<b>0.313</b>	<b>0.681</b>	<b>0.590</b>	<b>0.903</b>
<b>DC value</b>	<b>0.892</b>	<b>0.781</b>	<b>0.938</b>	<b>0.753</b>	<b>0.892</b>	<b>0.897</b>	<b>0.906</b>	<b>0.968</b>

### 6.3 Modeling waste management system

#### 6.3.1 Waste flow analysis

The aim of the dissertation is that of considering a general model, which is considering all technical, economic, and environmental aspects of MSW management. The proposed model can help decision makers choose the solution to manage the waste stream, the capacity of potential treatment facilities, by a careful analysis of waste material flow. Nonlinear mathematical programming will be applied to solve the model, and the optimal configuration of the system can be determined, as well as the optimal flows among the various plants in the system. A non-linear model was developed in General Algebraic Modeling System (GAMS) software. The model has

277 variables and 191 constraints with 1255 Jacobian elements, 3 of which are nonlinear, and 3 nonlinear variable. The size of the program is 4 MB and it takes 0.5 seconds to solve by GAMS. The waste composition analysis results (in section 4) indicated that there is no significant difference in waste composition among areas in HAC, author, therefore waste from different areas was not considered.

This model based on the waste flow analysis approach.  $W$  denotes the daily waste generated in HAC,  $R_{i,k}$  represents the amount of waste fraction  $i$  which will be transported to treatment facility  $k$ . It should be noted that recycling is possible for 6 kinds of materials including paper, cardboard, plastic, plastic bags, metal and glass, those can be separately collected by informal recycling such as scavengers collects from treatment plants, from collection points or buying directly from households. Also, the organic material (Food and Garden waste) is recycled at home by feeding animals or home composting by few households. According to [Chu \(2014\)](#) total amount of waste recycled was about 5% and 5-10% of total MSW for organic materials and recyclable waste, respectively. The remaining fraction of MSW (after separated for recycling at home) is separated into 2 types of waste degradable and nondegradable, then collected and transported to treatment facilities: Composting (COM), Anaerobic Digestion (AD), Incineration (INC) and Incineration with electricity production (INCE). Those were chosen as potential treatment technologies for HAC by eighteen interviewed DMs.

Each treatment facility generates their own residuals which need to be treated. The waste flow  $WRAD_{i,k}$  is the residual of material  $i$  after being processed by anaerobic digestion process (including primary treatment and anaerobic process), which go to COM, or INC, or INCE or LF for further treatment. Similarly,  $WRCOM_{i,k}$  is the residual of fraction  $i$  after being processed in Composting facilities, that will be treated at incineration or landfill later.  $WRINC$  is the total amount of residual from incinerator being landfilled. Products produced from composting plant and energy generated from Incineration will be sold to the market.

To obtain the data of material flow after each treatment facility, LCA and LCI study should be conducted for that treatment plant. However, it also should be noted that the direct implementation of LCA for each treatment facility is complicated, costly and time-consuming ([Chiu et al., 2008](#)). However, the exact LCI calculation or environmental impact is not the main

purpose of this study. Thus, we applied data from various reliable scientific reports, articles. Data and sources are presented in table 6.5 and 6.6.

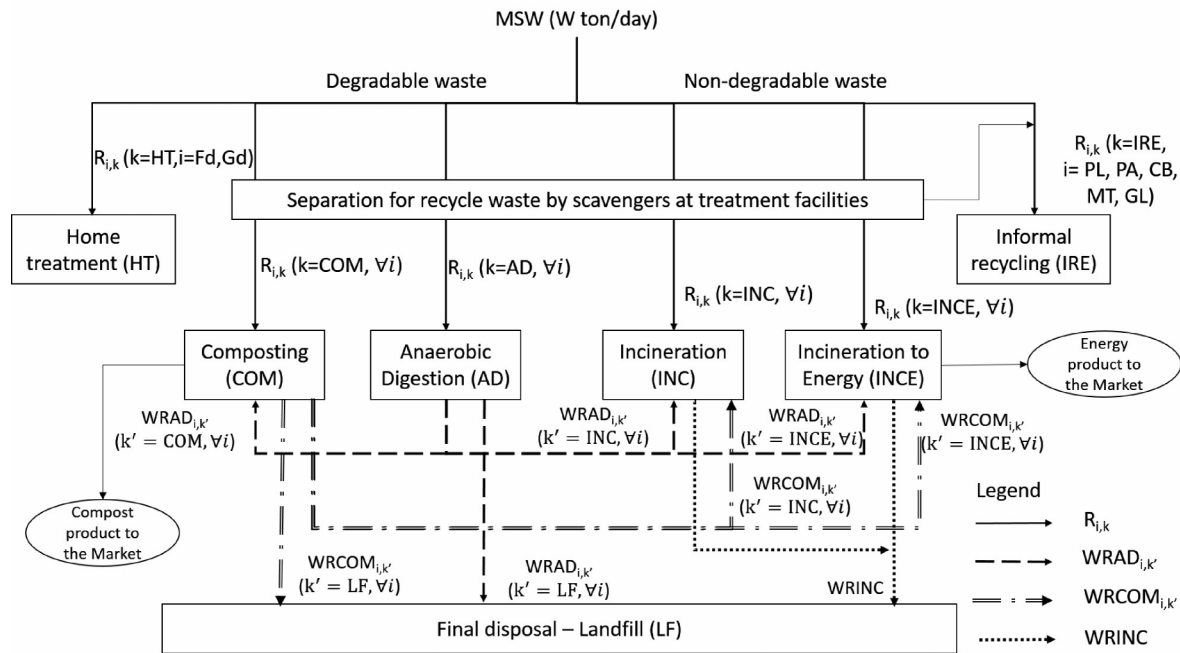


Figure 6.2 The waste flow structure of the model

### 6.3.2 Waste flow modelling

The input and output flow of different treatment facilities are described in the model. The indices that are used in the mathematical model are introduced as follows. Waste types  $i$  is generated from residents in ward  $j$  and transported to treatment facility  $k$ . Moreover, the index  $p$  denotes the type of pollutants emitted from treatment technology  $k$ . The list and explanation of sets, parameters and variables used in the model are shown in Table 6.5. The Eq. 6.7-6.8 emphasise that the available waste  $i$  should be allocated to different treatment facility  $k$ . The set of Eq 6.9-6.25 describes the waste flow going in and going out for different treatment facility  $k$ .

Table 6.5 Sets, parameters and variables

Set	
$i$	Waste type: Food (Fd), Garden (Gd), Plastic (Pl), Plastic bags (Pb), Cardboard (Cb), Paper (Pp), Metal (Mt), Glass (Gl), Combustible waste (Co), Inert (In), hazardous waste (Hz).
$i_d$	A subset of $i$ denotes the degradable waste fraction including Fd and Gd
$i_n$	A subset of $i$ denotes the nondegradable waste materials
$k$	Solid waste treatment options for the city including Composting (COM), informal recycling (IRE), home treatment (HT), anaerobic digestion with energy recovery (ADE), Incineration (INC), Incineration to energy (INCE), Landfill (LF)
$k'$	A subset of $k$ , present for treatment option which can treat the waste residual from other waste disposal facilities including COM, INC, INCE, IRE and LF
$p$	Pollutants emitted set including CH <sub>4</sub> , CO <sub>2</sub> , SO <sub>2</sub> , NO <sub>x</sub> , Heavy Metal, VOC, N <sub>2</sub> O.
Parameters	
$\alpha_i$	Percentage of waste $i$ in MSW
$\beta_{i,k}$	The amount of residual generated from treatment technology $k$ by treating 1 ton of waste $i$ (Table 6.6).
$\lambda_{i,k}^m$	The amount of product produced from treatment technology $k$ by treating 1 ton of waste $I$ (Table 6.6).
$\lambda_{res,INC}^s$	Amount of residual generated from incineration of 1 ton of anaerobic digestion sludge (equal to 0.4) ( <a href="#">FHWA, 2016</a> )
$\lambda_{res,COM}^s$	Amount of residual generated from incineration of 1 ton of anaerobic digestion sludge (assumption equal to 0)
$\lambda_{pro,COM}^s$	Amount of compost product generated from composting of 1 ton of anaerobic digestion sludge
$LHV_{sludge}$	Lower heating value of sludge generated by AD (9.7Mj/kg)( <a href="#">Khan et al., 1991</a> )
$LHV_i$	Lower heating value of waste $i$
$e_k$	Electric consumption of treatment $k$ for a ton of input waste
$\delta_k$	The efficiency concerning of energy production concerning heat produced by combustion of waste in incinerator and biogas from AD.
$\mu_{p,k}$	Amount of pollutant $p$ emitted from treatment process $k$ by treating 1 ton of input waste
$c_k^{cap}, c_k^{op}$	Investment and operation cost of 1 ton of waste to treatment facility $k$ .
$c^{trans}$	Transportation cost of 1 ton waste to treatment facility $k$
$b_{com}$	Price for 1 ton of compost fertilizer
$b_{energy}$	Price for 1 kWh of electric by Waste to Energy
Variables	
$R_{i,k}$	Amount of waste $i$ transported to treatment facility $k$
$RAD_{i,IRE}$	Amount of recyclable waste type $i$ collected from the input waste of AD facility by scavengers

$RCOM_{i,IRE}$	Amount of recyclable waste type $i$ collected from the input waste of Composting facility by scavengers
$RINC_{i,IRE}$	Amount of recyclable waste type $i$ collected from the input waste of Incineration by scavengers
$WRAD_{i,k'}$	Amount of residual sludge generated after treatment from AD facility type $i$ to facility $k'$
$WRCOM_{i,k'}$	Amount of residual generated after treatment from Composting facility type $i$ to facility $k'$
$C_k$	Amount of waste will be processed in facility $k$

### ***Waste flows***

$$W \times \alpha_i = \sum_k R_{i,k} \quad \forall i, k \quad (6.7)$$

The amount of recyclable waste after

$$C_{IRE} = \sum_i R_{i,IRE} + \sum_i RAD_{i,IRE} + \sum_i RCOM_{i,IRE} + \sum_e \sum_i RINC_{i,IRE}^e + \sum_i WRCOM_{i,IRE} + \sum_i WRAD_{i,IRE} \quad \forall i \text{ recycle} \quad (6.8)$$

### ***Constraints for recyclable waste recycled informally***

$$R_{i,IRE} = RAD_{i,IRE} = RCOM_{i,IRE} = RINC_{i,IRE}^e = 0$$

$$\text{with } i = \text{Fd, Gd, Co, In, Hz (fraction } i \text{ is not recyclable waste)} \quad (6.9)$$

The Eq 6.10 is a constraint indicating that the total amount of recycled waste is less than 10% of total MSW.

$$\sum_i R_{i,IRE} + \sum_i RAD_{i,IRE} + \sum_i RCOM_{i,IRE} + \sum_e \sum_i RINC_{i,IRE}^e + \sum_i WRCOM_{i,IRE} + \sum_i WRAD_{i,IRE} \leq 0.1 \times W,$$

$$\rightarrow C_{IFR} \leq 0.1 \times W$$

$$i = \text{recyclable waste} \quad (6.10)$$

### ***Home treatment for degradable waste***

$$C_{HT} = \sum_i R_{i,HT} \quad \forall i = \text{Fd, Gd} \quad (6.11)$$

The amount of degradable waste treated at home less than 5% of total MSW

$$C_{HT} \leq 0.05 \times W \quad (6.12)$$

$$\sum_i R_{i,HT} = 0, \forall j, \forall i \neq Fd, Gd \quad (6.13)$$

### **Anaerobic Digestion**

$$C_{AD} = \sum_i R_{i,AD} \quad \forall i \quad (6.14)$$

$$WRAD_{i,k'} = (R_{i,AD} - RAD_{i,IFR}) \times \beta_{i,AD} \quad \forall i = Fd, Gd, Pp, Cb, \\ k' = \text{COM, INC, INCE, LF} \quad (6.15)$$

Sludge generated from anaerobic digestion from Food and Garden waste will be transported to other treatment such as composting, incineration, landfill.

Biogas product

$$BO = \sum_i (R_{i,AD} - RAD_{i,IRE}) \times \lambda_{i,AD}^m \quad (6.16)$$

### **Composting**

$$C_{COM} = \sum_i R_{i,COM} + \sum_i WRAD_{i,COM} \quad (6.17)$$

$$\sum_{k'} WRCOM_{i,k'} = (R_{i,COM} - RCOM_{i,IFR}) \times \beta_{i,COM} + WRAD_{i,COM} \times \lambda_{res,COM}^s, \forall i \quad (6.18)$$

Waste generated from composting plant not re-treated at composting facility

$$\sum_i WRCOM_{i,COM} = 0 \quad (6.19)$$

Compost product:

$$CF = \sum_i R_{i,COM} \times \lambda_{i,COM}^m + \sum_i WRAD_{i,COM} \times \lambda_{pro,COM}^s \quad (6.20)$$

### **Incineration**

$$C_k = \sum_i R_{i,k} + \sum_i WRAD_{i,k} + \sum_i WRCOM_{i,k} \quad \forall i; k = \text{INC, INCE} \quad (6.21)$$



$$WRINC = \sum_k \sum_i (R_{i,k} - RINC_{i,IFR}^e) \times \beta_{i,k} + \sum_{k'} \sum_i WRCOM_{i,k'} \times \beta_{i,k'} + \sum_{k'} \sum_i WRAD_{i,k'} \times \lambda_{res,INC}^s \quad (6.22)$$

### **Landfill**

$$C_{LF} = \sum_i R_{i,LF} + \sum_i WRAD_{i,LF} + \sum_i WRCOM_{i,LF} + WRINC \quad (6.23)$$

Table 6.6 Product and residual rate of treatment alternatives

Waste fractions	Composting (ton per ton)		AD (ton per ton)		Incineration	
	Compost $\lambda_{i,k}^m$	Residual $\beta_{i,k}$	Biogas $\lambda_{i,k}^m$	Residual $\beta_{i,k}$	LHV (MJ/t) <sup>(d)</sup>	Residual <sup>(d)</sup>
Food (Fd)	0.25 <sup>(a)</sup>	0.059 <sup>(a)</sup>	0.130 <sup>(c)</sup>	0.2 <sup>(c)</sup>	1.792	0.194
Garden (Gd)	0.649 <sup>(b)</sup>	0.0793 <sup>(b)</sup>	0.039 <sup>(c)</sup>	0.2 <sup>(c)</sup>	5.625	0.191
Plastic (Pl)	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	29.170	0.047
Plastic bag (Pb)	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	24.888	0.047
Cardboard	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0.144 <sup>(c)</sup>	0.2 <sup>(c)</sup>	10.932	0.125
Paper	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0.129 <sup>(c)</sup>	0.2 <sup>(c)</sup>	11.707	0.114
Metal	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>
Glass	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>
Combustible	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	19.818	0.048
Inert	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>
Hazardous	0 <sup>(e)</sup>	1 <sup>(e)</sup>	0 <sup>(e)</sup>	1 <sup>(e)</sup>	23.505	0.038

Source: <sup>(a)</sup> (Kim et al., 2010), <sup>(b)</sup> (Jacob K Andersen et al., 2010),

<sup>(c)</sup> Database of waste management technologies (EPEM), <sup>(d)</sup> Sample analysis by author, <sup>(e)</sup> assumption

### **Energy consumption and production**

#### *Energy consumption for treatment facilities*

$$EC_k = \sum_i R_{i,k} \times e_k, \forall k \quad (6.24)$$

The amount of energy consumption per ton of waste ( $e_k$ ) is various depend on numerous factors such as the facility technology, capacity, ages or managerial capacity, etc. Thus, the author used available data from existing LCA study as references for energy consumption rate of

different treatment techniques. The power consumption rate parameters are presented in Table 6.7.

Table 6.7 Energy consumption coefficients

	COM	AD	INC	INCE	LF	HT	IFR
$e_k$ (Kwh per ton)	62 <sup>(1)</sup>	57 <sup>(2)</sup>	70 <sup>(3)</sup>	70 <sup>(3)</sup>	7 <sup>(4)</sup>	0	0
<i>Sources:</i> <sup>(1)</sup> ( <a href="#">Lee et al., 2007</a> ), <sup>(2)</sup> ( <a href="#">Khoo et al., 2010</a> ), <sup>(3)</sup> ( <a href="#">Tan et al., 2006</a> ), <sup>(4)</sup> ( <a href="#">Ngoc, 2016</a> )							

*Energy produced by AD*

$$EP_{AD} = \delta_{AD} \times BO \times LHV_{biogas} / f \quad (6.25)$$

*Energy produced by INCE*

$$EP_{INCE} = \delta_{INCE} \times \left( \sum_i (R_{i,INCE} - RINC_{i,IFR} - RINCE_{i,IFR}) \times LHV_i + \sum_i WRCOM_{i,INCE} \times LHV_i + \sum_i SAD_{i,INCE} \times LHV_{studge} + \sum_i (WRAD_{i,INCE} - SAD_{i,INCE}) \times LHV_i \right) / f \quad (6.26)$$

$$EP_k = 0, \forall k \neq AD, INCE \quad (6.27)$$

Where,  $\delta_{AD}$  and  $\delta_{INCE}$  is the efficiency concerning energy production concerning heat produced by combustion. An assumption of 40% and 27% are made for  $\delta_{AD}$  and  $\delta_{INCE}$ , respectively.

$f$ : energy conversion factor from MJ to Kwh, equal to 3.6 MJ/Kwh

***Emission from treatment facilities:***

$$EM_k = \sum_p C_k \times \mu_{p,k} \quad (6.28)$$

Table 6.8 Emission factors  $\mu_{p,k}$

$\mu_{p,k}$	COM	AD	INC	HT <sup>(2)</sup>	LF
CH <sub>4</sub>	4 <sup>(3)</sup>	1 <sup>(3)</sup>	0 <sup>(3)</sup>	2	500 <sup>(3)</sup>
CO <sub>2</sub>	291	227	1000	252	300
NO <sub>x</sub>	-	0.188	1.6	-	0.68
SO <sub>2</sub>	-	0.03	0.042	-	0.053

VOC	24	2.1	0.008	24	6.4
Heavy metal <sup>(1)</sup>	0.00265	0.0027	0.01253	0	0.00007
N <sub>2</sub> O	0.3 <sup>(3)</sup>	0 <sup>(2)</sup>	0.05 <sup>(2)</sup>	0.45	0

Source: <sup>(1)</sup> (DEFRA, 2004), <sup>(2)</sup> (J. K. Andersen et al., 2011; EPEM), <sup>(3)</sup> (IPCC, 2006) and (Harijani et al., 2017)

### **Total cost for waste management**

According to the general plan of the city, there is only one area for a solid waste treatment complex located in Cam Ha Ward. Therefore, the waste collection and transportation fee in this study is calculated based on the financial data provided by HAPWS Ltd.Co, via a personal interview with the vice-director. Hoi An is a small city, and the distance from the city centre to the waste treatment complex is about 10km. Thus, in this study author will not consider the distance from different places to waste disposal plant and the waste collection and transportation cost for 1 ton of MSW ( $c^{trans}$ ) is about 275.000VND (equivalent to 13UD per ton) (Ngoc, 2016).

$$TC = \sum_k \sum_i R_{i,k} \times c^{trans}, \forall i, k \neq \text{HT, IFR} \quad (6.29)$$

The unit costs of investment (capital) and operation (variable) for treatment facilities in Viet Nam are regulated in Decree 32/QD-BXD (MOC, 2012). However, due to the lack of information in AD with energy recovery in Viet Nam, author assume the cost for investment and operation of AD and INCE technology, also assume the lifetime of the system is 20 years. Capital and variable cost will be presented in Table 6.9, the rate used is for the small scale treatment facility. Thus, the capital cost per day for each facility is presented as follows:

$$CC_k = \sum_i R_{i,k} \times c_k^{cap} / (30 \times 365) \quad (6.30)$$

$$COP_k = \sum_i R_{i,k} \times c_k^{op} \quad (6.31)$$

Table 6.9 The capital cost and variable cost of treatment facilities

Cost (US\$ per ton.day)	COM	AD	INC	INCE	LF	HT	IFR
Investment	21140	34225	27307	38000	9899	0	0
Operation	12	15	18	20	6	0	0

Source: (MOC, 2012)

### **Revenue from selling composting product**

$$\text{Composting plant: } B_{COM} = CF \times b_{com} \quad (6.32)$$

### ***Revenue from selling electricity product***

$$B_{energy} = \left( \sum_k EP_k - \sum_k EC_k \right) \times b_{energy} \text{ moreover, } B_{energy} = 0 \text{ when } \sum_k EP_k - \sum_k EC_k \leq 0 \quad (6.33)$$

Vietnamese Government supports energy production from renewable energy power plant. The buyer is responsible for purchasing the entire power generated from projects treating solid waste with the price of 2,114 VND/kWh (equivalent to 10.05 US cents/kWh) for power generating directly from burning solid waste ([Decision:31/2014/QĐ-TTg, 2014](#)). The price for 1 ton of composting fertilizer in HAC is 7 US\$ per ton as the result of author's survey in 2015.

### ***Positive constraints***

$$R_{i,k}, RAD, RCOM, RINC, RINCE, WRAD_{i,k}, WRCOM_{i,k}, C_k \geq 0 \quad (6.34)$$

## **6.4 Single objective optimization model**

### ***6.4.1 Objective function***

The waste management system needs to operate at a cost accepted by the community including local government, stakeholders and citizen. Thus, minimising cost or maximising benefit of the whole system is widely used in previous studies of optimisation model of waste management to consider the economic aspects ([N.-B. Chang et al., 1996](#); [Galante et al., 2010](#); [Harijani et al., 2017](#)).

In this study, authors considered estimating the total cost of the system including transportation cost, capital cost, variable cost and the revenue from selling recycle material and energy products. The goal of gaining economic profit from waste management is difficult to achieve, especially in a developing country like Vietnam. Also, as the result of the expert's survey, Therefore, the optimisation model in this research is developed to minimise the cost of the municipal waste management system.

The objective function developed in this model is presented as the following equation

$$\text{Minimize } Z = \sum_k TC_k + CC_k + COP_k - B_{com} - B_{energy} \quad (6.35)$$

## 6.4.2 Scenarios development

### 6.4.2.1 Landfill reduction initiatives

One of the most significant problem in HAC currently is the landfill problem. A major amount of waste has been dumped in an open landfill for a long time, and it has become overload and full from 2015. Thus, most of the waste generated in the city now has being transported and dumped in Nui Thanh landfill, which is about 70km far away from the city centre. In addition, due to the rapid growth of tourism industry, a land resource for landfill is limited. Therefore, landfill reduction target has the most concern from authorities and waste management experts as the results of expert's survey. However, reducing waste-to-landfill needs a wise initiative with a clear plan of action. Thus, this study will evaluate different targets of landfill reduction to have a transparent view of system capacity in local conditions to support decision makers in creating a plan for landfill reduction. Three targets of landfill reduction including 50%, 25% and 10% of MSW being landfilled will be set for calculation of minimizing system cost, GHG emission and various pollutants emission.

A constraint of landfill target will be added to the model, which is described in the equation 6.36

$$C_{LF} \leq LT \quad (6.36)$$

LTR is landfill target reduction, equals to 0.5, 0.25 and 0.1

### 6.4.2.2 Sensitive analysis for waste separation efficiency

The efficiency of waste sorting at source affects significantly to system effectiveness including technical and economic aspects. Hoi An is the first, and the only city in Vietnam has succeeded in separation program, but the rate of separation is low and varied (approximately 70-85% as reported in 2014-2015). Sensitive analysis for waste separation efficiency provides information about the effect of sorting waste to the system cost and pollution emission, which might support decision makers in controlling and evaluating a reasonable separation rate for optimizing the system. The method approach in this study for sensitive analysis of waste separation efficiency is scenarios analysis. Thus, the author will estimate the result of a model for different sorting efficiency as assumed: 70%, 80%, 90% and 100% for completely separated.

Two constraints for the efficiency of waste separation at source for nondegradable waste and degradable waste are formulated in the model:

Non-degradable waste not separated and transported to the biotreatment plant (AD and COM)

$$R_{i_n,AD} + R_{i_n,COM} = (1 - SE) \times W \times \alpha_{i_n} \quad (6.37)$$

Degradable waste not separated and transported to the INC, INCE and LF

$$R_{i_d,INC} + R_{i_d,INCE} + R_{i_d,LF} = (1 - SE) \times W \times \alpha_{i_d} \quad (6.38)$$

With three values for LT and four waste separation rates, 12 scenarios are developed as presented in Table 6.10

Table 6.10 Scenario description

		SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12
Landfill (LT), %	target	50	50	50	50	25	25	25	25	10	10	10	10
Separation (SE), %	rate	100	90	80	70	100	90	80	70	100	90	80	70

Thus, the model includes Variable, parameters and constraints was explained above.

### 6.4.3 Results of Scenarios analysis by single optimization model

#### 6.4.3.1 Economic assessment

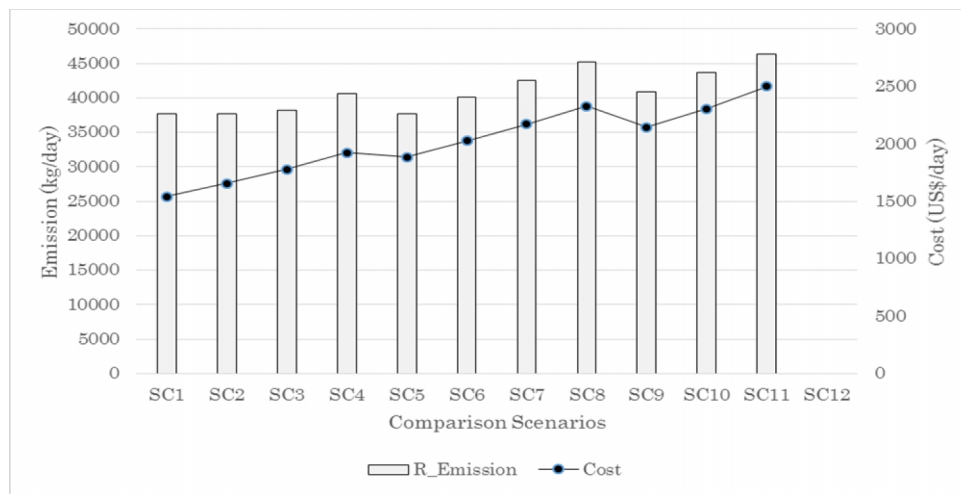


Figure 6.3 Total Cost and Emission for 12 Scenarios

The Single optimization model searches for the optimal solution of minimizing cost for each examined Scenarios. Figure 6.3 presents the results of cost and total emission from each scenario. The results show that Cost is proportional with the landfill target, the higher landfill reduction target, the higher cost for the system. Also, the comparison among scenario of a group with the same landfill target (SC1-SC4 (LT:50%), SC5-SC8 (LT:25%) and SC9-SC12(LT:10%)) shows that the separation efficiency affects significantly to the system cost. The lower separation efficiency leads to higher cost of the system. The blank result of SC12 means that the model show infeasible solution of the model with the constraint of 10% waste-to-landfill and low separation efficiency of 70%. In another word, The target of 10% waste-to-landfill cannot be reached if the rate of waste separation at source is lower than 70%. For each landfill target, the lowest cost is found when MSW is separated completely (SC1, SC5 and SC9) and the SC1 has the lowest cost among all scenarios in the evaluation.

The waste separation has the same effect with emission, a lower rate of waste sorted at source causes higher emission (comparing among the scenarios with the same LT (SC1-SC4: 50%, SC5-SC8:25% and SC9-SC11:10%). The total emission is proportional with the system expense which seems not reasonable because it is expected that spending more money can reduce emission. However, the system emission depends on the technologies used. Figure 6.4 presents treatment alternatives of scenarios as the results of the mode. The landfill is known as a large producer of CH<sub>4</sub> and CO<sub>2</sub> and Incineration is the generated highest amount of CO<sub>2</sub> per ton of waste treated among treatment technologies considered in this study. CH<sub>4</sub> and CO<sub>2</sub> have the largest emission in weight in waste among all pollutants considered in this study. When the landfill rate is high ( in scenario SC1-SC4), a big amount of MSW waste will be landfilled, less composted and no incineration. As a result, high amounts of CH<sub>4</sub> and CO<sub>2</sub> (Figure 6.5) is emitted from landfill leads to an increase in total emission of the system.

The scenario SC9-SC11 produces a high amount of emission due to the low landfill target of 10%, which causes the system favour incineration more than composting or anaerobic digestion. The LT of 25% is more reliable in term of emission because the system can favour recycling technology such as Composting or Anaerobic Digestion, which generated fewer pollutants. The scenario SC5 has the lowest emission among all evaluated scenarios as a result of the model.

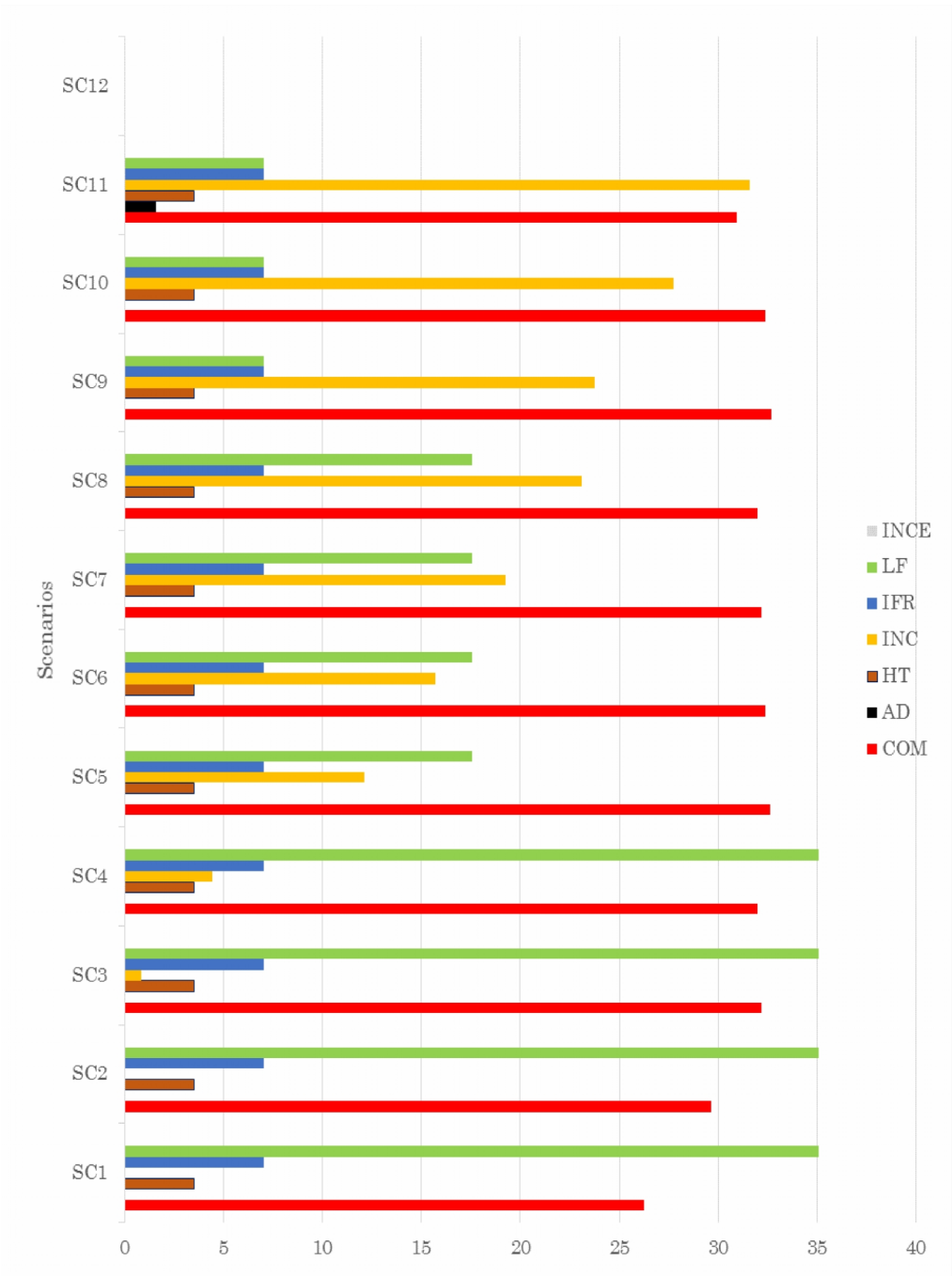


Figure 6.4 Treatment options for 12 Scenarios



### 6.4.3.2 Waste management emission

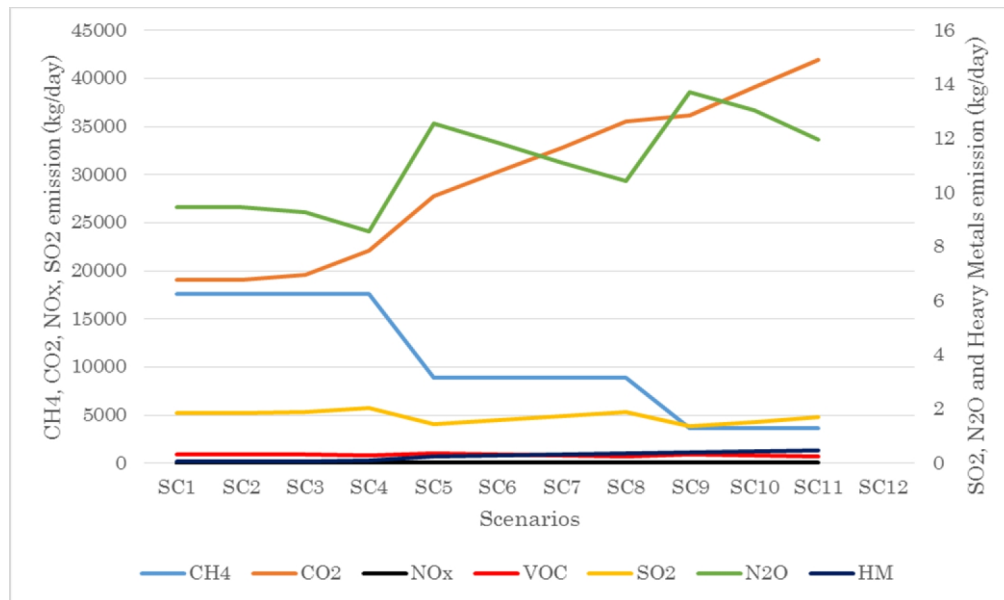


Figure 6.5 Emission of CH<sub>4</sub>, CO<sub>2</sub>, NO<sub>x</sub>, VOC, SO<sub>2</sub>, N<sub>2</sub>O and heavy metals

Figure 6.5 shows the emission of each pollutant for each scenario. The CH<sub>4</sub> and SO<sub>2</sub> are emitted more when the landfill is favoured (SC1, SC2, SC3, SC4) while CO<sub>2</sub>, N<sub>2</sub>O is generated more when incineration and composting is applied (SC5-SC11).

### 6.4.3.3 GHG emission and reduction

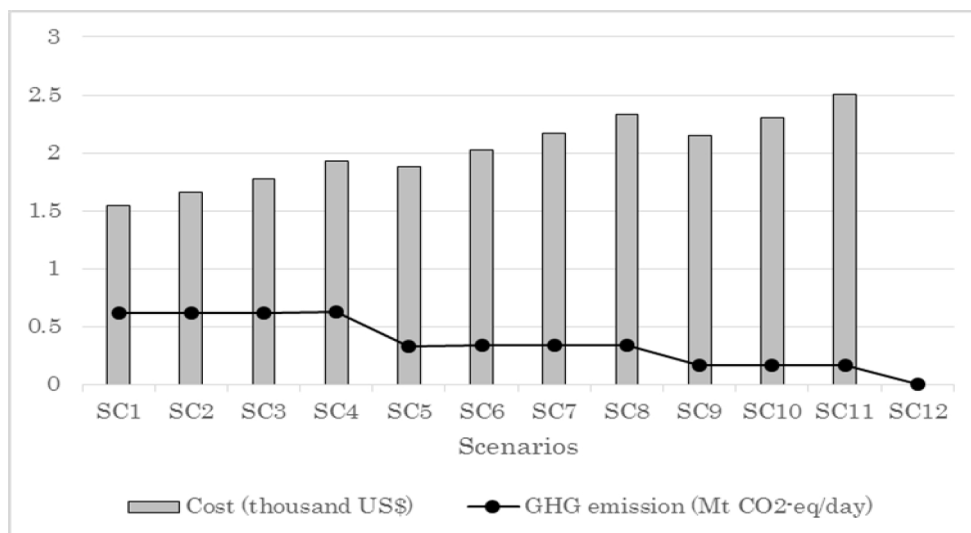


Figure 6.6 GHG emission of alternative Scenarios

Figure 6.6 compares the GHG emission (GWP applied for a period of 100 years) of 12 alternative scenarios. The results show that the scenario with a high amount of waste to landfill (SC1, SC2, SC3, SC4) are the largest GHG emission of about 0.622 Mt CO<sub>2</sub>-eq per day (SC1) and 0.624 Mt per day (SC4). The slight increase of GHG caused by the increase of waste being composted and incinerated (which generates CO<sub>2</sub>) to deal with lower separation efficiency to ensure the amount of waste-to-landfill being unchanged. However, to reduce the GHG emission, composting and waste incineration technology should be applied.

#### 6.4.3.4 Waste flow analysis

The result of Scenarios SC5 (LT:25% and SE:100%) was applied for result explanation. The specified amount of each waste fraction go to each treatment alternative is presented. As a result, Food waste is favoured for home treatment by citizens which can be used for home composting or feeding animals (3.5 t/day). 25 ton of Food waste and 7.6 ton of Garden waste are transported to composting plant whose capacity should be 32.6 t/day. Thus, the plant capacity for Composting is 32.6 ton per day. The total amount of waste to landfill is 17.532 t/day including 14.86 ton of mixed waste (accounted for 21.2% of MSW waste), 2.1 ton residual of composting plant and 0.57 ton residual from incineration and 22.44% of MSW is incinerated. The decision variables and waste stream of MSW system as results of the model for SC5 is showed in Figure 6.7

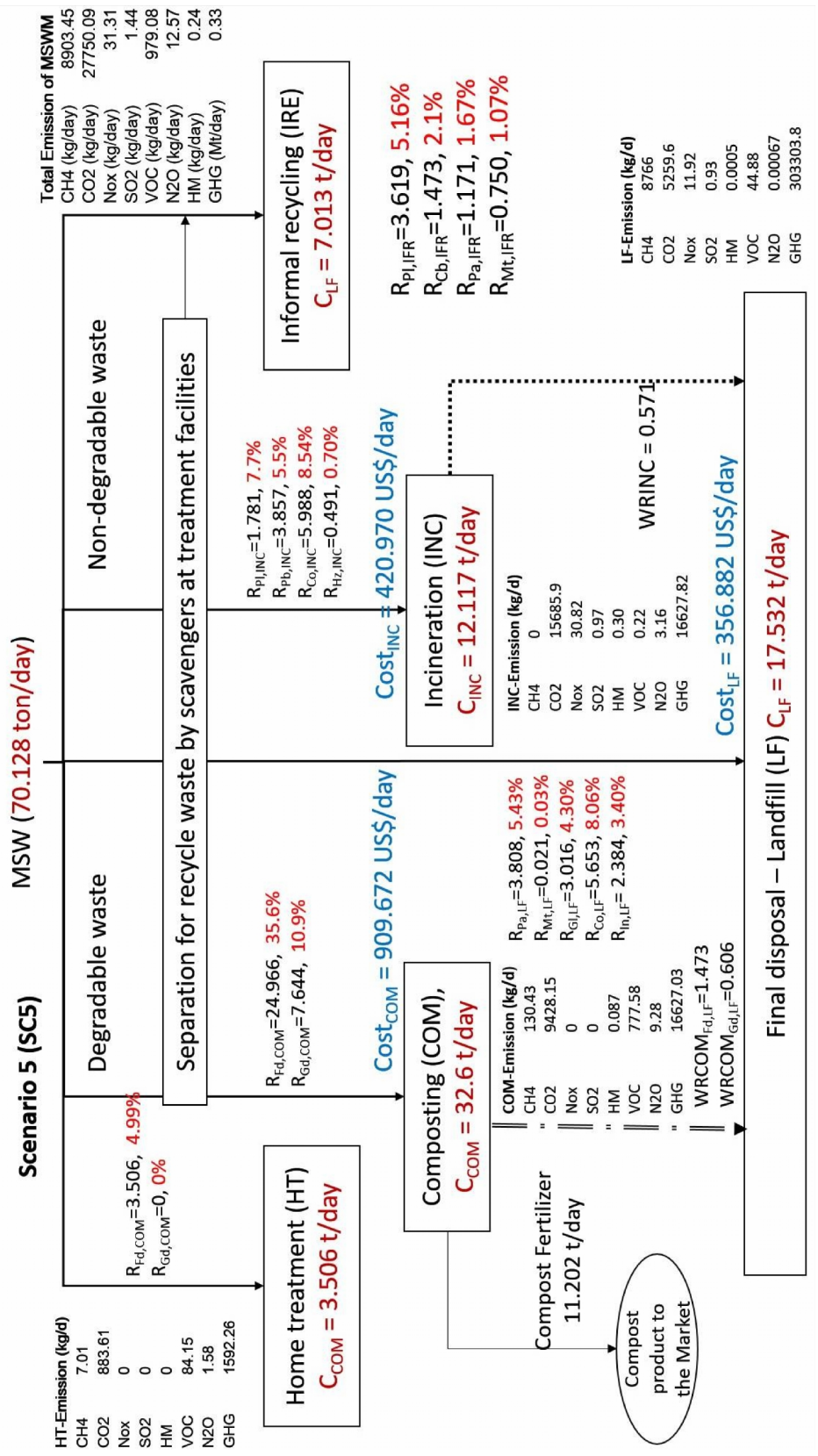


Figure 6.7 Material Flow of Waste Management System  
 Landfill target of 25% and separation efficiency of 100%

## 6.5 Multi-objectives optimization decision-making model

### 6.5.1 Objective functions of the model

According to the CAM analysis for experts consensus. The Economic objective should minimize the cost of the system rather than benefit gaining. Also, GHG emission reduction got less attention in environmental objectives than landfill reduction and emission reduction. Thus, three objective functions modelled in this study are explained as follows:

#### *Minimizing Cost*

Authors considered estimating the total cost of the system including transportation cost, capital cost, variable cost and the revenue from selling recycle material and energy products. The equation 6.36 of single optimization model was used.

$$\text{Minimize } Z_1 = \sum_k TC_k + CC_k + COP_k - B_{com} - B_{energy} \quad (6.39)$$

#### *Minimizing Emission*

According to [F.R. McDougall and Hindle \(2001\)](#), the term “environmentally effective” means that the waste management system must reduce as much as possible the amount of pollutant from waste management such as CO<sub>2</sub>, CH<sub>4</sub>, SO<sub>x</sub>, NO<sub>x</sub>, heavy metal,... In this study, the minimisation of the total amount of pollutants is considered as the environmental objective of the model. Emission of various pollutants in this article including CH<sub>4</sub>, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, N<sub>2</sub>O, VOC and heavy metal were calculated according to emission factors reported in previous studies and reliable scientific reports.

$$\text{Minimizing } Z_2 = \sum_k EM_k \quad (6.40)$$

#### *Minimizing waste to landfill*

The landfill reduction gain the most attention from local experts (CR value is equal to 0.9) reflects correctly the real situation in Hoi An city, when the land resource for landfill is limited, the current landfill has been full and caused pollution. Thus an important objective will be applied in the study is minimizing the amount of waste to landfill which is presented in the following equation.

$$\text{Minimizing } Z_3 = \sum_i R_{i,LF} + \sum_i WRAD_{i,LF} + \sum_i WRCOM_{i,LF} + WRINC \quad (6.41)$$

In the Multi-objective model, we will not compare the landfill reduction target. Thus, the Equation 6.37 and Equation 6.38 will not be used in the model.

### ***Social Agreement***

A sustainable waste management system should be environmentally effective, economically affordable and socially acceptable ([F.R. McDougall and Hindle, 2001](#)). In this study, to assess the social acceptance, the author will apply The Reference Point Method and its interactive technique, which was firstly proposed by [Wierzbicki \(1982\)](#) and later successfully implemented in engineering design, solving environmental management problems as well as other fields of decision support ([Wierzbicki et al., 2000](#)).

### ***6.5.2 Decision-making process approach***

The interactive procedure of Decision-making process applied in this study with RPM is described in Figure 6.8. The MODM method is applied here determines efficient solutions using interactive procedure with reference point optimization method, which was developed by [Wierzbicki et al. \(2000\)](#) and implemented in waste management in a study of [Minciardi et al. \(2008\)](#). The process of decision-making is explained as follows:

Vector  $x$  represents the decision variables to be selected within the feasible set  $Q$ , and  $F(x) = (f_1(x), f_2(x), \dots, f_m(x))$  is a vector function that maps the feasible set  $Q$  into the Criterion space  $R^m$ .

An outcome vector  $Z$  is attainable if it express outcomes of feasible solution, if each element  $Z_{j,j \in [1,2,\dots,m]} = \min_{j \in [1,2,\dots,m]} f_j(x)$  or  $Z = \min(F(x))$  for  $x \in Q$ .

Value  $\lambda_j = \frac{z_j - z_j^{\min}}{z_j^{\max} - z_j^{\min}}$  plays the role of a normalizing factor of objective value  $z_j$ . For each criterion  $j$ ,  $z_j^{\max}$  and  $z_j^{\min}$  are respectively defined by maximum and minimum values of  $f_j(x)$  obtained by performing the corresponding single objective optimization. Thus,  $\lambda_j \in [0,1]$  ( $\lambda_j = 0$  when  $z_j = z_j^{\min}$  and  $\lambda_j = 1$  when  $z_j = z_j^{\max}$ ). The  $z_j^{\max}$  and  $z_j^{\min}$  are presented in the trade-off Table 6.11

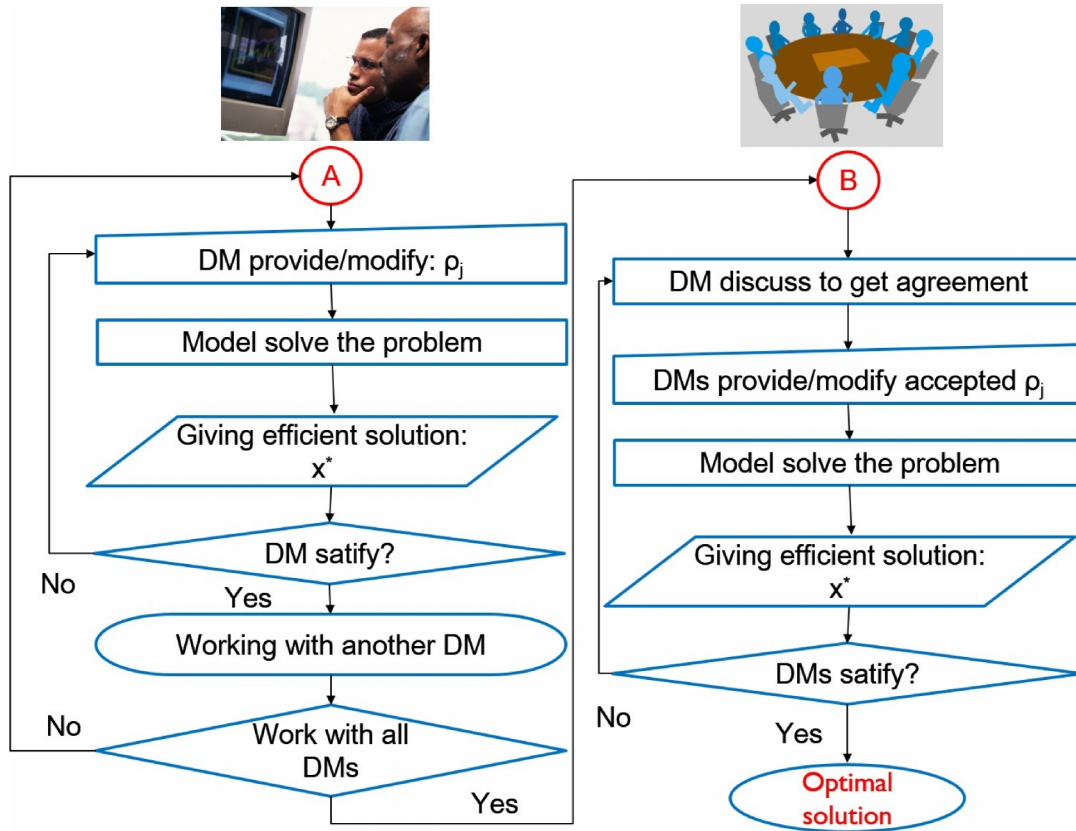


Figure 6.8 Decision-making process

The basic procedure of decision making is described as the following. Firstly, the DM choose a set of aspiration values of objective function, denoted as the initial reference point  $\rho_j$ . Then, a simple form of order-consistent achievement function is created as follows:

$$\sigma = \min_{1 \leq j \leq m} (\rho_j - \lambda_j) + \varepsilon \sum_{j=1}^m (\rho_j - \lambda_j) \text{ with } \varepsilon \text{ is a very small positive parameter} \quad (6.43)$$

The Equation 6.43 is a prototype of all order-consistent achievement scalarizing function and is monotone concerning all  $\lambda_j$ . Thus, all its minima are Pareto-optimal (Wierzbicki et al., 2000). Lastly, a new solution of decision variables  $x^*$  is determined by maximizing the achievement function  $\sigma$ . Figure 6.8 describes the whole procedure of decision making.

An experiment of the MODM process was conducted in 2017. Three colleagues of the author were invited to play the role of different DMs. The role of each DM as follows: The

Decision maker 1 (DM1) represents for Authority, DM2 represents for citizen who generated waste and the DM3 is from a waste collection and treatment contractors.

Table 6.11 Trade-off table

Single objective	Cost (US\$/day)	Emission (kg/day)	Landfill (t/d)
Minimizing Cost ( $Z_1$ )	1213.4 (min)	50 080 (max)	59.6 (max)
Minimizing Emission ( $Z_2$ )	2099.8	32 415 (min)	27
Minimizing Landfill ( $Z_3$ )	3226.2 (max)	38 909	5.36 (min)

### 6.5.3 Results of MODM

#### 6.5.3.1 Pareto-optimal solutions of decision-making process

After having analyzed the results obtained in the first interaction, DM1 decided quickly with the second interaction with landfill reduction is the priority objective. DM1 was willing to accept a worsening in objective  $Z_1$  (cost), accepting emission reference point value of 0.3, with the goal of minimizing waste to landfill (RP=0). The DM2 was more interesting in pollution reduction as he did not change the RP of Emission (RP=0), he slightly made a trade-off between for Cost and Landfill to keep minimizing the Emission. The DM3 spent more time to learn the model behaviour, he made four interactions with the model, trying to sacrifice Landfill and Emission objective for Cost. DM3 shows some awareness about the possible outcomes for the MSW management problem and starts from a reasonable reference point which he hoped to minimizing cost and give an adequate value for Emission and Landfill. However, the objective values obtained at the first iteration are not good for Cost value as he expected. Thus, he tried to reduce the Cost value by increasing the RP for other two objectives. This kind of behaviour continues until iteration 4, which provides an acceptable solution for DM3.

The Step A of the DM procedure was finished when all DMs obtained their optimal solution. Step B has started with an agreement of 3 DMs, that they will use mean value of obtained RP of each objective value for the first interaction in step B. However, the result of the model favoured the Emission (normalized value = 0.09) objective while giving a higher value for Landfill

objective (normalized value = 0.38) than expected. The Cost objective was not changed much from the RP given.

Table 6.12 Interactions of decision-making process with Multi-objective model

DM	Time	Reference points			Normalized objective			Optimal objective value		
		Cost $\rho_1$	Emission $\rho_2$	Landfill $\rho_3$	Cost $\lambda_1$	Emission $\lambda_2$	Landfill $\lambda_3$	Cost (US\$/d)	Emission (kg/d)	Landfill (t/d)
<i>Step A: Individual learning and evaluating the system with the model, choosing the best solution with a RP</i>										
DM1	1	0.4	0.2	0	0.68	0.14	0.28	2590.76	34886.32	20.78
Selected RP1	2	<b>0.6</b>	<b>0.3</b>	<b>0</b>	<b>0.66</b>	<b>0.35</b>	<b>0.06</b>	<b>2541.33</b>	<b>38586.44</b>	<b>8.60</b>
DM2	1	0	0	0	0.42	0.1	0.42	2052.13	34196.72	27.96
	2	0.3	0	0.3	0.40	0.05	0.40	2016.04	33354.83	27.00
Selected RP2	3	<b>0.4</b>	<b>0</b>	<b>0.4</b>	<b>0.42</b>	<b>0.02</b>	<b>0.40</b>	<b>2055.97</b>	<b>32743.67</b>	<b>27.29</b>
DM3	1	0	0.3	0.3	0.27	0.34	0.57	1766.10	38370.05	36.53
	2	0	0.4	0.6	0.19	0.59	0.75	1604.89	42916.83	45.79
	3	0.1	0.5	0.6	0.22	0.55	0.72	1649.93	42113.38	44.24
Selected RP3	4	<b>0.1</b>	<b>0.6</b>	<b>0.6</b>	<b>0.14</b>	<b>0.48</b>	<b>0.64</b>	<b>1489.42</b>	<b>40868.86</b>	<b>39.92</b>
<i>Step B: Discussion, to get the compromise solution with a compromise RP</i>										
Mean		0.37	0.3	0.33	0.42	0.09	0.38	2061.23	33957.00	26.04
<b>Compromise</b>		<b>0.4</b>	<b>0.3</b>	<b>0.2</b>	<b>0.48</b>	<b>0.15</b>	<b>0.28</b>	<b>2183.20</b>	<b>35013.7</b>	<b>20.64</b>

Figure 6.9 describes the behaviour of the model with all chosen RP. The compromise solution seems to balance all three objectives and expected of all DMs. All proposed solutions of DMs are the result of optimization processes, and all respect the model constraints. The final discussion is more about solutions with real situation basis which is HAC needs a reliable solution to reduce waste-to-landfill and emission for environmental protection as well as tourism development. In the end, three DM agreed to choose a set of RP for 3 objectives having close value with the mean value. it is better to spend more money because the difference in the amount of money spent is not very high (about 100US\$ per day) but can reduce 6 ton of waste to landfill, which is important for Hoi An. As a result, a final RP was decided to obtain a result which slightly increases the Cost and Emission to reduce the Landfill. All DMs seem satisfied with the compromise solution and the decision-making process stopped. Table 6.12 shows the results of decision-making procedures with all interactions of DMs with the model.



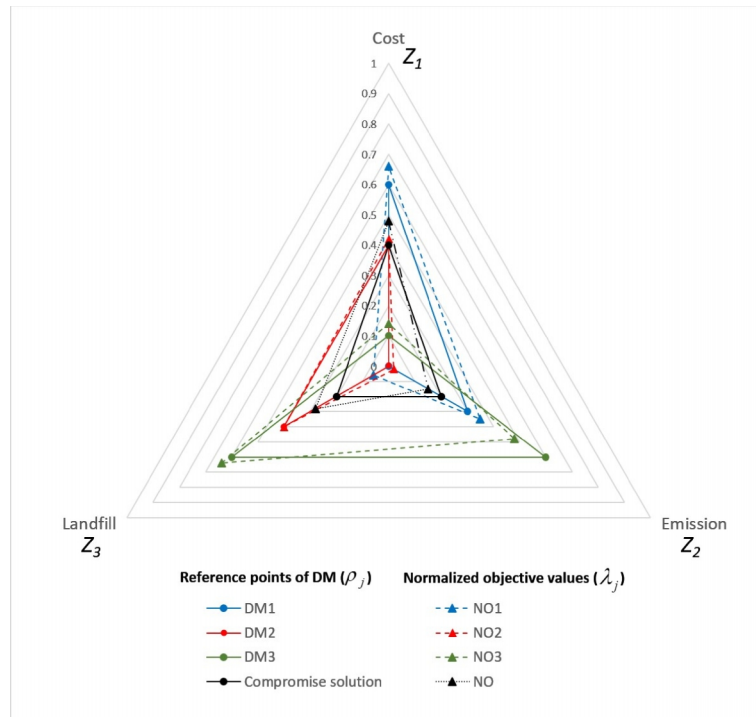


Figure 6.9 MOMD model with all reference points

Figure 6.10 shows 10 obtained Pareto-optimal solution of multi-objective optimization model of the case study with 3 DMs and visualize the procedure of decision-making process of 3 DMs step by step to reach the compromise solution.

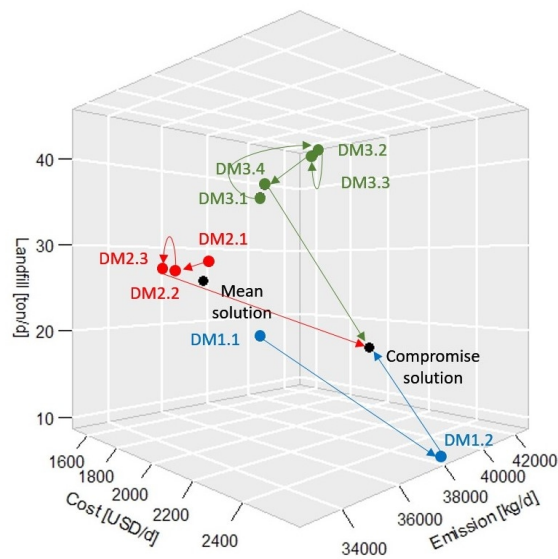
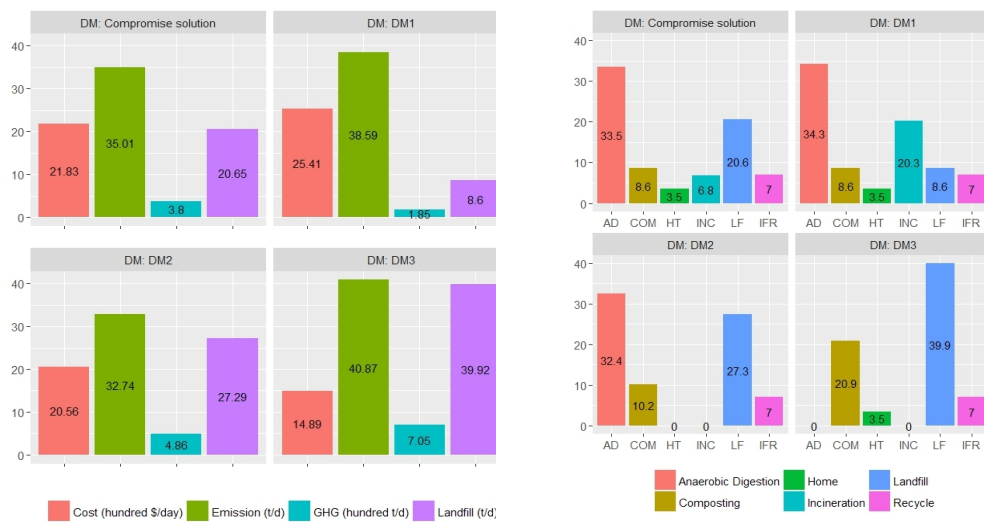


Figure 6.10 Pareto-Optimal solutions of decision-making process

### 6.5.3.2 Solutions and decision variables

Figure 6.11 compares Cost, Emission, Landfill, GHG emission and treatment alternatives used in for the system of the Pareto-optimal solution of each DM. The optimal solution of DM3 emitted the largest amount of GHG of approximately 700 ton CO<sub>2</sub>-eq /d and total pollutants emission of about 41 t/d due to a significant amount of MSW being landfill (40 t/d). However, the cost of the solution chosen by DM3 was the most economical of approximately 1490 US\$/d because of the application of low-cost technologies (Landfill and Composting). Although the DM2 was focused more on emission reduction, but the Pareto-optimal solution was closest to the compromise settlement in all aspects. The solution favours a combination of AD treatment for degradable waste and Composting treatment for sludge residual of AD and landfill for non-degradable waste. Especially, Incineration and home treatment alternatives were not selected in DM2's solution. This might be due to the high emission rate of Incineration and a higher rate of pollution emission from uncontrolled home composting than Anaerobic digestion. The Pareto-optimal solution chosen by DM1 has the highest cost because of utilization of incineration for the desire of landfill minimization, which leads to the highest emission of CO<sub>2</sub> (Figure 6.12) contributing a major part of pollution emission.



(a) Objective values and GHG emission

(b) Capacity of treatment alternatives (t/d)

Figure 6.11 Objective values and treatment alternatives of four optimal solutions

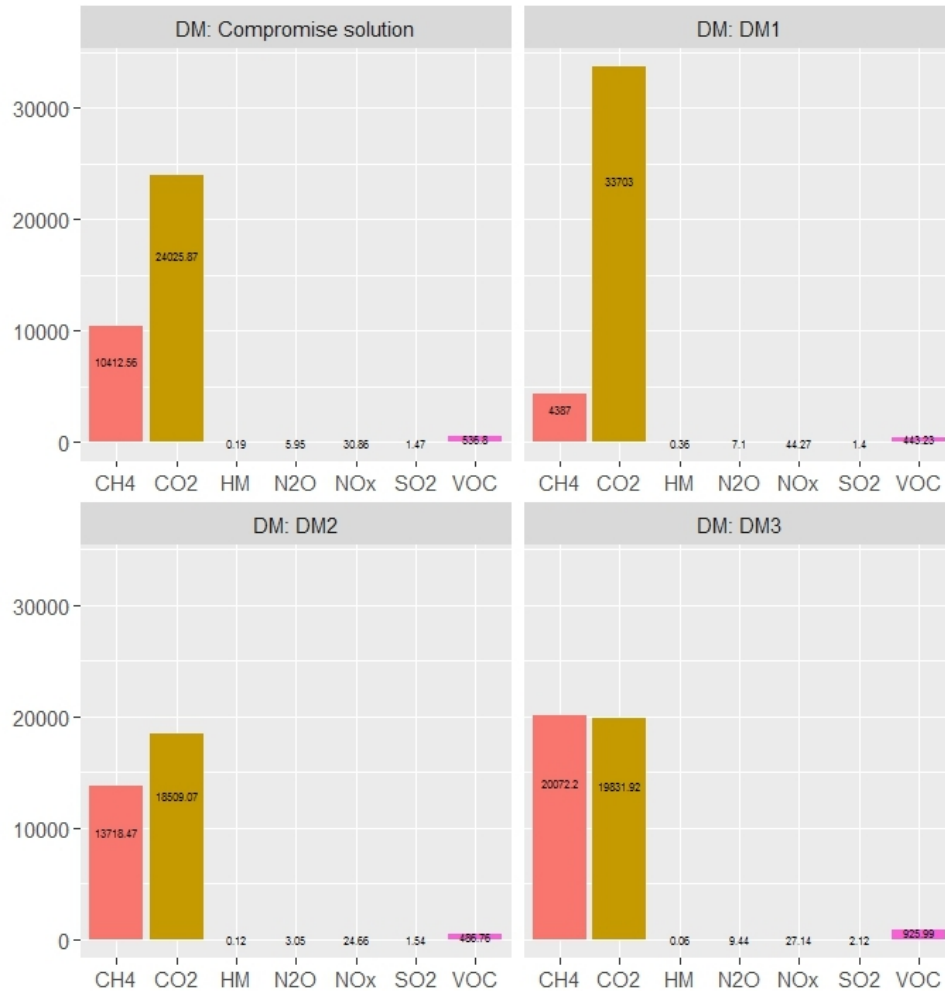


Figure 6.12 Pollution emission of obtained Pareto-optimal solution from DMs

Finally, the compromise Pareto-optimal solution chose to apply various treatment alternatives including AD for degradable waste in combination with composting for sludge treatment. The incineration with no energy recovery is used to reduce the waste to landfill, but due to economic and environmental objective, the capacity of incineration was relatively small. The compromise solution balances all objectives and requirement of DMs.

Figure 6.13 present the decision variables on the system waste flow theme as result of optimal compromise solution defined by the model, the amount of pollution emission from each treatment alternative is also presented.

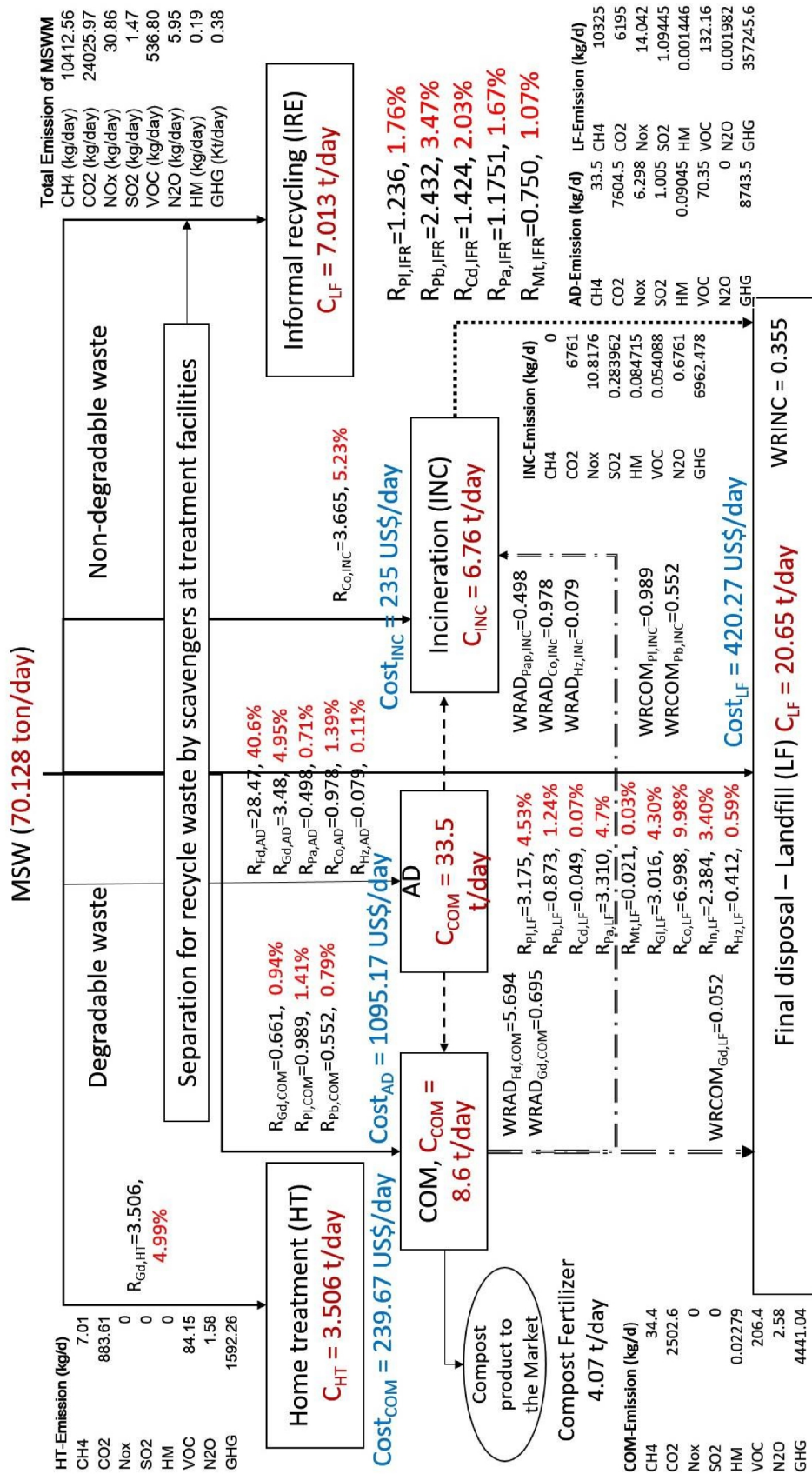


Figure 6.13 Material Flow of Sustainable Waste Management System of compromise solution

### 6.5.3.3 Sensitive analysis

The table 6.13 present the rate of waste separation at source for each optimal solutions chosen by DMs, calculated from the result of the model. For sensitive analysis, the author will recalculate the solution with the additional constraint of higher separation efficiency of the system.

Table 6.13 Waste separation rate of optimal solutions

Separation rate	DM1	DM2	DM3	Compromise solution
Degradable waste	97.9%	100%	67.96%	100%
Non-degradable waste	86.16%	100%	100%	90.8%
Average	92.3%	100%	84%	95.4%

The waste separation rate effects to model behaviour. The figure 6.14 shows that lower waste separation rate results in further the distance of obtained optimal solution and reference points. The black triangular points present the compromise reference points (0.4, 0.3, 0.2) and other colours present the normalized objectives ( $\lambda_j$ ) obtained by different waste separation rate.

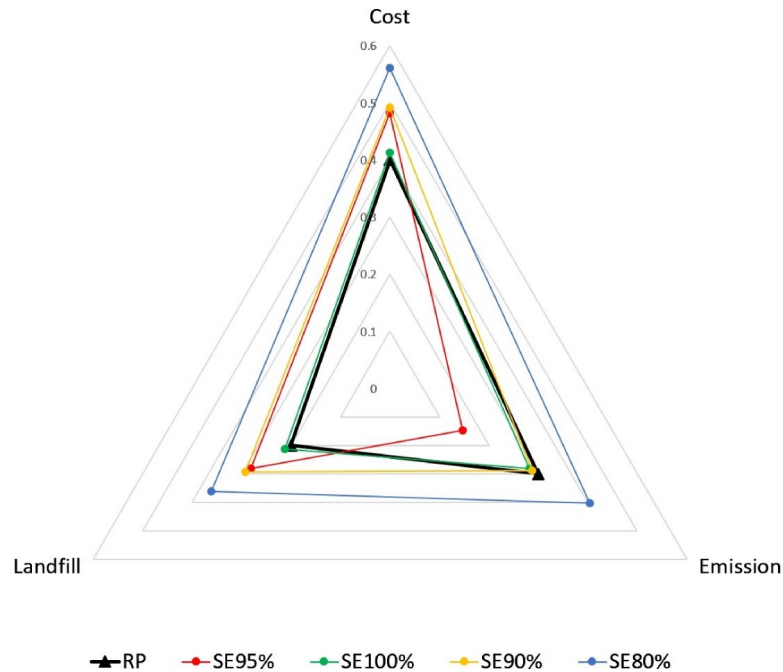


Figure 6.14 Model behaviour under uncertainty of waste separation rate

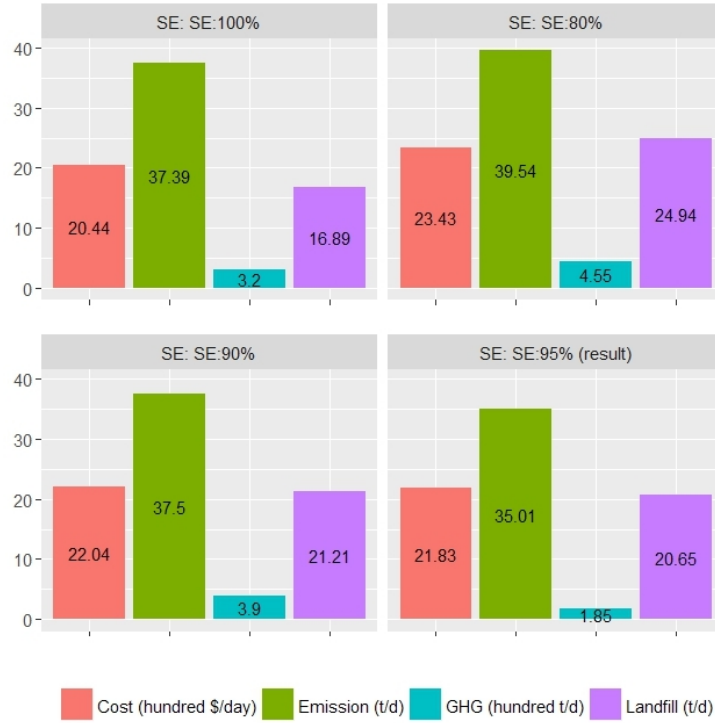


Figure 6.15 Comparison of different separation efficiency

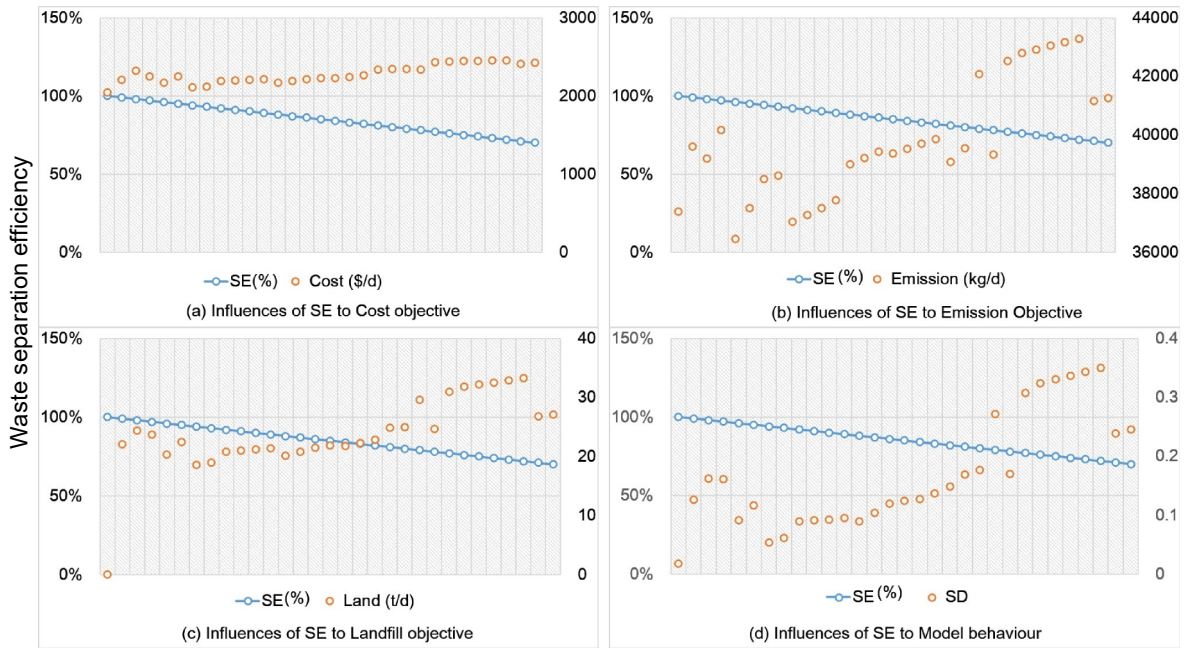


Figure 6.16 Distance and objective values associated with waste separation rate

Figure 6.16d. shows the standard deviation (SD) of  $\lambda_j$  and reference points  $\rho_j$  for 31 separation efficiency from 70% to 100%. The results indicate that the distance of waste separation affects significantly to the behaviour of the model. The Higher rate of waste separation, the closer the optimal results to the reference points. The Figure 6.16a, 6.16b and 6.16c show the real values obtained for Cost, Emission and Landfill objective associated with the separation rate from 70%-100%. The range of separation rate show the lowest objective values is from 92 to 96%.

## 6.6 Conclusion

Authors developed optimisation models for developing sustainable waste management in HAC.

The single objective optimisation model help authority to evaluate the ability to implement landfill reduction targets of the city. Higher landfill reduction target leads to higher cost for the system due to the utilisation of incineration. The system cost is also influenced by the efficiency of waste separation at source, lower rate of separation costs more. Higher landfill reduction target also causes higher pollution emission as the result of the model. In order to reach the goal of waste-to-landfill, the amount of waste incinerated should be increased, which can lead to the higher emission of CO<sub>2</sub>, the largest contributor of waste management emission (Fig 6.3, 6.4, 6.5). However, regarding GHG emission, the SC9, SC10 and SC11 emitted less GHG due to high landfill reduction goal. Thus, incineration is an important treatment alternative for landfill decrease and GHG emission reduction. However, in term of total amount of pollution emission, incineration is not favoured due to a high amount of CO<sub>2</sub> emission. Composting is the most favoured treatment practice for degradable waste as the result of the single objective model due to the low cost and low emission factors. However, the single objective model was not able to evaluate the social aspects in consideration of sustainable development.

The consensus analysis model shows that minimizing cost, emission and landfill are the most important targets of waste management in Hoi An. Also, seven treatment alternatives including COM, AD, INC, INCE, HT, IFR and LF were chosen by local experts as potentially suitable treatment options for the city. The multi-objective optimization model was developed based on targets and options chosen by local experts to minimize cost, emission and landfill. The

result indicates that the compromise solution for sustainable waste management in Hoi An chose the combination of AD and composting for degradable waste treatment (Figure 6.13). Incineration is not favored when consider emission reduction. The capacity for waste incinerator is less than 20 ton per day in all optimal solution chosen by DMs (Figure 6.11). Incineration for energy production is no chosen due to the high capital cost.

The RP method can support citizens who generated waste involving in decision making process. It shows a high potential in getting agreement of various DMs and reasoning conflicting objectives. Also, RP method in decision making process optimize social acceptance objective of the system since it comes to the compromise solution based on intensive discussion and agreement of DMs.

Sensitivity analysis indicates that the waste separation at source has significant impact to sustainable waste management. The waste management system will have more benefit (lower cost and lower emission) with higher waste separation efficiency.

## 6.7 Reference

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## **7. CONCLUSION AND RECOMMENDATION**

The aim of this dissertation was to develop a methodology of solid waste management system planning using MODM towards environmental efficient, economic affordability and social acceptance. The case study was conducted in Hoi An, a famous tourist city in Viet Nam. A holistic method approach for developing a waste management plan was discussed step by step in detail. Results were analysed and discussed to explain the model. Also, some concerning contents were provided, such as waste generation relevant households factors and improvement for household waste collection system or an increase of fee for business sectors. The evaluation of landfill reduction alternatives and waste separation rates influences to the waste management cost and system emission by single optimisation model was provided. Finally, MODM model and decision-making process by RP method suggested a sustainable solution for waste management in Hoi an city. The optimal solutions provided a detailed flow of waste materials, appropriate treatment technology and their size.

### **7.1 Summary of key findings**

An overview of the research area was introduced in the first section. Rapid urbanisation and industrialisation in Viet Nam caused the increase of waste generation and the variety of composition. In addition, inappropriate waste management system in Viet Nam has led to various environmental and health issues. Sustainable solutions for waste treatment and waste stream management is essential to improve the current status of waste management in Vietnamese cities. A study on sustainable waste management using MODM model has never been carried out in Viet Nam. Thus the study proposed a MODM model to define optimal solutions of sustainable waste management in Viet Nam.

Through the review of existing literature regarding MODM model as well waste composition and generation studies. The model proposed in this dissertation tends to cover some gaps of previous MODM model studies in waste management including optimization of social acceptance objective, measurement more pollutants emission for environmental objectives and consideration of waste cycle. To gather the input data and parameters for the model's various methods were applied such as a sampling waste at source for waste composition and generation,

face-to-face interview for collecting household's socioeconomic information and laboratory for waste characteristics and calorific values. Also, secondary data were collected from Hoi An waste treatment plant to estimate daily waste transported for treatment and local authorities' offices for demographic and economic information. Moreover, in considering waste cycle and multi-pollutants emission in the model, reliable studies and scientific reports in LCA and LCI were referred. To identify the principal objectives of the waste management system and potential treatment alternatives in the city, a face-to-face interview with 18 local experts was conducted. The main achievement is presented as follows:

1. Daily per capita household waste generation was  $0.223 \text{ kg capita}^{-1} \text{ day}^{-1}$ . Total household waste generation rate in Hoi An City was 20.75 tonnes per day, which accounted for about 30% of total municipal waste generation. People living in rural areas generated about half of the amount of daily waste compared to people living in urban areas. On the other hand, residents in the urban areas highly affected by tourism activities produced less waste than in areas not affected by such activities. Hotels generated about  $0.6 \text{ kg room}^{-1} \text{ day}^{-1}$  and one restaurant in HAC produced an average of  $26.18 \text{ kg day}^{-1}$ . The mean of waste generation from tourist streets was  $6.99 \text{ kg } 100\text{m}^{-1} \text{ day}^{-1}$ . Regarding the correlations between the waste generation rate and the number of hotel rooms, the result indicated a statistically significant correlation between the number of rooms and total waste generation of hotels.
2. The municipal waste composition of the city had food waste as the largest proportion (42%) and hazardous waste as the smallest contributor (less than 1%). Total biodegradable waste (food and yard trimmings) was approximately 53%. Combustible waste was the second significant component of about 16% while other recyclable contributed about 20% of the municipal waste composition. Waste composition in the city centre was affected by tourism services because it was different from other areas and likely alike with the waste composition of the tourism sector in food, garden, and some other components. Results of ANOVA shows that waste generation is significantly different in urban and rural areas. Meanwhile, there is no significant difference in waste composition among three strata.

3. Recyclable waste (plastic, cardboard, paper, and metal) accounted for a significant percentage of around 20% giving a good chance for material recovery. However, informal recycling activities for plastics, cardboard, and some other materials by organized waste pickers at treatment plants are currently adequate. Also, current recycling activities employ residents living nearby Hoi An waste treatment plant and are supported by local people. A material recovery program, therefore, may not be warranted for now because of social and technological constraints but should be taken into account in the future.
4. Results of this study suggested a methodology of waste generation and composition survey, the classification category list for sustainable waste modelling and planning. The results and methodology are useful for decision makers, authorities, planners as well as researchers to develop or modelling sustainable waste management.

The results of waste physical and chemical characteristics also analysed and discussed:

5. The moisture content of MSW in Hoi An is about 53%. The high moisture content is caused by Food and Garden waste, which accounted for 40% and 10% in composition and the moisture content is 75% and 57% respectively. The high moisture will affect the thermal treatment of MSW but is essential for biological treatment technology. Also, the C:N ratio of biodegradable waste (Food and Garden waste) is 22.1, which is a good ratio for composting. However, since the composting planting in Hoi An has been operating ineffectively, a deeper study in socio-economical and technical efficient assessment might be needed to improve the treatment efficiency.
6. The average heating value of MSW is about 9.4 MJ/kg waste (ranged from 2 – 30 MJ/kg). An incineration could be a potential technology to reduce the waste amount quickly in the city. WTE has been one of the best technology in term of energy recovery in MSW management. The result from energy content of MSW in Hoi An indicated that a WTE system might be a potential option for the city waste treatment system.

Another content included in this study is household relevant factors of waste generation and waste generation predictive model were presented with following findings:

7. The study indicated that the impacts of socio-demographic, geographic variables and family economic activities on waste generation rate are highly significant. The location of the house is the most affected predictor for the daily amount of waste generated per capita. The model showed that a person in an urban house produced much higher solid waste (70-80%) than one living in a countryside family. Another important factor influenced the household waste generation in HAC is family economic activities. If a family is holding a business at home, the waste generation rate of the household will increase by about 35%. The study found that household size and the area of the house are also significant determinants of per capita waste generation while other variables, particularly income per person, prove to not significant as correlates of waste production.
8. Regarding waste generation modelling, results from this study demonstrate that Bayesian Model Average method was a robust method to determine solid options in multiple linear regression models, especially dealing with a big number of independent variables. The result of BMA indicated that the linear regression model with four independent variables was the best model for estimating waste generation in HAC. Meanwhile, the model with three regressors has slightly lower performance but is also useful to predict the waste generation of household quickly because of availability information of predictor variables in census database. Linear tests and model validation results proved that both model a reliable for estimating waste generation in the city. The study attempted to increase the understanding of waste generation to support waste management planning for the city. Thus, the two models are useful in addressing waste generation for not only analysing key factors influencing the waste generation, but they also giving waste managers a link to have a model for estimating waste generation to improve waste reduction and management efforts. The results and methodology are accepted to be informative for authorities, decision makers, stakeholders and planners to develop a waste management plan.
9. The multivariate linear regression model provides an exact estimation of waste generation in rural and urban areas in better calculation and arrangement of vehicles, labours, collection routes. It also suggests that a decentralised treatment approach could

benefit to reduce the collection cost for the small amount of waste generation in further areas. However, the approach needs to be studied carefully to have the applicable implications and appropriate legislation to encourage decentralised waste treatment. Also, the Waste fee for business sector might be an important factor to take into consideration in waste collection and management planning when the number of household opening business at home for tourism and local services such as small restaurants, homestays, shops, convenience stores and vehicle rental shops have been rising gradually in the city.

To evaluate the ability of landfill reduction implementation and effects of waste separation efficiency, a single optimization model minimizing the total cost of the system were developed under various possible analysis scenarios. The model was searching for the optimal solution of minimizing cost for 12 examined scenarios, created by the combination of three values of landfill target (50%, 25% and 10%) and four values of separation rate (100%, 90%, 80% and 70%). Multiple assessments based on main aspects such as pollution emission (including CH<sub>4</sub>, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, N<sub>2</sub>O, VOC, heavy metal...), GHG emission, cost, land use, etc. The key findings are shown as follows:

10. The Cost is proportional with the landfill target, the higher landfill reduction target the higher cost for the system. The target of 10% waste-to-landfill cannot be reached if the rate of waste separation at source is lower than 70%. For each landfill target, the lowest cost is found when MSW is separated completely (SC1, SC5 and SC9) which has the efficiency of waste separation of 100%. Thus, the separation efficiency affects significantly to the system cost. The lower separation efficiency leads to higher cost of the system. The waste separation has the same effect on emission, a lower rate of waste sorted at source causes higher emission (comparing among the scenarios with the same LT (SC1-SC4: 50%, SC5-SC8:25% and SC9-SC11:10%).
11. Incineration is an important treatment alternative for landfill and GHG emission reduction. However, in term of total amount of pollution emission, incineration is not favoured due to a high amount of CO<sub>2</sub> emission. Composting is the most favoured treatment practice for degradable waste as the result of the single objective model due to

the low cost and low emission factors. However, the single objective model was not able to evaluate the social aspects in consideration of sustainable development.

Multi-objective model and decision making procedure were applied to identify sustainable solution for waste management in Hoi An. Firstly, the objectives and potential treatment alternatives were identified via a face-to-face interview questionnaire survey, analysed by consensus analysis model. Then, the multi-objective model was developed with three objective functions including minimizing cost, minimizing emission and minimizing waste to landfill with seven potential treatment alternatives. The decision-making process was conducted with three decision makers presenting authority, citizen and waste management contractor using RP method. A sensitivity analysis was carried out to evaluate the model behaviour as well as the objectives value due to the variation of waste separation rate. The major findings are presented as follows:

12. The result indicates that the compromise solution for sustainable waste management in Hoi An. The capacity for the waste incinerator is less than 20 ton per day in all optimal solution chosen by DMs. The compromise solution showed that the total cost of the system is about 2200 \$/d, the total emission of various pollutant is 35 t/d and waste to landfill is approximately 20 t/d. GHG emission of chosen solution is about 3.8 t/d. Incineration for energy production is not chosen due to the high capital cost. The combination of AD and composting was suggested for degradable waste treatment, in which degradable waste is processed in AD then the sludge residual will be treated with composting. Incineration is not an optimal option when considering emission reduction. Thus, the amount of waste incinerated is relatively low. The results indicated that collecting and treating degradable waste separately is a sustainable option for HAC (also other cities in Viet Nam) due to high moisture, low calorific values of food waste as well as low cost and low emission factors of treatment technologies (anaerobic digestion and composting). Incineration contributes significantly to the reduction of waste to landfill, but a high financial burden and CO<sub>2</sub> emission.
13. The RP method and CAM can support citizens who generated waste involving in the decision-making process, to optimizing the social aspects in optimization model. It shows a high ability in supporting DMs for agreement and reasoning conflicting



objectives. Also, RP method in decision-making process optimizes social acceptance objective of the system since it comes to a compromise solution based on intensive discussion and agreement of DMs. Sensitivity analysis indicates that the waste separation at source has a significant impact on sustainable waste management. The waste management system will have more benefit (lower cost and lower emission) with higher waste separation efficiency.

## **7.2 Limitations of the study and recommendations for future studies**

The dissertation aimed at to develop a holistic methodology of sustainable waste management planning for cities in Vietnam by using MODM model. However, there are limitations and lessons learned from this study.

1. Regarding waste generation and composition, household waste and tourist waste generation was well and detailed identified but not other sources such as hospital, institutional, industrial, market waste. Further studies should focus on waste from more sources.
2. In addition, tourist waste has a major contribution in the city as well as great variation in different types of source. Thus, detailed study in tourist waste generation and composition based on scales of sources, characteristics of sources and location of sources will provide beneficial data in model calculation. Studying on tourist waste generation and composition is being carried by another member of our lab.
3. The seasonal variation was not concerned in this study. Thus, solid waste characterization variation between dried and rainy season was not verified. Waste characterization associated with seasonal variation study is also recommended.
4. The linear regression models constructed in the current study is valuable in estimating waste generation as it provides observational evidence of the influences of multiple factors. However, it is not reliable for predicting waste generation in the future. Lack of historical data in caused difficulties for modelling waste model predicting the future. Thus, modelling municipal waste generation model which can forecast the future is essential and needed to be studied. Consumption habits and attributions of residences

should be studied in association with waste generation and composition, which can provide additional information in predicting waste generation and composition.

5. The parameters for waste flow, waste residual, pollutant emissions factors in the model proposed were referred from other studies. The author was not able to conduct independent LCA and LCI study for various waste treatment process to obtain the parameters due to the complexity, high cost and time-consuming. Thus, LCA and LCI studies for different waste treatment technologies in Viet Nam is essential. That will contribute significantly in waste cycle calculation and model precision and therefore, provide more accurate results.
6. The study proposed a deterministic model to identify the optimal solution for the city. The sensitivity analyses were conducted in this study, but just for the variation of waste separation efficiency, other variations such as waste generation input, variation in cost was not able to be conducted. Thus, it is recommended that more sensitivity analysis with more variation of parameters should be assessed to examine the diverse of the solutions. Stochastic modelling of the system is also suggested to identify the change of the solution when waste generation input varies.

## ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my principal supervisor Prof. Fujiwara Takeshi for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. His valuable advices, creative ideas and excellent guidance helped me in all the time of research and writing of this dissertation. Thanks for his enthusiasm and patience, not only in teaching me to do research, but also in instructing me the Japanese cultures and working manners, I improved myself in many ways. I could not have imagined having a better advisor and mentor for my Ph.D study.

Besides my advisor, I would like to send my profound gratitude to Prof. Kawamoto Katsuya and Prof. Matsui Yasuhiro, who gave me insightful comments and enthusiastic supports, and also excellent suggestions which incited me to widen my research from various perspectives as well as my dissertation composition.

My sincere thanks also goes to Ms. Chujo Yoko, who provided me kind support and great encouragement throughout the period of my study, and Ms. Ono Yoko, a very nice, friendly and helpful person who has been constantly supportive during my first two years. Thank you for your supports and guidance to help me in life and work since the first day I have been in Japan. Without your precious support it would not be possible to conduct this research.

I also wish to convey my grateful to Prof. Watanabe Masaji for his great mathematical modelling lectures that I attended, also his patience and enthusiastic suggestions.

I would like to thank people in Sanyo Bigyo Co. Ltd, where I stayed during my internship. Special thanks to Mr. Muroyama Koichi, who gave me great support and helpful guidance in the company.

I am grateful all the people that I worked with in Hoi An city, Mr. Quang (Hoi An Environment and Natural Resource Office), who provided me a lot of important information; Ms. Ngoc and Ms. Thuy (Hoi An Public Work Service Ltd. Co), who helped me a lot when I worked in the field. Also, I would like to thank to director board of Hoi An Puplic Work Service Ltd. Co and College of Technology - The University of Danang for the use of their facilities. The

financial support from the Research Grant for Encouragement of Students of Okayama University is also greatly acknowledged.

I thank to my friend Dr. Nguyen Phuc Thanh for his long and informative discussion also his excellent experience sharing. I thank to a fellow, Mr. Dinh Tien Tai for his interesting discussion and his helpful comments in data analysis. I also thank to my colleagues in Department of Environmental Technology and Management, National University of Civil Engineering in Viet Nam, who always support and cheer me up. Special thanks to Prof. Nguyen Thi Kim Thai, who provided me huge support and valuable suggestions in my research.

I thank my fellow labmates in for the stimulating discussions, for the funny time we were spending and working together. My sincere appreciation goes to Mei, Seng, Lena, Dinh, Yoneda, Wada, Ogasawa, Fukuyama, Yamashita, and other members for your kindly help, your support and providing favorable conditions for my study in the lab and for all the fun we have had in the last three years. Special thank is due to Toan, my lab-mate for his valuable support, constant and continuous help during the time of conducting survey and sampling in Hoi An city. I also thank to Phuoc, who help me a lot in analyzing waste samples.

I also thank my friends (too many to list here but you know who you are!) for providing support, friendship and love that I needed. I would like to thank to all of you for sharing, enjoying with me, always being supportive throughout my time here and for enrich my life in Japan in many ways.

I especially thank my mom, dad, and sister, brother-in-law and my niece, who gave my grate support and love. My hard-working parents provided me unconditional love and care. I would not have made it this far without them and I know I always have my family to count on when times are rough.

I cherish the inspiration of my best friend, soul-mate, and beloved wife. I married the best person out there for me. Phuong is the only person who can appreciate my personality and sense of humor. She has been a true and great supporter and love me unconditionally during my good and bad times. These past three years have not been an easy ride, both academically and personally. I truly thank her for sticking by my side, even when I was irritable and depressed in struggling for research. I feel that what we both learned a lot about life and to live life to the

fullest. There are no words to convey how much I love her. Also thanks to my beloved son, Minh Duong, my treasure, energy recharger and mental power for his unconditional love. This work cannot be finished without their love and support.