Sustainable Solutions for Municipal Solid Waste Treatment: A Multi-stakeholder Decision-making

by

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Abstract

Municipal solid waste treatment options are not necessarily pragmatic if their long-term benefits don't mutually satisfy all related stakeholders such as industry, municipality, etc. Stakeholders are inclined to select an option with the maximized benefits and minimized lifecycle costs. A decision support framework is needed to identify and evaluate available waste treatment options under diverse multiple criteria and conflicting preferences of multiple stakeholders. This study developed a decision support framework that guides stakeholders to reach an agreement on the most sustainable and pragmatic waste treatment option. The framework compares lifecycle sustainability impacts of different waste treatment options and uses Analytical Hierarchy Process to determine a weighting scheme, which has an ability to combine diverse impacts based on stakeholders' preferences. It also employs Game Theory to model stakeholders' dialogues and behaviors in the group decision-making. The outcome of the framework is to recommend fair shares of costs and benefits to assist stakeholders in reaching a mutually agreeable solution.

The application of the developed framework is demonstrated through a case study of waste treatment in Metro Vancouver (British Columbia, Canada), where the industry and the municipality are proposing the production of Refuse Derived Fuel (RDF). Results show that both industry and the municipality may benefit from RDF and waste-to-energy options, respectively; however as a compromised solution, the industry should pay a tipping fee to access the required amount of solid waste from the Metro Vancouver to substitute the use of fossil fuels with RDF.

Uncertainty is unavoidable due to the inherent complexity in the methods and input data, and should be acknowledged to enhance the reliability in decision-making process. Most common uncertainties encountered in such environmental management problems are in cost and benefit estimates, and stakeholders' ability in verbalizing their preferences, and their knowledge about each other's priorities. The decision support framework used sensitivity analysis, Fuzzy Set Theory, and Bayesian Games to study the uncertainty impacts on the decision-making process.

Preface

I, Atousa Soltani, gathered and developed all the contents in this thesis under the supervision of Drs. Rehan Sadiq and Kasun Hewage. They have reviewed all the manuscripts and provided comprehensive feedback to improve the manuscripts as well as the thesis. Most of the content of this thesis is published or submitted to scientific journals. Three journal papers directly formed the body of this thesis, while two journal papers indirectly helped the development of this thesis.

- A version of Chapters 2 is published in the journal of *Waste Management* with the title "Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: A review" (Soltani et al., 2015a). I conducted the analysis and wrote the manuscript. In addition, a portion of Chapter 2 is published in the *International Journal of Systems Assurance Engineering and Management* with the title of "Human HEalth Assessment for Remediation Technologies (HEART): A Multi-Criteria Decision Analysis Tool" (Soltani et al., 2015b). This paper is a collaborative work and my contributions were in the Multi-criteria Decision Analysis section and I also participated in analysis and writing of the paper.
- Chapter 3 is based on a paper titled "Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: a game theory approach for group decision-making". This paper is under review in the *Journal of Cleaner Production* (Soltani et al., 2015c). I wrote the manuscript and performed all the analysis in this study.
- A version of Chapter 4 is published in Soltani et al. (2015c) and a paper titled "Environmental and economic aspects of production and utilization of RDF as alternative fuel in cement plants: A case study of Metro Vancouver Waste Management", which is published in the journal of *Resources, Conservation and Recycling* (Reza et al., 2013). I developed and wrote the economic aspects of the analysis and the remaining study was a collaborative work.
- A version of Chapter 5 is under review in the journal of *Environmental Modelling and Software* as a study titled "Studying the impacts of uncertainty in group decision-making setting: strategizing municipal solid waste treatment" (Soltani et al., 2015d). I conducted the analysis and wrote the manuscript.

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List of Abbreviations

2,4-D	2,4-Dichlorophenoxyacetic
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
BC	British Columbia
BEES	Building for Environmental and Economic Sustainability
CFC-11	Trichlorofluoromethane
C_2H_6	Ethane
CI	Consistency Index
CO_2	Carbon Dioxide
CR	Consistency Ratio
DEA	Data Envelopment Analysis
DEMATEL	Decision Making Trial and Evaluation Laboratory
EAV	Equivalent Annual Value
EDIP	European Life Cycle Database
ELECTRE	Elimination Et Choix Traduisant la REalite
EPP	Environmentally Preferable Purchasing
Eq	Equivalent
GHG	Greenhouse Gas
GIS	Geographic Information Systems
H+	hydron
HANP	Hierarchical ANP
ISO	International Organization for Standardization
Kg	Kilogram
KWh	Kilowatt hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAUT	Multi Attribute Utility Theory

MCDA	Multi-criteria Decision Analysis
MJ	Megajoules
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
MWh	Megawatt hour
N	Nitrogen
NO_x	Nitrogen Oxide
NPV	Net Present Value
NSERC CRD	Natural Sciences and Engineering Research Council Collaborative Research and Development
OWA	Ordered Weighted Average
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
RBMCA	Risk-Based Multi-Criteria Assessment.
RDF	Refuse-derived Fuel
RI	Random Index
SAW	Simple Additive Weighting
SETAC	Society of Environmental Toxicology and Chemistry
SI	Sustainability Index
SO_2	Sulfur dioxide
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRACI	Tool for Reduction and Assessment of Chemical and other environmental Impacts
TBL	Triple Bottom Line
UK	United Kingdom
UNEP	United Nations Environment Programme
USA	United States of America
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WLC	Weighted Linear Combination
WTE	Waste-to-Energy

Acknowledgements

This work is the result of many people's and God's support and kindness towards me. First and foremost, I would like to express my sincere gratitude to my advisor Professor Dr. Rehan Sadiq, who believed in me and encouraged me to strive for the best. Dr. Sadiq is an outstanding mentor and a passionate researcher. I am grateful for the chance he gave me to follow what I love and for the time I spent at the University of British Columbia to work under his supervision. His encouragement, generosity, and hard work inspired and shaped me to be a better researcher and a better person. I would also like to thank my co-supervisor, Dr. Kasun Hewage, for his creative comments on my research and his continuous support throughout my studies. He is a very compassionate teacher and one of the friendliest people I know. I am deeply grateful for his guidance and for listening to my concerns with patience.

I am also grateful for Dr. Shahria Alam for kindly accepting to be on my doctoral committee and for his insightful comments on my research. I also thank Dr. Arjun Bhardwaj for being my proposal defense examiner and for his positive attitude and his refreshing suggestions on my research.

I am thankful for the support and help provided for me from the staff and faculties in the School of Engineering at the University of British Columbia. I would like to thank Dr. Bahareh Reza for providing insights on my publications and for her friendship. I am thankful for Dr. Husnain Haider's help and suggestions for this thesis. I am also fortunate to have worked with many talented students and colleagues at the Project Lifecycle Management Laboratory. I am deeply grateful for Amanda Brobbel at the Centre for Scholarly Communication for helping me revise this thesis.

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I am grateful for the time I spent in Kelowna and the people I met here. I would like to thank my amazing roommate and friend, Shelir, who made our place feel like home and for many great memories. I appreciate the friends I found here - Salma, Maziyar, Golriz, Hadi, Elaheh, Mohsen, and Shabnam - for their support when I was new in town. I am very thankful for my life time friends, Elham, Neda, Golshid, and Shahrzad, who were always there when I needed them the most. I would also want to thank my aunts who were very kind and helpful to me. I am also very grateful for Shirin and for her kind heart and soul.

I am genuinely grateful for Navid Hossaini Fard, who helped me find my way when I was lost and supported me to follow my dreams. He has always cheered me up and inspired me to be fearless. He is the reason behind the beginning of an amazing era in my life and I am truly happy that I got to know him.

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To my lovely Maman and Baba

Chapter 1 Introduction

1.1 Background

Waste generation is an unavoidable consequence of anthropogenic activities, which has a huge impact on the quality of life (Boyle, 2000). Since the start of the industrialization and urbanization, Municipal Solid Waste Management (MSWM) has been a challenge for municipalities around the world. Municipal Solid Waste (MSW) is defined as "refuse that originates from residential, commercial, institutional, demolition, land clearing or construction sources" in the *Environmental Management Act* (BC Ministry of Environment, 2013). In addition, MSW is the non-hazardous solid waste (Figure 1.1). With more than half of the world's population residing in urban areas, where most of the MSW is generated and disposed, its management becomes the corner stone of urban planning and management policies (Dewi et al., 2010).

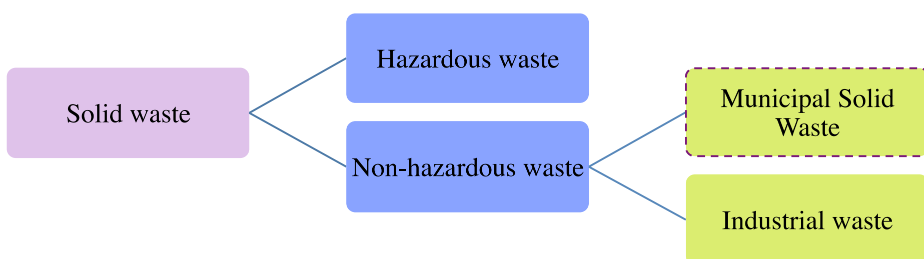

Figure 1.1 Solid waste categories (USEPA, 2013a)

Globally, the generation of MSW has doubled to 1.3 billion tonnes/yr (1.2 kg/ cap/ day), in the past decade, and is anticipated to double again to 2.2 billion tonnes/yr in the next decade (Hoornweg & Bhada-Tata, 2012). In 2008, Canada disposed[1] of 777 kg of MSW per capita, the third highest amount in the world and the highest amount among the developed countries (Hoornweg & Bhada-Tata, 2012); This is more than twice Japan with the lowest amount among the developed countries. Figure 1.2 shows the generation of MSW per capita in

[1] The disposed waste refers to the amount of generated waste after diversion and recycling.

Canada as compared to some other major contributors. Figure 1.3 also compares Canada's contribution towards world's MSW generation. Despite of the mere reduction in MSW disposal (735 and 720 kg per capita in 2010 and 2012, respectively), Canada is still a top contributor to the global disposal of MSW. Canadians disposed of about 25 million tonnes of MSW in 2012, with the province of British Columbia (BC) making up to 10% of that share (Statistics Canada, 2015). MSW's mixed origins and increasing rate of generation has made it a complex and yet critical stream of waste around the world. High generation of waste in North America can be linked to consumerism, increased packaging, the availability of land, and the lack of both effective upstream strategies and pragmatic downstream plans.

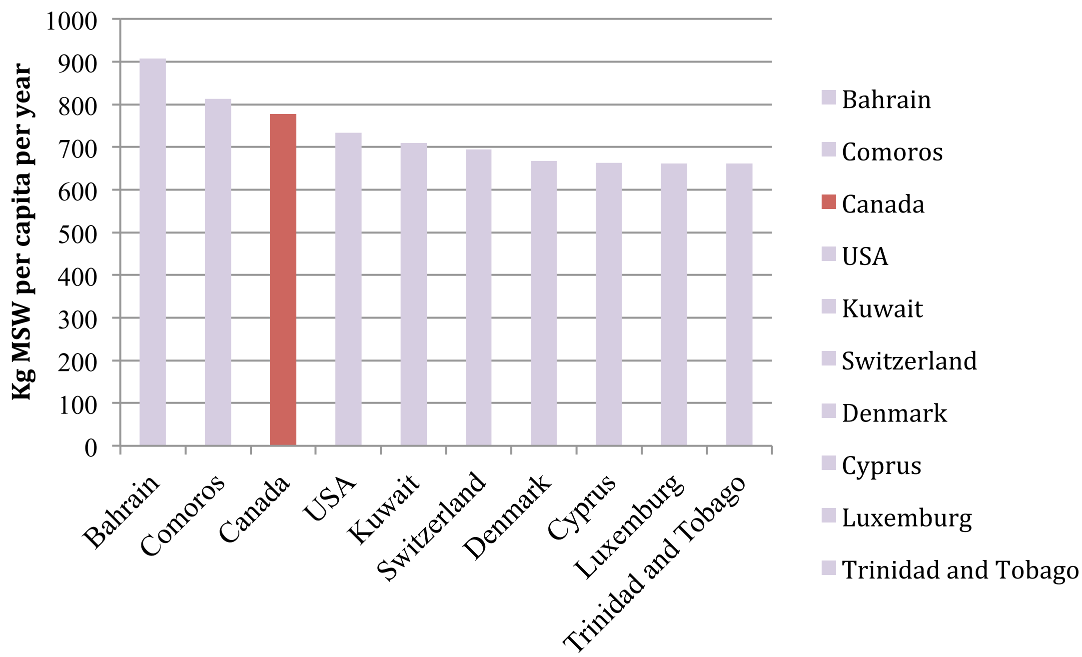

Figure 1.2 Ten countries with the highest disposal of MSW per capita in 2008 (derived from D-waste (2015)**, data published in 2012)**

Unattended MSW can threaten human health and the environment. In 2012, one in eight deaths worldwide were linked to air pollution, a consequence of unsustainable policies in transport, energy, and waste management sectors (WHO, 2014). Abandoning waste irresponsibly or burning waste without the necessary precautions can release hazardous pollutants and toxicants into air, soil, and water, causing health issues such as heart disease, acute/chronic respiratory illnesses, dermatological diseases, eye irritations, and reproductive disorders (Rushton, 2003; Porta et al., 2009). Hence, governments and scholars constantly look for effective MSWM strategies to avoid these hazards.

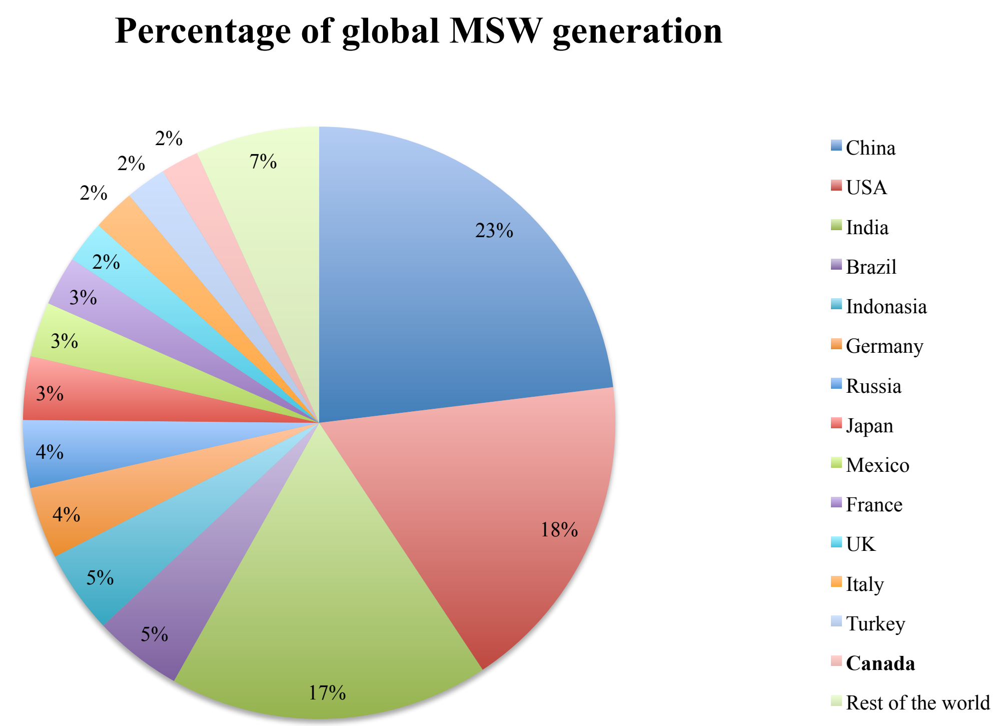

Figure 1.3 Countries' shares of MSW generation in the world in 2008 (derived from D-waste (2015)**, data published in 2010-2012)**

The main objective of MSWM is to protect human health and the environment, support economic development, and fulfill social and regulatory requirements. Finding a balance between the scarcity of natural resources and unlimited needs of humans has gone beyond just financial planning and urgently requires an arrangement that can protect resources of all kinds. Sustainability paradigm refers to the assessment of environmental, economic, and social impacts of available options to find a long lasting balance among these criteria. Sustainable decision-making on MSWM strategies will save natural and financial resources for the future generations.

In MSWM studies, sometimes elements of MSWM such as plant locations or waste treatment technology are optimized and other times MSWM is analyzed as a system (Hung et al., 2007). Nonetheless, selecting and implementing a viable waste treatment option is the core path to meet the MSWM objective and the most debated issue in the MSWM literature, due to the significance of its ecological and financial impacts. There are several treatment options for MSW, therefore choosing the optimal waste treatment option(s) usually involves decisions about the technology, location, and capacity of the treatment plant (Achillas et al., 2013). In this study, an optimal option is defined as the best or most satisfactory option that is reasonably accessible with regards to the criteria and constraints.

Sustainable decision-making on waste treatment options requires a holistic assessment of available options based on various conflicting criteria. Consideration of these criteria changes a simple optimization problem with a unique optimal solution into a complex problem with countless suitable options (Wiecek et al., 2008). Hence, an optimal waste treatment option is selected among available and suitable options based on their performance in the sustainability criteria and the satisfactory of decision-maker(s) from those performances.

Reaching to an optimal decision becomes more challenging when multiple stakeholders with conflicting interests are involved. The involvement of multiple stakeholders can result in free rider's problem, where a municipality bears all the costs of waste treatment while other stakeholders benefit from it. The municipality is responsible for providing the public goods and services, such as waste treatment, and ends up paying the associated costs. They are fully aware of potential risks associated with poor MSW treatment and they have the right intentions to try to prevent these risks (Joseph, 2006). The free rider problem can discourage the municipality from choosing the more advanced and more expensive technologies or can result in the over-using of the provided service. A solution to this problem is to involve other stakeholders in the decision-making and execution process. Other stakeholders will be encouraged to contribute towards the relevant costs of sustainable waste treatments, if municipalities combine these services with other in-demand services (Carraro & Marchiori, 2003). A group decision-making on waste treatment options is widely impacted by the type of partnership and priorities of stakeholders.

Waste treatment options often comprise landfilling and execution of waste-to-energy (WTE) technologies. WTE technologies recover energy and retrieve reusable materials from disposed waste. In recent years, MSW treatment is facing new challenges because of limited space for landfills, increasing cost of disposal, and stringent environmental regulations (Reza et al., 2013). Hence, recovering energy would mitigate these issues by conceiving waste as a resource rather than a liability. Municipalities use the recovered material and energy towards the city's needs or sell them to an interested industry to substitute fossil fuels (Metro Vancouver, 2014a). WTE technologies can mitigate the free-riding problem by offering environmental and economic benefits to both stakeholders.

Although they often look like win-win solutions; stakeholders find themselves in competition for sharing more of the costs and less of the benefits. Therefore, the first step in choosing a proposed WTE technology is to prove that it performs better than the other available options in at least one criterion. The next step is to mutually satisfy municipality and industry with its overall performance. When none of the available options is dominantly the best in all criteria, the overall satisfaction of stakeholders is a function of their preferences. Since the goal is the selection of an optimal MSW treatment option, stakeholders should establish a trade-off among the criteria. This is a complex problem, as stakeholders often have conflicting preferences over the criteria, in a group decision-making process. A fair share of costs and benefits can result in a mutual agreement on a proposed MSW treatment option.

In summary, selecting an optimal MSW treatment option(s) requires the application of an integrated framework where MSWM objectives are effectively met (Caputo & Pelagagge, 2002). A comprehensive decision support framework can facilitate sustainable decision-making on waste treatment options in a group of stakeholders with conflicting preferences. In general, a procedure that can guide and support to form a decision is defined as decision support (Sullivan, 2002; Bardos et al., 2001). A decision support framework is an outlined procedure that supports individuals or groups in their decisions toward achieving specific objectives, guides them to the optimal solution, and has enough flexibility to be modified (Karmperis et al., 2013).

1.2 Research Question

Sustainability assessment methods such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are used to evaluate the performance of different options based on environmental and economic criteria, respectively. However to determine the overall impacts, Multi-criteria Decision Analysis (MCDA) techniques are used to aggregate the results and compare the options. MCDA is an effective tool for handling complex environmental decision-making problems (van den Hove, 2006). However, when stakeholders value criteria differently, these techniques fail to help stakeholders achieve an optimal option. Hung et al. (2007) argue that common MCDA techniques discuss trade-offs between criteria of concern but do not entertain trade-offs among stakeholders. In these trade-offs, sometimes stakeholders compete to trade less or pay a smaller share of costs.

In a group decision-making setting, stakeholders consider each other's preferences and potential decisions; but the existing literature falls short to consider the interactions among stakeholders, especially in the context of MSWM. Game theory can be an ideal platform to model group decision-making problems, which can guide a fair trade-off among stakeholders. Game theory is a collection of mathematical solutions for modeling the stakeholders' interactions (Leyton-Brown & Shoham, 2008). There have been very few reported studies in peer-reviewed literature that used game theory for decision-making in MSWM (e.g., Achillas et al. (2013); Jørgensen (2010)). However, these studies fail to use game theory models for competitions and hierarchy among stakeholders.

Another shortcoming in the existing MSWM frameworks is the lack of effective communication among various stakeholders (Bani et al., 2009). Open discussions/ negotiations consume time, are expensive, and sometimes reach to non-pragmatic solutions or even "no decision" at all. Morrissey & Browne (2004) argued that MSWM frameworks should focus more on improving the participation of relevant stakeholders instead of just focusing on technical assessment. Joseph (2006) and Joseph et al. (2012) also argued that the participation of involved stakeholder in the decision-making process is the main path towards sustainable MSWM. Therefore, a comprehensive framework that facilitates communication among stakeholders to improve their participation is needed urgently.

This study attempts to fill the knowledge gap by developing a decision support framework to guide to a mutually agreed "optimal" option that considers stakeholders' conflicting preferences, and helps them share the costs and enjoy the benefits fairly.

1.3 Research Objectives

The primary goal of this research is to develop a comprehensive decision support framework that can facilitate group decision-making for selecting a sustainable MSW treatment options as the core of an MSWM strategy. This study focuses on waste treatment technologies used in MSW treatment. Proposed framework is a conceptual model, which is focusing on MSWM issues; however it will have a potential to be applied for other engineering projects and policy-making issues, where multiple stakeholders are involved. Specific goals of this research are:

- Objective 1: Identify and provide a critical review of the state-of-the-art methods and trends in MSWM in the context of environmental decision-making and sustainability assessment.
- Objective 2: Develop a decision support framework for multi-stakeholder decision-making for selecting sustainable MSW waste option(s).
- Objective 3: Apply the developed framework to decide on the production and utilization of the MSW treatment option of Refuse-derived Fuel (RDF) in Metro Vancouver case study. This proof-of-concept will provide guidelines for the municipality and involved industry on how to work together towards sustainable solutions under conflicting preferences.
- Objective 4: Study the impacts of uncertainties on the solutions provided by the developed decision support framework.

1.4 Thesis Structure and Organization

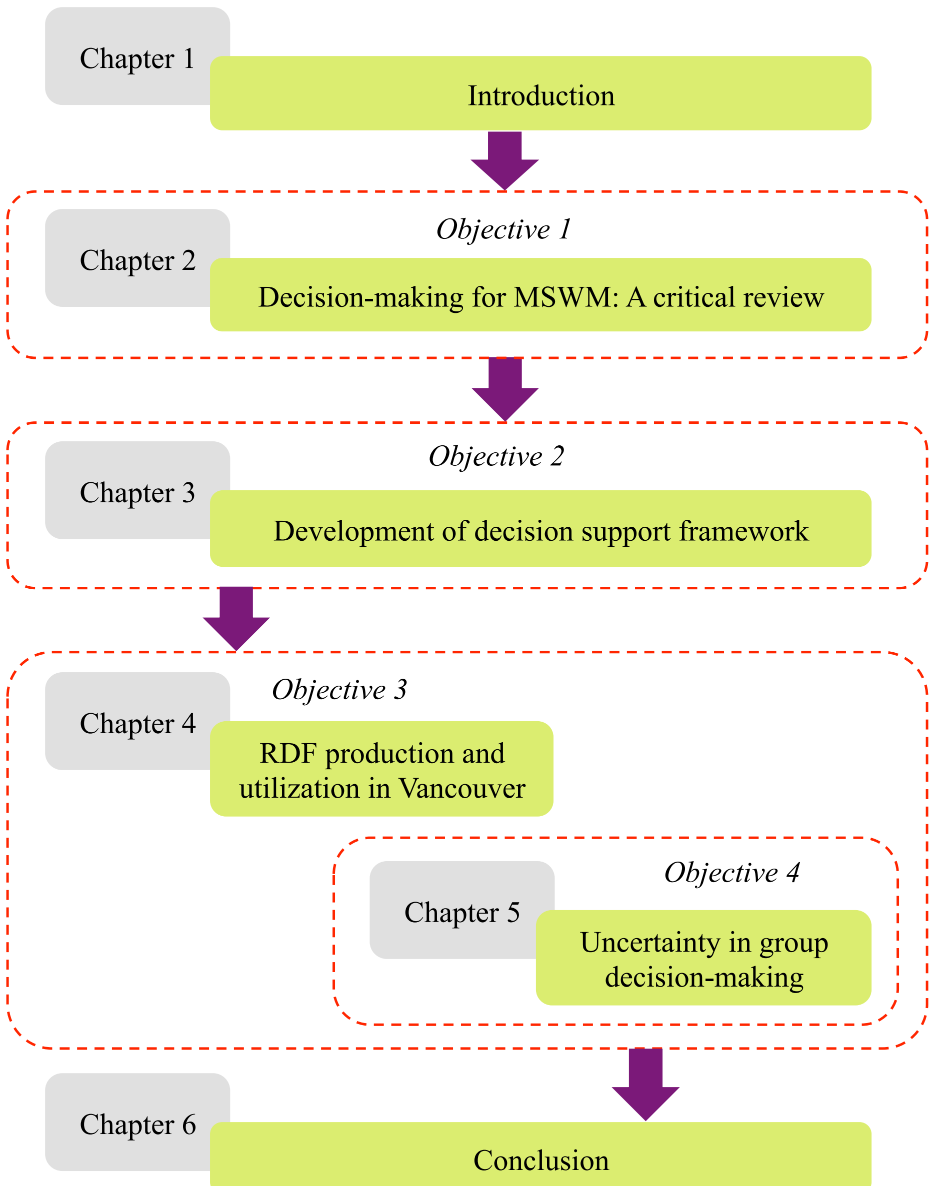

Figure 1.4 Thesis structure and objectives

Figure 1.4 illustrates the structure and organization of thesis including six chapters to achieve above objectives. Chapter 1 provides the basic introduction to the problem addressed in this thesis. Chapter 2 provides a critical review on the existing methods and frameworks for MSWM and analyzes the trends in these studies. Chapter 3 proposes and develops a new decision support framework for a multi-criteria and multi-stakeholder problem. Chapter 4 applies the developed framework to the production and utilization of RDF in Metro

Vancouver. Chapter 5 discusses the impacts of uncertainties in the inputs, models, and scenarios on the final outcome of the developed framework. Finally, Chapter 6 presents the summary and conclusion of the research and recommends potential future research.

Chapter 2 Decision-making for MSWM: A critical review

A portion of this chapter has been published in the journal of *Waste Management* as a review article titled "Multiple Stakeholders in Multi-criteria Decision-making in the Context of Municipal Solid Waste Management: A Review" (Soltani et al., 2015a). In addition, sections of this chapter are also published in the *International Journal of Systems Assurance Engineering and Management* with the title of "Human HEalth Assessment for Remediation Technologies (HEART): A Multi-Criteria Decision Analysis Tool" (Soltani et al., 2015b).

This chapter presents background information on sustainable MSW treatment, which is the core element of Municipal Solid Waste Management (MSWM). To reach this objective, sustainability assessment frameworks and tools as well as integrating frameworks have been introduced. This review shows that consideration of multiple stakeholders in MSWM is a new trend and an emerging problem, which leads to the development of a comprehensive decision support framework to facilitate such problem in the following chapters.

2.1 Municipal Solid Waste Treatment

MSWM is a multifaceted process including waste collection routes, transfer station locations, treatment strategy, treatment plant location, and energy recovery (Dewi et al., 2010). In order to design and implement a suitable MSWM, decision-makers should set regional goals for optimization of all or some of these stages and then plan a strategy accordingly. Waste treatment is often the core of MSWM due to the significance of its impacts on public safety, human health, and the environment (Achillas et al., 2013).

Waste treatment strategies often comprise landfilling and waste-to-energy (WTE) technologies. Landfilling is the burial of solid waste in excavated land after the diversion of recyclables. A significant amount of waste is landfilled around the world, mainly due to its low cost, simple technology, and the availability of land. In recent years, landfilling is facing new constraints as a result of limited space, increasing opportunity cost of disposed waste, and strict environmental regulations (Reza et al., 2013). In addition, the biodegradable components of MSW (e.g., paper and food wastes) decompose in the landfilling process and release a significant amount of methane (Environment Canada, 2013). Furthermore, landfilling may cause other significant environmental impacts such as leachate causing groundwater pollution and unpleasant odors (Reza et al., 2013).

The other waste treatment option, WTE technologies, recovers energy in the form of heat, electricity, or steam, and retrieves bottom ash, and metal from disposed waste. Recovering energy from disposed waste can generate power for municipalities, offer fossil fuel substitutes to industries, and reduce greenhouse gases and other hazardous pollutants (Metro Vancouver, 2014a). Various WTE technologies are as follows (Metro Vancouver, 2014a):

1. Mass-burn incineration is the most commonly used WTE technology. In mass-burn incineration, waste is directly combusted after mild or moderate pre-processing to produce electricity. In this study WTE option refers to mass-burn incineration.
2. Gasification and pyrolysis converts waste to syngas or vapour to generate electricity and heat.
3. Co-combustion of Refuse-derived fuel (RDF) in a cement kiln is another use of WTE technology in MSW treatment that substitutes fossil fuels with RDF in the production process of cement. RDF is a solid fuel recovered from high-calorific value fraction of mixed MSW (Genon & Brizio, 2008). RDF is obtained through conventional separation systems and is comparatively a higher-quality fuel than mixed MSW (UNEP, 2005). RDF can be employed in industrial plants to substitute fossil fuels. The extent of environmental impacts and economic net costs of RDF depends on MSW composition in the region and recovery rate; but substitution of fossil fuels in energy-intensive industries, such as cement, with RDF will definitely reduce greenhouse gas emissions and mitigate many environmental concerns (Reza et al., 2013). RDF can be classified into coarse RDF, fluff RDF, powder RDF, densified RDF, slurry RDF, or syngas RDF based on its form and density. In the production of RDF, MSW can undergo several processes including (Gendebien et al., 2003):
    - Separation at source,
    - Sorting or mechanical separation,
    - Size reduction (shredding, chipping, and milling),

- Screening,
- Blending,
- Drying and pelletizing, and
- Packaging.

The sorting, screening, and separation stages extract three major divisions of the mixed MSW (Gendebien et al., 2003):

1. The recyclable fraction (such as ferromagnetic metals). The magnetic separation unit segregates ferrous metals from mixed MSW using a magnetic head pulley, drum, and magnetic belt as separators (Figure 2.1). A single-stage magnet recovers 80 to 90% of the ferrous metal in mixed MSW (Nithikul, 2007).
2. The inert fraction (such as glass).
3. The wet putrescible fraction (such as food and garden waste).

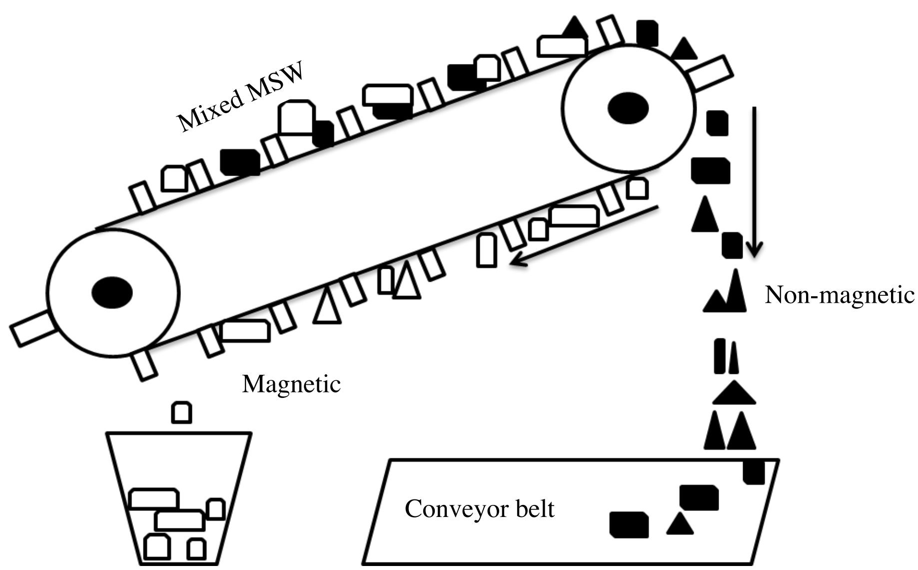

Figure 2.1 Magnetic pulley for separation of ferrous materials (Adapted from WPE (2015))

The combination of these units for each RDF facility is different and should be decided based on the waste stream and the utilization purpose. In general, RDF can be utilized in various forms (Gendebien et al., 2003): Integrated thermal conversion, co-

combustion in coal fired boilers, co-processing in cement kilns, and co-gasification with coal or biomass.

An industry that is well-suited to the employment of RDF is the cement industry (Mokrzycki et al., 2003). Globally 5–7% of human generated CO_2 emissions are contributed by the cement manufacturing (Karagiannidis (2012); Ali et al. (2011)). Cement manufacturing requires high temperature conditions, which are suitable for the thermal destruction of residuals, without producing adverse environmental effects (Baird et al., 2008). Due to the heterogeneous nature and relatively high moisture content of MSW, cement plants do not burn unsorted MSW as it can affect the quality of cement products and may cause environmental damage. RDF, on the other hand, is uniform in shape and size as well as in calorific value (Mariani, 2012).

RDF's environmental impacts and financial benefits are debatable dependent on a number of factors such as MSW composition, recovery percentage, RDF production line, heating value, etc. But, experiences of European nations suggest that the use of RDF in cement manufacturing offers environmental benefits in terms of GHG reduction (UNEP, 2005b). The use of MSW to produce RDF and its usage in cement kilns are still a relatively new concept in North America. A detailed literature review and discussion with Canadian cement manufactures revealed that RDF has not yet been used as an alternative fuel in cement manufacturing in Canada. In Chapter 4, the co-processing of RDF in cement manufacturing in Vancouver is investigated.

Since the range of waste treatment options are quite diverse, choosing a single approach or an arrangement that satisfies the decision-makers' objectives is challenging. Optimal waste treatment strategy is the result of prudent and scientifically justifiable decision-making that minimizes the risks to the environment and human health, and maximizes cost efficiency (Sadiq, 2001). Sustainability paradigm provides the mind-set that helps decision-makers achieve these goals.

2.2 Sustainable Waste Treatment

Sustainable MSW treatment attempts to re-direct the generated waste back to the consumption cycle. By reducing the extraction of material and re-purposing the generated waste, more resources will last for the future generation (Figure 2.2). Selecting a sustainable waste treatment requires the consideration of various criteria such as environmental impacts, associated economic costs and benefits, regional characteristics (e.g., waste generation rate), and social factors.

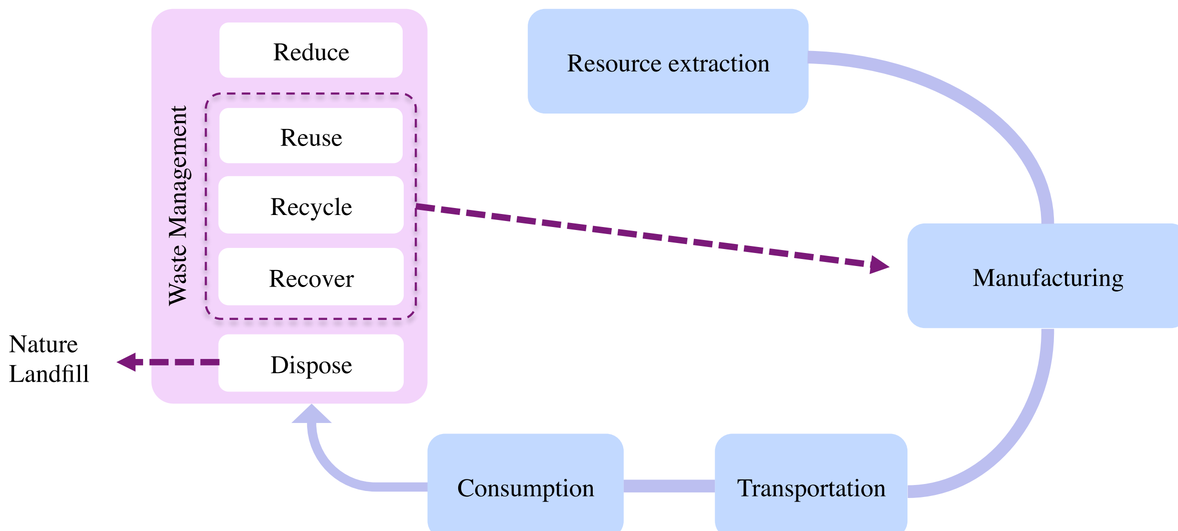

Figure 2.2 Sustainable waste treatment cycle

Sustainability assessment evaluates the implications of a proposed or existing policy, plan, or project on sustainability (Pope, Annandale, & Morrison-Saunders, 2004). More precisely, sustainability assessment helps decision-makers decide on what actions to take or avoid, to have a more sustainable society (Devuyst et al., 2001). Sustainability assessment approaches are either based on the 'triple bottom line' (TBL) concept, or the two-pillar model initially used in the Brundtland Commission (Gibson, 2001). The TBL concept promotes environmental, economic, and social criteria, while the more classical two-pillar model concentrates on the environment and development (Figure 2.3). Since the study and estimation of social impacts are subjective, complicated, and sometimes misleading, sustainability approaches focus on environmental and economic criteria and consider social impacts only if they can be assessed through these two pillars.

Decision-makers need to compare the waste treatment options based on their level of performance in fulfilling the sustainability criteria. There are various sustainability assessment frameworks available for calculating environmental impacts (e.g. LCA (the International Organization for Standardization (ISO), 2006a), environmental risk analysis (SETAC, 2004), environmental impact assessment (Canter, 1977)) and net economic costs (e.g., LCC (Blanchard et al., 1990)). In addition to these frameworks, there are numerous frameworks for comparing the performances in one criterion to another and finding a balance.

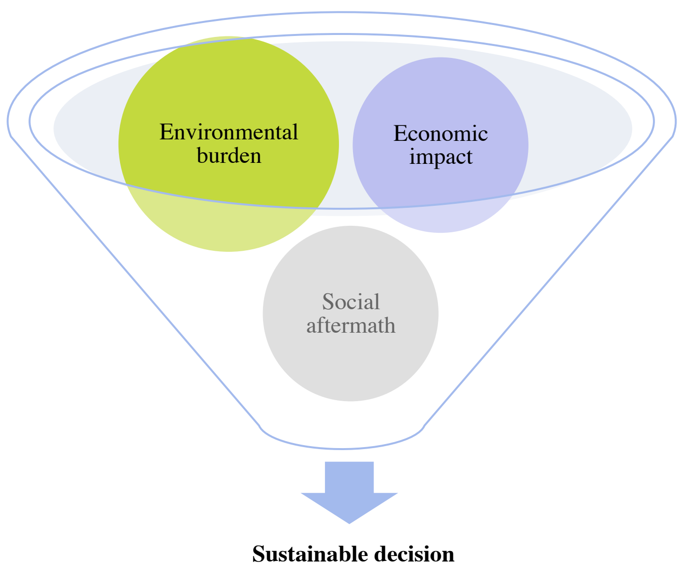

Figure 2.3 The structure of sustainable decision

When performing a comprehensive sustainability assessment, various frameworks should be incorporated. Hence, in choosing among available frameworks, decision-makers should deliberate on the following factors (Ness et al., 2007):

- The temporal aspect. Different frameworks can assess either an existing or prospective project.

- The focus or goal. Each framework is suitable for one stage of sustainable decision-making and can assess performance of projects in a specific criterion.
- The level of Integration. Various frameworks can combine environmental, social, and economic performances to a different extent.

Based on these factors, Ness et al. (2007) categorize sustainability assessment frameworks into three major groups:

- *Indicators and indices* are retrospective frameworks with simple measurements that quantify economic, social, and/or environmental parameters for a product or project.
- *Product-related assessment* frameworks focus on the material and energy flows in the life of a product. These methods do not integrate nature and society systems; however, methods such as LCC and LCA can be integrated to address both environmental and economic criteria. These methods can be both retrospective and prospective.
- *Integrated assessment* frameworks usually combine the results of previous frameworks to find a suitable trade-off among criteria. Some of the most popular methods in this group are Multi-Criteria Decision Analysis (MCDA), Risk Analysis, and Cost-Benefit Analysis. Integrated assessment techniques are prospective.

Integrated assessment methods (in collaboration with some product-related assessment methods such as LCA and LCC) deal with these concerns more efficiently and therefore, satisfy the objectives of sustainability assessment in a broader perspective. In fact, LCA and LCC are essential elements of a comprehensive MCDA approach (Morrissey and Browne, 2004). As a result, selecting the best and most effective waste treatment option(s) requires the application of an integrated framework with various methods in an effective manner (Caputo & Pelagagge, 2002).

In addition, sustainability frameworks for waste management can also be categorized based on the selected criteria. Dewi et al. (2010) categorized these frameworks into *cost-based*, *environment-based*, and *multi-criteria-based*. Cost-based frameworks evaluate alternatives based on the monetary values. Environment-based frameworks evaluate the use of natural resources and potential impacts on the environment. Multi-criteria-based models including Multi-criteria Decision Analysis (MCDA) methods consider and integrate criteria with various natures and therefore deliver more robust decisions than the two previous ones (Morrissey & Browne, 2004). LCA, LCC, and MCDA, are explored and then used in this study.

2.2.1 Life Cycle Assessment (LCA)

The LCA is a popular environment-based sustainability assessment framework that helps experts estimate environmental burdens of products, processes, and services throughout a product or service's life (USEPA, 2006). LCA studies potential environmental impacts from material extraction to production and final waste disposal (ISO, 2006a). The Society of Environmental Toxicology and Chemistry (SETAC, 1993) defined LCA as "*a process to evaluate the environmental burdens associated with products, processes, or activities by identifying and quantifying energy and material used and waste released to the environment; to assess the impact of this energy, and material; and to identify and evaluate opportunities to affect environment improvements*".

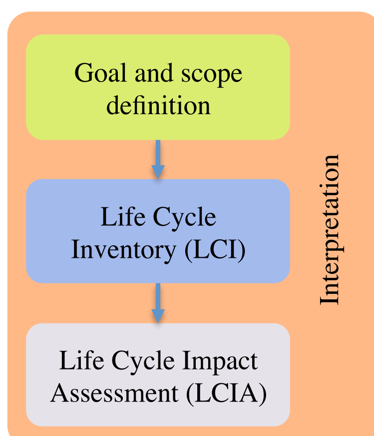

Figure 2.4 Main phases of Lifecycle Assessment (ISO, 2006)

According to the ISO 14040 and 14044 standards, LCA consists of four general steps (ISO, 2006a; 2006b) (Figure 2.4):

1. Goal and scope definition

In this step, system boundary, functional unit, criteria under study, available options, and involved stakeholders are defined. The system boundary is the section of the life of a product or service that is considered in the LCA. Waste treatment is often the end-of-life process for products, but in waste management studies, the life of a disposed waste is often from the collection point to the waste treatment plant, landfill, and even the re-using destination. The boundary of the system is often recognized with the following terminologies (Theis & Tomkin, 2013):

- Cradle-to-cradle: The entire life cycle of a product.
- Cradle-to-grave: The entire life cycle of a product except the disposal of waste.
- Cradle-to-gate: The life cycle of the product from material extraction up to the consumption of product or the execution of project.

The functional unit is the homogenous unit of waste for which all impacts are estimated. The criteria are directly connected to the goal of the study. In sustainable waste management, these criteria include environmental, economic, and - when available - social criteria. The available options are the alternatives that are being compared based o the selected criteria and the stakeholders are the agents or individuals that are impacting or being impacted by the outcomes of these assessment.

2. Life cycle inventory

In the Life Cycle Inventory (LCI) phase, data related to a project or product is collected and the level of data's accuracy is investigated (USEPA, 2006). The main purpose of LCI is to gather a list of all required material and energy and released discharges to the atmosphere, land, and water (Reza et al., 2011; USEPA, 2006). Collection of data can be costly, complicated, and tedious. Therefore, databases can simplify the process and prevent correlation among data (Reza, 2013). LCI databases are developed in regional, national, or global extent and might focus on a specific industry (Finnveden et al., 2009). LCA software tools (e.g., SimaPro and GaBi) have access to some of these databases. SimaPro is a comprehensive tool for collecting data and analyzing the impacts of various products and services, with access to various databases (e.g., ecoinvent, Agri-Footprint, European reference Life Cycle Database, and U.S. Life Cycle Inventory Database).

There are four key steps in developing an LCI (USEPA, 2006):

- Developing a flow diagram to map the inputs and outputs of a product or service based on the system boundary.
- Developing a data collection plan to identify the purpose of the inventory, geographic scope of the data, and data collection methods.
- Collecting data as a combination of research, expert contacts, site visits, and LCA software packages.
- Evaluating and documenting the results to explain the methodology. The results should include the overall system, the contributions of each stage in the system, data categories (i.e., resource use, energy consumption, and emissions), and the impacted media.

3. Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) uses the LCI data to estimate impacts on the environment (Theis & Tomkin, 2013). LCIA section classifies the potential impacts based on their consequences on human health and the environment and then converts the impacts in each group to a reference unit as a basis for comparison. Seven key steps are followed in the LCIA phase (USEPA, 2006):

- Selecting impact categories. The selection of impact categories highly depends on the preferences of individual users, the topic of study, and the type of databases. Impact categories are selected based on the mid-point impacts of the pollutants on the environment. Based on the ISO standards 14040 and 14044 for Life Cycle Impact Assessment and their technical report ISO/TR 14047, the most common environmental impact categories are introduced in Table 2.1. (ISO, 2006a; 2006b; 2012). These impact categories are selected in order to protect human health, the wild-life, oceans and fisheries, forests, and the resources they all share (e.g., atmosphere, plants, and energy sources).

Table 2.1 Impact categories and common characterization factors (adapted from USEPA (2006))

Impact category	Characterization factor
Ozone depletion	Kg CFC-11 eq[2]
Global warming	Kg CO_2 eq
Acidification	Kg H+ or SO_2 eq
Eutrophication	Kg N (Nitrogen) eq
Smog (photochemical oxidation)	Kg C_2H_6 (Ethane) or NO_x eq
Human health carcinogen (cancer)	Kg Benzene eq
Human health non-carcinogen (non-cancer)	Kg Toluene eq
Terrestrial and aquatic ecological toxicity (ecotoxicity)	2,4-D eq
Resource (fossil fuel) depletion	Quantity of used resources to reserves
Land use	Volume of land used for waste per availability of land
Water use	Quantity of used water per reserves

- Classifying LCI results under the selected categories, based on their mid-point impacts. For example CO_2 discharges are classified under the global warming.
- Characterizing impacts within each category, using scientific factors (i.e. characterization factors). This step helps unifying impacts from different pollutants for simpler comparison using equation [2.1]. Impact indicators show the total impact in each mid-point impact category (USEPA, 2006). For example, characterization factor for Methane and carbon dioxide are 21 and 1, respectively; hence, to calculate global warming potential (impact indicator) the LCI data on carbon dioxide is added to the 21 times the LCI data on Methane.

  $$\textit{Inventory data} \times \textit{Characterization factor} = \textit{Impact indicator} \quad [2.1]$$

  SimaPro can present both mid-point and end-point impacts using different impact assessment methods (e.g., CML-IA, EDIP, ILCD, ReCiPe, BEES, and TRACI). SimaPro also follows different studies to develop the default characterization factors (e.g., Intergovernmental Panel on Climate Change for climate change impact category).

[2] Equivalent

- Normalizing impacts to compare the impact indicators from different impact categories. In this optional step, indicators are divided by an appropriate reference value such as the average emission in a region (USEPA, 2006).
- Weighting and aggregating indicators to create a single index. Weights are developed based on the significance of the indicators' impacts on human health and the environment. This step carries significant subjectivity and therefore should be presented with cautious. There are various general weighting systems and tools for combining the results of different impact categories.
- Evaluating and reporting the LCIA results.

4. Interpretation of results

In this step, experts evaluate the result of LCIA to identify the stages with the most significant impacts and eventually improve the project. Uncertainty analysis is also performed at this step, if necessary. Since LCA does not consider economic or social impacts of a product or process, LCC is often suggested to be used in parallel with LCA in sustainability assessment (Gluch & Baumann, 2004).

2.2.2 Life Cycle Costing (LCC)

The LCC method is a cost-based framework that collects and sums up the monetary values of costs and benefits from all stages of the life of a product or project in the system boundary (Gluch & Baumann, 2004). Cost values incorporate investment, operation, and borrowing costs, while benefits include sale revenues (Carlsson Reich, 2005). Some of these values are only considered once (e.g., Building cost and future re-sale value of the building), while others are recurring monthly or annually (e.g., transportation and sales). In waste management studies, various methods are used to aggregate costs and benefits: Net Present Value (NPV) (Carlsson Reich, 2005), equivalent annual cost (Tsilemou & Panagiotakopoulos, 2006), and internal rate of return (Caputo et al., 2003).

It should be noted that decision-making solely based on the outcomes of LCC will also end in subjective decisions that overlook the environmental dimensions (Gluch & Baumann, 2004).

Therefore, a multi-criteria-based framework is required that can use integrated assessment frameworks to combine the outcome of the LCA and LCC. Many social impacts can also be considered through economic assessment (e.g., employment, neighborhood land prices, etc.).

2.2.3 Multi-criteria Decision Analysis (MCDA)

Many frameworks have been developed to combine the results of environmental and economic assessments (e.g., energy and material intensity metrics (Schwarz, Beloff, & Beaver, 2002), sustainability accounting (Bebbington, Brown, & Frame, 2007), MCDA (Contreras, Hanaki, Aramaki, & Connors, 2008), and monetized ecological footprints (Sutton, Anderson, Tuttle, & Morse, 2012)). MCDA, the most popular among these frameworks, is a multi-criteria-based framework. Since impact assessments are presented in different units and the value of impacts in one criterion is different from the other ones, using MCDA is necessary to present a unified sustainability index. In addition, for deciding on investment opportunities in waste treatment, the concepts of MCDA is more helpful than relying solely on life cycle assessments (Spengler et al., 1998). MCDA attempts to find a suitable trade-off amongst sustainability criteria and choose the option with the lowest overall impact. MCDA process often follows three main steps: problem identification and organization, model building and evaluation, and development of an action plan (Belton & Stewart, 2001).

The advantages of MCDA methods include the freedom of decision-makers in expressing their preferences, the measurement of several criteria in different units, and easiness of pairwise comparison for non-expert users (Bhagtani, 2008; Achillas et al., 2013). MCDA methods will also diminish the complexity of problems by creating a structure that is easy to assess for humans (Ferreira, Spahr, & Pereira, 2011). Being an integrated assessment framework, MCDA can use the advantages of other methods, while using its elements to fill their gaps (Mendoza & Martins, 2006).

Achillas et al. (2013) also report the shortcomings and challenges of MCDA methods as being prone to uncertainties and having questionable mathematical models. Sensitivity analysis often follows MCDA techniques to deal with uncertainties (CHAPTER 5). Besides, critiques of the mathematical modelling of the MCDA techniques are not based on powerful proofs. In addition, there are critiques of the subjectivity of methods; but the fact is that these methods attempt to make the subjective decision-making process as transparent and explicit as possible (Belton & Stewart, 2001).

The broad spectrum of methodologies under MCDA makes it well suited for many complex decision-making problems (Zopounidis & Doumpos, 2002). Topics such as MSWM have greater impacts on people and the environment and therefore may involve more criteria and viewpoints (Belton & Stewart, 2001). Hence, there are specific advantages of MCDA that make it a suitable technique in MSWM: its effectiveness in complex analysis and flexibility in working with both qualitative and quantitative data (Mendoza & Martins, 2006). MCDA methods have been commonly applied for decision-makings in MSWM since 1991 (e.g., (Erkut & Moran (1991); Massam (1991); Vuk & Kozelj (1991)).

MCDA methods mainly follow systematic analysis techniques to evaluate and then choose among available alternatives based on several criteria (Linkov et al., 2004). Each technique presents results in a specific form whether by sorting the options, choosing the optimal alternative, or categorizing alternatives as acceptable/unacceptable (Linkov et al., 2004). Some MCDA methods are more common among researchers due to their vast applicability to different topics and their more sufficient results.

MCDA is a collection of various techniques, which have evolved as a solution for challenges caused by the inability of people to effectively analyze multiple streams of non-commensurate information. The common purpose of diverse methods is to evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the observed limitations of unstructured individual and group decision-making (Linkov & Ramadan, 2004). These methods can be categorized under three theoretical foundations of optimization, goal aspiration, and outranking models (Linkov et al., 2004).

In optimization, numerical scores are developed from the performances of alternatives with respect to each criterion and then aggregated into an overall score. Individual scores may be simply added up or averaged, or a weighting mechanism can be used to heavily favor some criteria over the others. Contrarily, in goal aspiration, good performance on one criterion may not compensate for poor performance of others. These models establish a satisfactory level of achievement for each criterion. Moreover, the outranking models favor the alternative that performs the best on the greatest number of criteria. They compare the performance of two or more alternatives at a time, initially in terms of each criterion, to identify the extent to which a preference for one over the other can be asserted (Linkov et al., 2004). Some of the most common MCDA methods are as follows:

1. Analytical Hierarchy Process

One of the most popular MCDA methods is Analytical Hierarchy Process (AHP), proposed and developed by Saaty (1980). AHP helps decision-makers by providing them with a structure to effectively compare the competing alternatives (Handfield et al., 2002). This structure provides a mathematical solution for presenting preferences by using a method of pairwise comparison (Hossaini et al., 2014; Sadiq, 2001; Huang, Keisler, & Linkov, 2011). AHP compares alternatives based on their performance in each criterion as well as decision-maker(s)' preferences over those criteria (Linkov et al., 2004).

AHP builds hierarchies starting from the proposed problem as the base and moving up to criteria and alternatives as the upper levels (Saaty, 1980). This hierarchy system simplifies various objectives and goals into a single score and chooses the alternative with highest score for the decision-makers. The comparison is based on a quantified scale and comparative scores are entered in a judgmental matrix that facilitates calculation and aggregation of weights (Kabir et al., 2013). Weights are then normalized using various mathematical methods (Linkov et al., 2004). AHP has advantage of generating inconsistency index relative to decision-maker's inconsistency index (Pohekar & Ramachandran, 2004); but, its simplifying method may come at the risk of losing some information along the way.

2. Multi-attribute Utility Theory

Multi-Attribute Utility Theory (MAUT), developed by Keeney and Raiffa (1976), compares options based on numerical scores. These scores are derived by aggregating the performances of alternatives on each criterion. MAUT quantifies individual's preferences, by creating utility function, in order to facilitate trade-offs among several attributes (Abdellaoui & Gonzales, 2009). The main objective of MAUT is to maximize the overall utility considering the given preferences of decision-makers.

In MAUT, decision-makers are asked to assign weights to each criteria of interest based on its importance. The performances of alternatives in each criterion are ranked and quantified on different scales (e.g., 0 to 1 or 1 to 10) to create utilities. Later, an appropriate combining function is used to aggregate these utilities and generate an overall utility function for each alternative (Winterfeldt & Fischer, 1973). While MAUT generates similar scores to AHP, the interpretation of scores is quite different in AHP, as the structure of problem in AHP can change the ordering of alternatives (Huang et al., 2011b). Among difficulties of using MAUT is the requirement of an interactive environment for decision-makers to effectively produce a utility function (Pohekar & Ramachandran, 2004).

3. Preference Ranking Organization METHod for Enrichment Evaluations

Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) is an outranking method which, unlike AHP, ranks alternatives based on their dominance instead of choosing the optimal option (Linkov et al., 2004). An option outranks the other if it performs better on more number of criteria or on more preferred criteria, and equally as good on the remaining criteria (Linkov et al., 2004). In PROMETHEE, ranking of alternatives is based on their deviation from optimal point according to each criterion (Kabir et al., 2013). PROMETHEE uses a generalized criterion to build a quantitative outranking relation (Brans et al., 1986).

There are various versions of PROMETHEE including PROMETHEE I for partial pre-order (Brans, 1982), PROMETHEE II for complete pre-order (Brans, 1982), PROMETHEE III (Brans & Vincke, 1985), PROMETHEE IV (Brans & Vincke, 1985), PROMETHEE GAIA (Mareschal & Brans., 1988), PROMETHEE V (Mareschal & Brans, 1992), and PROMETHEE VI (Brans & Mareschal, 1995).

4. ELimination Et Choix Traduisant la REalité

ELimination Et Choix Traduisant la REalité (ELECTRE) is another outranking method that uses a complex mathematical process to rank or present leading alternatives. ELECTRE assigns higher ranks to alternatives that are preferred in most criteria and pass acceptable levels on all criteria at the same time; then, indices are defined for the strength of evidence for outranking relationship among alternatives (Pohekar & Ramachandran, 2004). ELECTRE, similarly to AHP, uses a pair-wise comparison technique; but ELECTRE methods are often more suitable when more alternatives and criteria are involved, compensation of one criteria for another is not applicable, aggregation of criteria in a unified scale is difficult (Figueira et al., 2005).

ELECTRE, in fact, refers to a family of methods including ELECTRE I (Benayoun et al., 1966), ELECTRE II (Roy & Bertier, 1973), ELECTRE III (Roy, 1978), and ELECTRE IV (Hugonnard & Roy, 1982). ELECTRE II was developed to deal with ranking problematic or tie situations illustrated in ELECTRE I, ELECTRE III introduced the idea of using fuzzy outranking relations; and while ELECTRE IV stopped using "relative criteria importance coefficients" (Figueira et al., 2005).

5. Technique for Order Preference by Similarity to Ideal Solution

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a series of methods developed by Hwang & Yoon (1981). TOPSIS looks for alternatives with shortest distance from the most ideal option and farthest distance from the most disadvantages option (Cheng et al., 2002; Kabir et al., 2013). It compares alternatives by assigning weights to dimensions and then quantifying the distance between alternatives and both optimal and most disadvantaged alternatives in each dimension. The ratio of distance for disadvantaged alternative and the sum of both calculated distances helps in ranking alternatives (Huang et al., 2011b).

To choose the right MCDA method for the MSWM problems, it is essential to recognize the body of knowledge on MSWM studies with multi-criteria problems. In the years 1991-2013, 68 studies have discussed and applied MCDA methods in MSWM problems on finding suitable locations for MSW disposal facilities or the optimal waste treatment option. A review of these studies will help to discover the trends and limitations in MCDA methods and draw out the type of multi-criteria problems that MSWM is facing. Table 2.2 shows how often various MCDA methods have been used and which topics have been discussed in MSWM studies (up to 2013).

Table 2.2 Studies on MSWM that have used MCDA techniques

Publications (Authors, year)	MCDA method					Topic	
	AHP/ANP/ F-AHP	PROMETHEE	ELECTRE	TOPSIS	Others[1]	Location	Treatment
(Erkut & Moran, 1991)*	✓					✓	
(Massam, 1991)*			✓	✓		✓	
(Vuk & Kozelj, 1991)*		✓				✓	
(Hokkanen & Salminen, 1994)*			✓				✓
(Hokkanen at al., 1995)*			✓				✓
(Siddiqui et al., 1996)*	✓					✓	
(Charnpratheep et al., 1997)*	✓					✓	
(Hokkanen & Salminen, 1997a)*		✓				✓	
(Hokkanen & Salminen, 1997b)*			✓				✓
(Karagiannidis & Moussiopoulos, 1997)*			✓				✓
(Berger et al., 1998)*					✓		✓
(Haastrup et al., 1998)*					✓		✓
(Chang & Wei, 1999)*					✓		✓
(Cheng et al. , 2002)*			✓	✓		✓	
(Vaillancourt & Waaub, 2002)*		✓			✓	✓	

Publications (Authors, year)	MCDA method					Topic	
	AHP/ANP/ F-AHP	PROMETHEE	ELECTRE	TOPSIS	Others	Location	Treatment
(Cheng et al. , 2003)*			✓	✓		✓	
(Karagiannidis et al., 2004)*			✓			✓	
(Chenayah & Takeda, 2005)*		✓					✓
(Gautam & Kumar, 2005)*					✓	✓	
(Norese, 2006)*			✓			✓	
(Banar et al., 2006)	✓					✓	
(Hung et al., 2007)	✓						✓
(Gemitzi et al., 2007)*	✓					✓	
(Kapepula et al., 2007)*		✓				✓	
(Louis et al., 2007)*					✓		✓
(Su et al., 2007)*	✓						✓
(Sumathi et al., 2008)	✓					✓	
(Ramjeawon & Beerachee, 2008)	✓					✓	
(Contreras et al., 2008)*	✓						✓
(Erkut et al., 2008a)*					✓	✓	
(Khan & Faisal, 2008)*	✓						✓
(Tuzkaya et al., 2008)*	✓						✓
(Önüt & Soner, 2008)*	✓			✓		✓	
(Vego et al., 2008)*		✓					✓
(Roussat et al., 2009)			✓				✓
(Ersoy & Bulut, 2009)	✓					✓	
(Garfì et al., 2009)*	✓						✓
(Tseng, 2009)*	✓						✓
(Guiqin Wang et al., 2009)*	✓					✓	
(El Hanandeh & El-Zein, 2010)			✓				✓
(Xi et al., 2010)				✓	✓		✓
(Su et al., 2010)	✓			✓			✓
(De Feo & De Gisi, 2010)*	✓					✓	
(Aragonés-Beltrán et al., & Pascual-Agulló, 2010)*	✓					✓	
(Ekmekçioğlu et al., 2010)*				✓		✓	✓
(Perkoulidis et al., 2010)*			✓				✓
(Nas et al., 2010)*					✓	✓	

Publications (Authors, year)	MCDA method					Topic	
	AHP/ANP/ F-AHP	PROMETHEE	ELECTRE	TOPSIS	Others	Location	Treatment
(Nazari et al., 2011)	✓					✓	
(Tavares et al., 2011)*	✓					✓	
(Aydi et al., 2012)	✓		✓		✓	✓	
(Yesilnacar et al., 2012)					✓	✓	
(Eskandari et al., 2012)	✓				✓	✓	
(Gorsevski et al., 2012)	✓				✓	✓	
(Makan et al., 2012)		✓				✓	
(Karmperis et al., 2012)					✓		✓
(Khadivi & Fatemi Ghomi, 2012)	✓				✓	✓	
(Paul & Krishnagar, 2012)					✓	✓	
(Madadian et al., 2012)	✓						✓
(Zelenović Vasiljević et al., 2012)	✓					✓	
(Herva & Roca, 2013)	✓	✓			✓		✓
(Korucu & Karademir, 2013)		✓				✓	
(Abba et al., 2013)	✓						✓
(Nixon et al., 2013)	✓						✓
(Gbanie et al., 2013)	✓				✓	✓	
(Alavi et al., 2013)	✓					✓	
(Makan et al., 2013)		✓					✓
(Oyoo et al., 2013)					✓		✓
(Karmperis et al., 2013)[2]					✓	✓	✓

* Studies that were also mentioned in Achillas et al. (2013)

1 WLC: Weighted Linear Combination, OWA: Ordered Weighted Average, SAW: Simple Additive Weighting, DEA: Data Envelopment Analysis, DEMATEL: Decision-Making Trial and Evaluation Laboratory, HANP: Hierarchical ANP, RBMCA: Risk-Based Multi-Criteria Assessment.

2 This study introduces a negotiating framework with examples on fees of both a treatment strategy plant and location of a plant.

Table 2.2 suggests that the overall application of MCDA methods in MSWM has increased (excluding some gaps) in the past 22 years. In addition, Figure 2.5 shows the distribution of

MCDA methods applied to MSWM studies throughout these years. According to this figure, AHP and its family (Analytical Network Process and fuzzy AHP) can be identified as the most dominant MCDA methods, PROMETHEE as an emerging method, and ELECTRE as the most consistently used method. In the recent years, the diversity of methods is expanding to include some new methods as well (e.g., WLC, OWA, SAW, etc.). While most popular MCDA methods are used at least once in MSWM studies, no study has used MAUT, which creates similar weightings as AHP through utility functions.

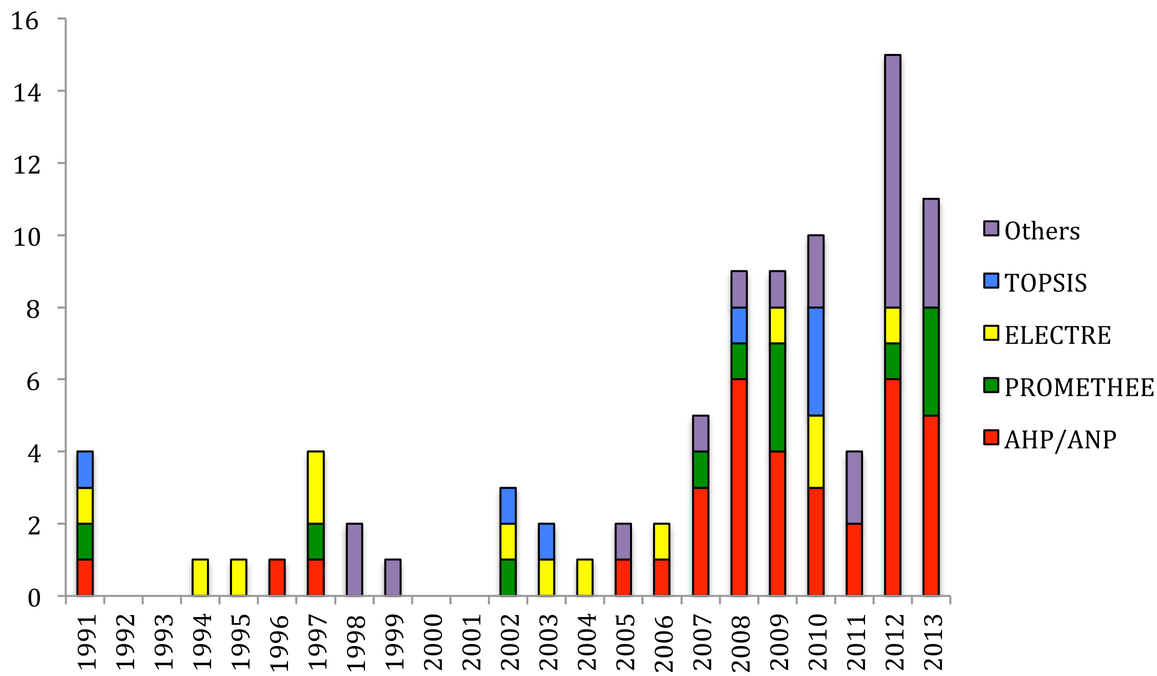

Figure 2.5 Distribution of MCDA methods in MSWM studies from 1991-2013

To separate the increase in the methods used from the increase in the number of the studies, Figure 2.6 shows the percentage of MCDA methodologies applied to MSWM studies in each year. This figure shows that the share of AHP has been steadily high, while the newer methodologies have emerged in the recent years. Studies, on average, have used less of TOPSIS and ELECTRE.

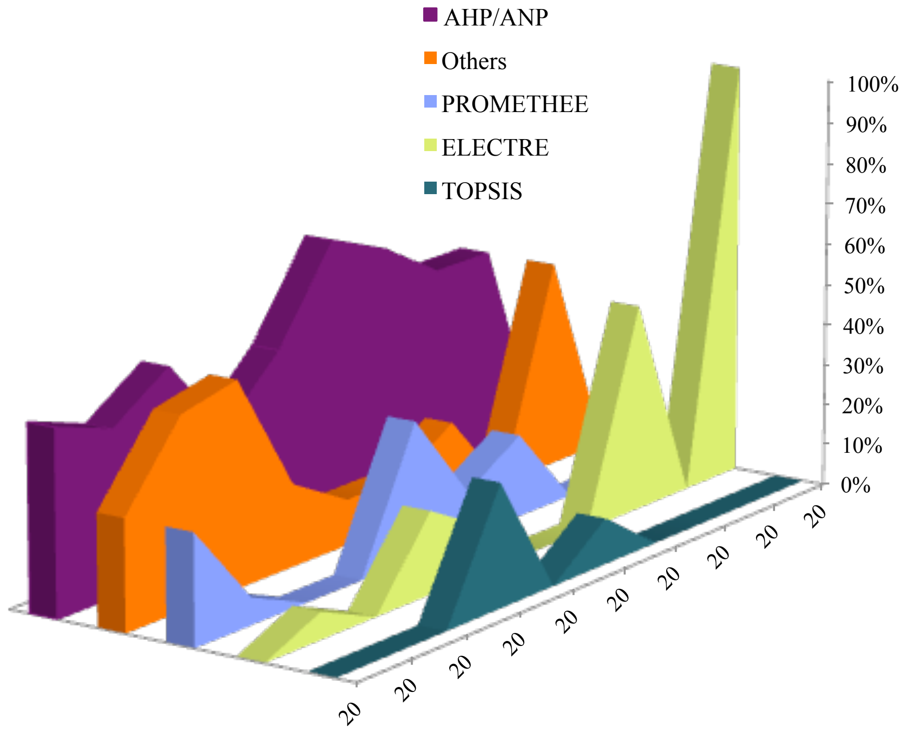

Figure 2.6 The percentage of MCDA techniques applied to MSWM in the past decade

It should be noted that a considerable portion of these studies use a combination of MCDA methods and other popular decision-making tools. AHP and Geographical Information System (GIS) is one of the most popular combinations used in the reviewed papers. GIS recognizes, connects, and analyzes the spatial data derived from maps (Malczewski, 2004). GIS model utilizes spatial data, integrates decision makers' preferences and develops a value for each alternative to help decision-makers derive the optimal option (Sumathi et al., 2008). This method helps identifying proper location for facilities and finding best routes, using optimizing techniques. Among the combinations of MCDA methods, ELECTRE and TOPSIS has been the most common.

MCDA techniques can be categorized in terms of their suitability for each topic. From the 68 MSWM studies reviewed, about 40% discussed treatment strategy and 60% the location of the treatment plant. Besides, AHP, PROMETHEE, TOPSIS, and a group of other new methods have been more commonly applied to find the location of treatment plants, while ELECTRE has been slightly more popular in treatment studies.

Finally, this analysis discovered that 38% of the reviewed studies on MSWM problems have acknowledged the involvement of multiple stakeholders in the decision-making process. More importantly, the number of these studies has tremendously increased in the past decade. These studies have used MCDA methods exclusively or in combination with optimization methods to solve the two main problems in MSWM decision-making: 1) several criteria and 2) multiple stakeholders. This trend highlights the importance of finding which stakeholders are involved in MSWM (and specifically waste treatment), and how they make a decision as a group.

Decision-making process has evolved from dealing with a single decision-maker and a single criterion to multiple decision-makers and several criteria (Banville et al., 1998). In many studies, MCDA methods have helped MSWM studies to model the impact of multiple stakeholders; examples are Garfì et al. (2009) on finding a waste management solution for a Saharawi refugee camp, Eskandari et al. (2012) on landfill siting with multiple experts, and Herva & Roca (2013) on choosing MSW treatment plants based on expert and non-expert opinions. One of the reasons why MCDA techniques are popular in multi-criteria and multi-stakeholder problems is that they can consider the stakeholders' preferences by assigning different weights to each criterion (Karmperis et al., 2013).

MCDA methods follow different paths in dealing with stakeholders. Guitouni & Martel (1998) and Vincke (1989) categorized MCDA methods for three groups based on their approach on modelling stakeholder preferences and performances: single synthesizing or MAUT, outranking, and interactive approaches (or interactive local judgement with trial and error). The first approach creates functions that aggregate and then maximize the preferences of alternatives over attributes or criteria (e.g., MAUT, AHP).

Methods following the second approach aggregate stakeholder preferences by comparing alternatives based on each criterion (Martel, 1999; Guitouni & Martel, 1998). Finally, methods with interactive approaches reach a conclusion through local gatherings and trial and errors. Guitouni & Martel (1998) differentiate the methods under these categories based on the following characteristics:

- Preferred elucidation mode (i.e. trade-off, lottery, direct rating, and pairwise comparison);
- Moment of requesting the elucidation of preferences (i.e. directly prior to, directly in the progress of, or indirectly following the assessment);
- Preference structure, which is built based on different combinations of binary relations;
- Kind of information (i.e. ordinal and/or cardinal);
- Information features (i.e. determinate or non-determinate);
- Discrimination power of the criteria (i.e. absolute, non absolute);
- Compensation (i.e. totally, partially, and none);
- Information inter-criteria (e.g., total and explicit, indirect, etc.);
- Hypothesis (i.e. independence, invariance, transitive, dominance, commensurability, inner and outer independence); and
- Treatment (i.e. thresholds, max and min operators, utility aggregation, algebraic sum, eigenvector method, etc.).

The involvement of multiple stakeholders in waste treatment is further explained in the next section of this chapter.

2.3 **Multiple Stakeholders in Waste Treatment**

In environmental decision-making such as waste management various stakeholders affect and/or are affected by the final decision. In Canada and most other countries, collection, diversion (i.e. reuse, recycle and composting) and treatment of waste are the responsibilities of the municipalities (Environment Canada, 2012). On top of municipal government, multiple stakeholders such as NGOs, environmental experts, general public, and industries affect policies and decisions related to MSWM. Municipalities seek other stakeholders' participation in decision-making through surveys, academic studies, consultations, and industry partnerships (Figure 2.7).

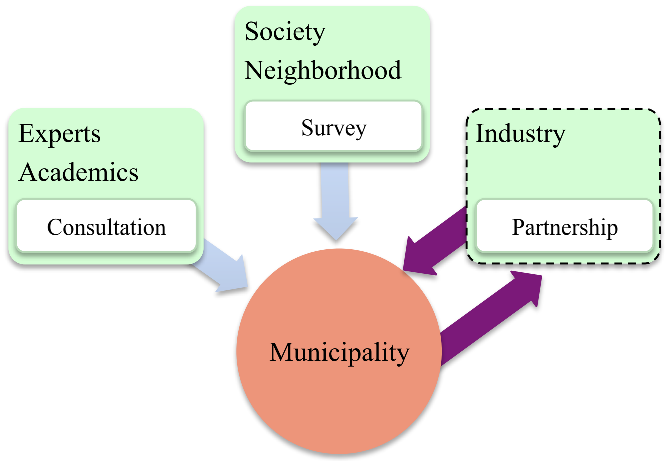

Figure 2.7 Multiple stakeholders in MSWM

When considering multiple stakeholders in MSWM, the following factors are important:

1. The extent of stakeholders' involvement in the decision-making process (i.e. stakeholders can choose the criteria of concern, rank criteria based on their importance, and/or evaluate the performance of alternatives in each criterion);
2. Stakeholder groups (i.e. local governments, municipalities, public or local residents, experts, and other non-governmental organizations or industry);
3. Hierarchy of stakeholders (i.e. some stakeholders may have priority or veto power in the decision-making); and
4. Relationship among stakeholders (i.e. competition or collaboration).

Table 2.3 shows that most studies (81%) allow stakeholders to assign weights to criteria, while only 35% require stakeholders to evaluate the alternatives on their own (Figure 2.8). Stakeholders usually assign these weights through surveys, interviews, and group meetings, or through expert knowledge. In most studies, stakeholders select the main sustainability criteria of environmental, economic and social as their main criteria of concern, while in some studies they also consider additional factors such as technological, functional, and operational criteria. The sub-criteria of interest in these studies are a combination of direct financial costs and benefits, land use, wildlife changes, human health, ecological impacts, social welfare, and public acceptance.

Table 2.3 Studies on MSWM that have acknowledged multiple stakeholders using MCDA techniques

Papers (Authors, Year)	MCDA steps			Consulted stakeholders				Relationship	
	Criteria	**Weight**	**Evaluation**	**Municipalities**	**Public or residents**	**Experts**	**Other organizations**	**Hierarchy**	**1. Coalition 2. Competition**
(Haastrup et al., 1998)			✓	✓	✓		✓	✓	1
(Cheng et al., 2002)	✓	✓		✓	✓	✓			1
(Cheng et al., 2003)	✓	✓		✓	✓	✓			1
(Hung et al., 2007)	✓	✓		✓	✓		✓		1
(Vego et al. 2008)	✓								1
(Khan & Faisal, 2008)	✓	✓	✓	✓	✓	✓	✓		1
(Contreras et al., 2008)		✓	✓	✓	✓	✓	✓	✓	1
(Sumathi et al., 2008)	✓	✓		✓		✓	✓		1
(Ramjeawon & Beerachee, 2008)		✓		✓		✓	✓		1
(Wang et al., 2009)		✓				✓			1
(Tseng, 2009)	✓		✓			✓			1
(Garfì et al., 2009)	✓	✓	✓	✓	✓	✓			1
(De Feo & De Gisi, 2010)		✓	✓		✓	✓			1
(Jun-Pin Su et al., 2010)		✓		✓		✓	✓		1
(Xi et al., 2010)		✓			✓	✓			1
(El Hanandeh & El-Zein, 2010)			✓					✓	1, 2
(Nazari et al., 2011)	✓	✓				✓			1
(Aydi et al., 2012)	✓				✓	✓		✓	1
(Zelenović Vasiljević et al., 2012)	✓	✓		✓	✓	✓			1
(Karmperis et al., 2012)	✓	✓						✓	1, 2
(Khadivi & Fatemi Ghomi, 2012)		✓		✓	✓		✓		1
(Eskandari et al., 2012)	✓	✓		✓		✓			1

(Korucu & Karademir, 2013)		✓		✓		✓	✓	✓	1
(Karmperis et al., 2013)		✓	✓						1, 2
(Abba et al., 2013)	✓	✓	✓	✓	✓		✓	✓	1
(Nixon et al., 2013)		✓		✓		✓			1

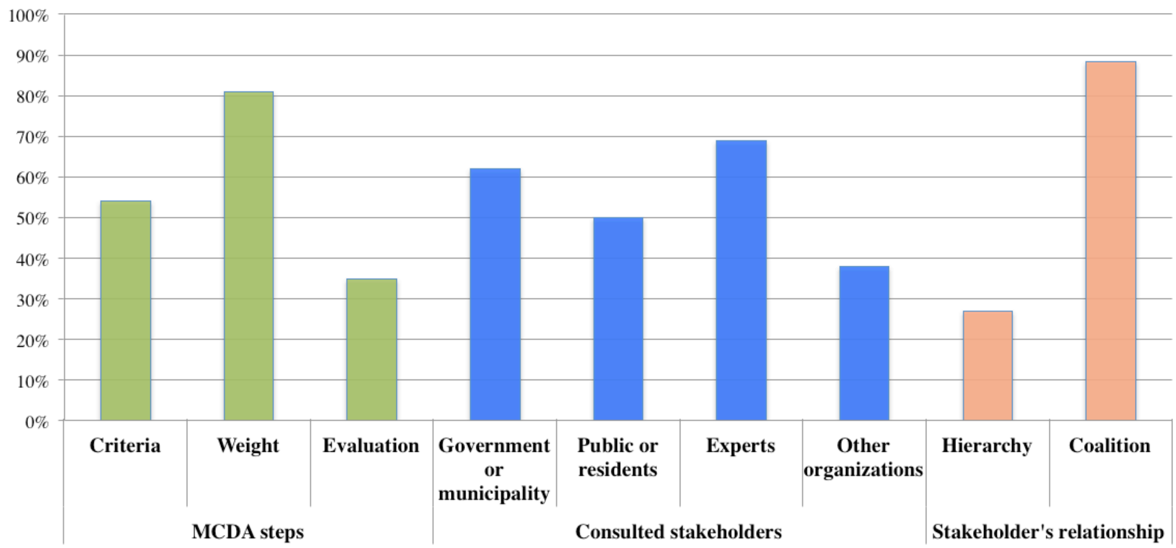

Figure 2.8 Percentage of studies with multiple stakeholders that have discussed elements of MCDA steps, stakeholders, and their relationships

Figure 2.9 shows that waste management experts have become more aware of the importance of considering multiple stakeholders in MSWM decision-making process; this happens as more stakeholders take part in municipal decisions, societies are more conscious of the environment, and more collaboration opportunities rise in newer waste treatment techniques such as the WTE techniques.

In addition, governments/municipalities and experts are the most studied stakeholders with participation rates of 62% and 69%, respectively (Figure 2.10). Governments/municipalities' involvement is justified, as they are often responsible for selecting and operating MSWM strategies. Experts are widely involved, as they are mostly undertaking these studies. Meanwhile, out of 26 studies, only 3 mentioned competitions among stakeholders and 7

(23%) considered hierarchy among stakeholders. It is obvious that most studies do not offer solutions for situations where stakeholders compete for more benefits in the considered criteria or when stakeholders have unequal voting powers. Meanwhile, the studies that address these issues are not designed for sustainable waste treatment problems.

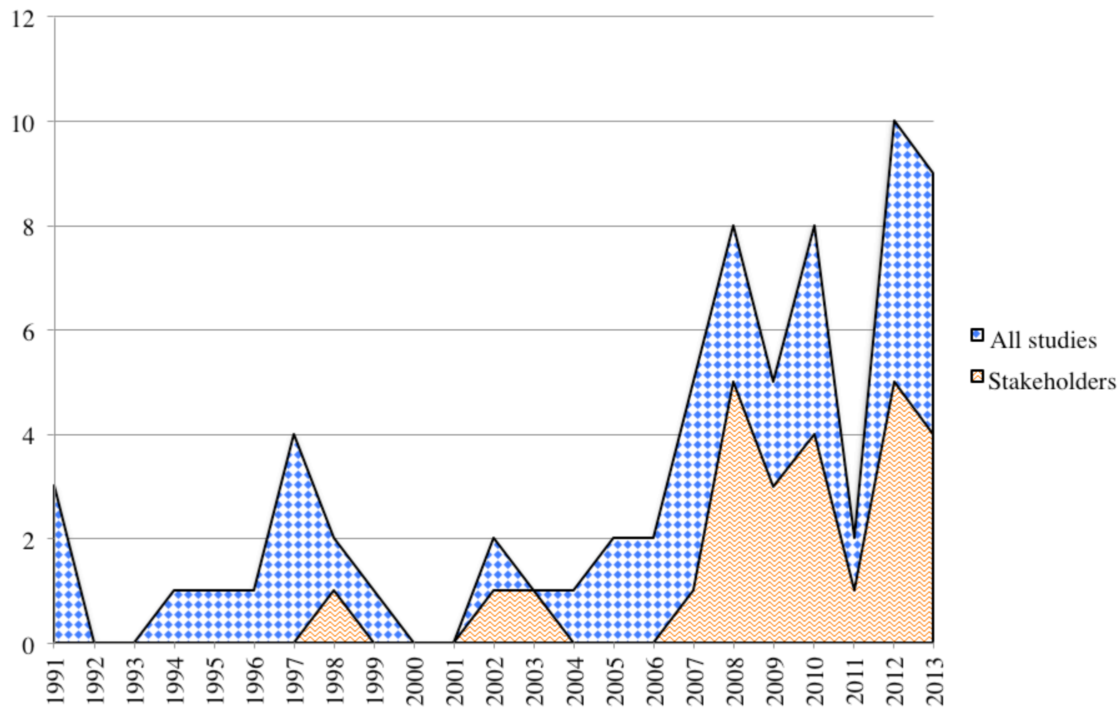

Figure 2.9 The number of studies that use MCDA methods for multi-stakeholders MWSM

In group decision-making problems, stakeholders make decisions based on the long-term impacts of options on their health and financial well-being. In sustainable waste treatment, stakeholders should first agree on the importance of each criterion in comparing the available options (van den Hove, 2006). However, If stakeholders have conflicting priorities over criteria, reaching an agreement is likely to be challenging (De Feo & De Gisi, 2010). Stakeholders can trade-off some of their benefits to help each other reach a mutual agreement on an optimal option. But, they find out that sharing the negative impacts is also challenging. Stakeholders often compete for paying less of the net costs. As a result, a series of dialogues are formed between them to share the costs in a fair and pragmatic way.

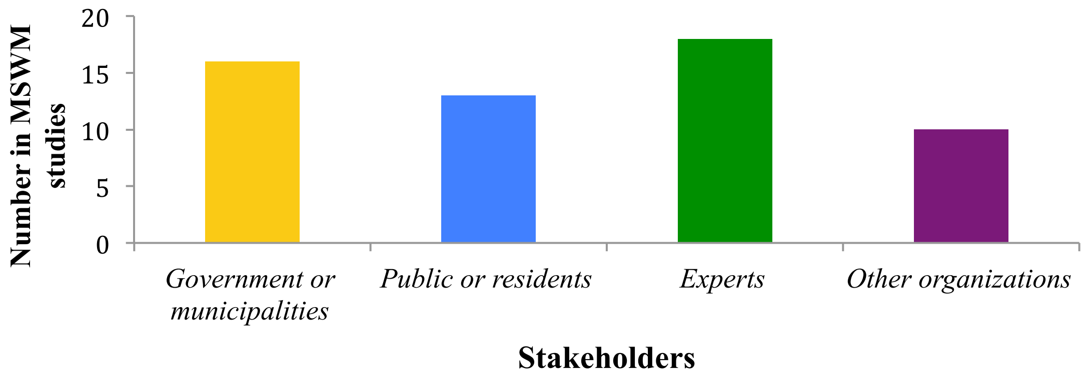

Figure 2.10 Categorizing MSWM studies based on the type of stakeholders

In the reviewed studies, AHP has been the dominant MCDA technique with application to 65% of the studies. Other methods have each been used in less than 15% of the studies (Figure 2.11). Studies using AHP, can often create confusion by double counting impacts that are correlated (Hossaini et al., 2014); to avoid such problem, some reviewed studies use ANP instead. Although ELECTRE and PROMETHEE are common in MSWM studies, they are incorporated less in studies with multiple stakeholders. One reason might be that ELECTRE follows a ranking system as opposed to an optimum selection procedure and does not discuss trade-offs among criteria. AHP follows a single synthesizing approach in modelling multiple stakeholders, which is more effective in finding an optimal option. It also makes it possible to plan a trade-off among sustainability criteria. AHP is also the most common and straightforward in modeling multiple stakeholders in MSWM studies; as a result AHP is used for this study.

Although AHP is more convenient and effective, it suffers from the same shortcoming as the other MCDA techniques when considering conflicts in group decision-making process. AHP has been introduced as an effective tool for tackling environmental decision-making with multiple stakeholders; But, to apply AHP, stakeholders should first agree on some elements including “set of alternative options, set of criteria, scores to be attributed to each of these criteria for each of those options, weights to apply to criteria, ranking method to be used to compare options” (van den Hove, 2006). Stakeholders have diverse and often conflicting interests, which can make reaching an agreement on these elements very challenging.

Conflicts often rise when stakeholders express different priorities over the criteria of decision-making (De Feo & De Gisi, 2010; Thorneloe, Weitz, & Jambeck, 2007).

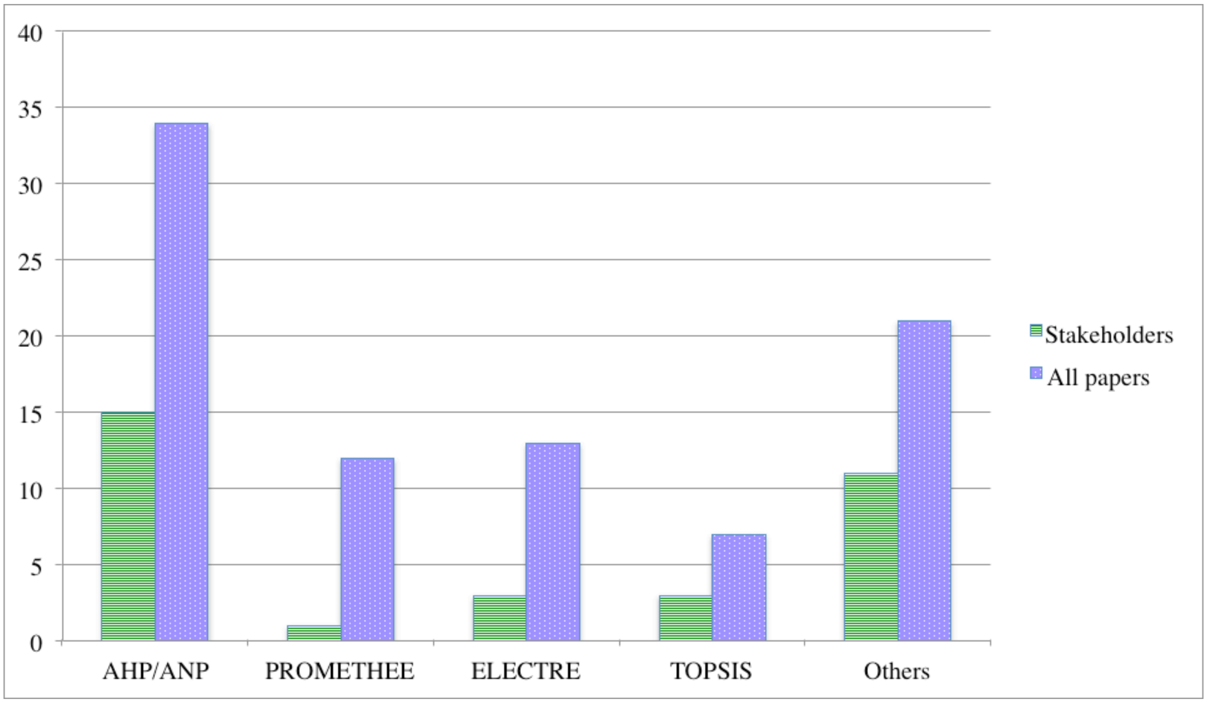

Figure 2.11 Number of times each MCDA method is used in MSWM studies with multiple stakeholders

Since AHP struggles to face this shortcoming in considering conflicts and competition in MSWM, researchers have suggested additional solutions. Munda (2002) proposed to assign equal weights to each criteria of sustainability (i.e. economic, social, and environmental) to reduce social conflicts and increase fairness. van den Hove (2006) suggested the addition of a participatory process to the existing MCDA methods in order to ensure that decision processes are fair and transparent. The participatory process is a setting where various stakeholders gather to contribute to a formal decision-making process. In addition, there are indeed studies that consider multiple stakeholders using methods other than MCDA (e.g., Visvanathan & Trankler (2003); Banville, Landry, & Martel (1998); Parrot, Sotamenou, & Dia (2009)).

MCDA techniques aggregate the impacts on stakeholders, but fall short on considering stakeholders' conflicts and their influences on each other in reaching a mutual decision on a sustainable waste treatment option. Game theory, on the other hand, is a natural choice for analyzing the trade-offs between the environment and economy, and considering stakeholders' conflicts and dialogues (Moretti, 2004).

2.4 **Game Theory**

Multi-stakeholder (i.e., multi-agent) systems are settings where two or more agents interact. These interactions can be based on either competition or coalition, meaning that stakeholders' desires can confront or coincide. In a problem with multiple stakeholders that the outcome depends on all stakeholders' decisions, game theory is a natural and effective tool (Nagarajan & Sošić, 2008). Game theory can help stakeholders to both reach and sustain a decision, when dealing with complex systems.

In addition, game theory can use its elements for fair distribution of costs and benefits among stakeholders, to stabilize environmental decisions; for example, McGinty et al. (2012) tested a model on international environmental agreements in a cooperative game; Weikard and Dellink (2008) examined renegotiations of international climate agreements; Finus (2000) thoroughly investigated coalitions in environmental issues; and Kaitala and Pohjola (1995) studied global climate change in the context of an environmental negotiation problem.

In a two-player game, game theory first gathers the information on stakeholders' utilities (or net benefits) from each pair of actions (e.g., how much will each stakeholder benefits if stakeholder 1 chooses action a and stakeholder 2 chooses action b). Based on the type of decision-making problem, this information is then portrayed in a decision-tree or a table. Although each stakeholder might choose an optimal option when deciding individually, game theory looks for solutions that are stable in a mutual setting. In this setting, stakeholders answer a series of "what if …" questions before finalizing their decision. These questions are often asking whether they would change their decision, if the other stakeholder chooses any of the possible options.

2.4.1 Definition and models

The mathematical foundation of Game theory was established by Professors Von Neumann and Morgenstern (1944) and was later developed into its current form through a series of studies by Nobel prize recipient Professor John Nash (1950; 1951; 1953). Game theory studies self-interested stakeholders when they interact in a series of games (Leyton-Brown & Shoham, 2008). Self-interested stakeholders prefer some situations to other situations (or states) and they will act toward making those situations happen (Leyton-Brown & Shoham, 2008).

Game theory identifies models and then offers various solutions for each model. Models are different states of players, while solutions are the logical presentation of the outcomes that may occur in the game. These models are generally divided into four groups (Osborne & Rubinstein, 1994).

1. Strategic (i.e., normal) and Bayesian games
2. Extensive games with perfect information
3. Extensive games with imperfect information
4. Coalitional games

Figure 2.12 portrays the differences between games and how these groups are formed. These groups are based on three different categorizations: The first categorization is concerned if the players define actions and express interests in each action as *a group, or individually*. In these situations, players are known to be playing *cooperative games* (e.g., group 4) or *non-cooperative* (e.g., groups 1, 2, 3), respectively. The latter notion might be confusing since some stakeholders might be a group of individuals, but not collaborate with the other groups of individuals. In cooperative games, individuals or groups of individuals do not benefit from each other's loss. Another categorization of games refers to the order of decision-making among players. In group 1, players make decisions *simultaneously* or once and for all without knowing the decisions of others. In groups 2 and 3, players make decisions *consecutively* or in each round with knowledge on decisions made in previous rounds. In the last division, information plays a significant role. Models in groups 2 and 3 are categorized based on whether the players are *fully* or *partially* informed about each other's moves.

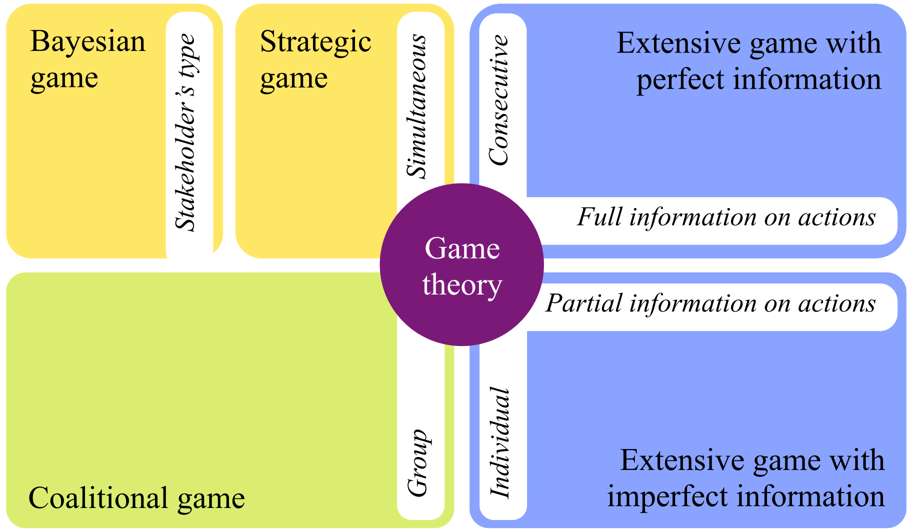

Figure 2.12 Models in game theory

In coalitional games, stakeholders act as a team. In environmental problems where municipalities involve society in the decision-making process, game theory can use coalitional games to model their interactions. Inter-governmental decisions can often use these games to predict the right move as well.

In strategic games, stakeholders are fully aware of each other's possible actions, but they cannot observe other stakeholders' actions. Hence, their actions/decisions are once and for all and cannot be revised. A strategic game is often portrayed in table-form (Table 2.4). Available actions can be similar for all stakeholders or different for each one. In environmental decision-making problems that stakeholders compete with other stakeholders for a project that needs immediate decisions (such as waste treatment), strategic games are useful.

Table 2.4 An example of a 2×2 normal or strategic game

Stakeholders		Player 2		
	Actions	a_1	a_2	a_3
Player 1	a_1	u_{11}, u_{21}	u_{11}, u_{22}	u_{11}, u_{23}
	a_2	u_{12}, u_{21}	u_{12}, u_{22}	u_{12}, u_{23}
	a_3	u_{13}, u_{21}	u_{13}, u_{22}	u_{13}, u_{23}

Extensive games explicitly represent the sequential structure of the decision-making process. In extensive games, players can observe the other players' decisions at each point of time and reconsider their initial decision plan (Osborne & Rubinstein, 1994). Although players can react to the decisions of other players, they cannot go back in time and change their previous decisions. An extensive game is displayed as a tree with *nodes* representing the choices of each player and *edges* representing the actions. Utilities from each series of actions and choices are shown at the final edge in each path. Figure 2.13 shows an example of the extensive game in which players choose to go Right or Left in each round. The utilities are represented as ($\mathbf{u}_1$, $\mathbf{u}_2$) or utilities of player 1 and 2 from their decisions of going R or L. Such extensive games can model environmental decision problems that require adjustments in consecutive formats or when stakeholders are bidding for a project. Based on the level of information the stakeholders receive in each round, an appropriate type of extensive games can be used.

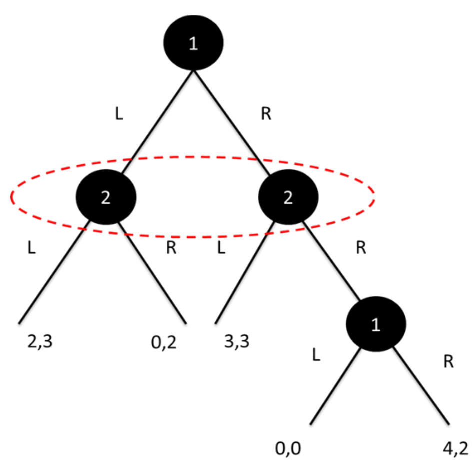

Figure 2.13 An example of the extensive game

In perfect information extensive games, players can decide in each round, knowing what action the other players have chosen in previous rounds. However, in many situations, agents act with partial or no knowledge of the nodes they are in. In other words, they may not know or remember what actions other agents have taken in the previous rounds. This environment is discussed through imperfect information extensive games. In Figure 2.13, this model is shown with broken lines; player 2 does not know whether player 1 has chosen to go Right or

Left.

There are various solutions available for the games. Nash equilibrium is the most common solution in Game theory. Nash equilibrium uses the concept of Pareto optimality in which no player can be better off without making another player worse off. A mixed strategy Nash equilibrium is designed for situations where the players are uncertain about their choices. The players then assign a probability to each action and use probabilistic rules to estimate the mutual probabilities.

2.4.2 Game theory in MSWM

Although waste often portrays itself as a liability rather than a competition-worthy asset, WTE technologies are examples that are changing this image. Industries and municipalities use the recovered energy and material from waste to substitute fossil fuels and therefore compete to pay less of the costs. They need to share costs and benefits in a way that satisfies both of them. Game theory is an effective method for decisions that require stakeholders' collaboration (Nagarajan & Sošić, 2008).

There have been only very few studies that used game theory for waste management decision-making. Cheng et al. (2002; 2003) applied a cooperative game theory approach to select a new landfill site. Moretti (2004) proposed a cooperative game theory method to divide the costs of waste collection between municipalities. Jørgensen (2010) used game theory for a regional waste disposal problem. Karmperis et al. (2013) proposed a framework called waste management bargaining game to help players negotiate over the surplus profit of various MSWM options. More details on studies with game theory solutions are presented in Table 2.5.

In Table 2.5, stakeholders' impacts on each other's decisions when all of them are required to reach a mutual decision are not discussed. These studies also fail to guide stakeholders to reach a mutual agreement by finding a way to distribute the costs and benefits among them. In the previous sections, shortcomings of sustainability assessment frameworks were also mentioned. MCDA methods were recognized to be effective in aggregating the sustainability results, but fell short on modeling stakeholders' competitions in sharing the costs and benefits of MSW treatment options. They also could not guide stakeholders to reach a mutual decision.

Table 2.5 MSWM studies with game theory models

Game theory model	Paper/Authors	Topic			Method	Stakeholders				Criteria			
		Location	Disposal / collection	Cost-benefit		Municipality	Experts	Public	Waste industry	Environment	Economy	Agriculture	Social
Cooperative	Cheng et al. (2002)	✓			Cooperative game theory – MCDA	✓	✓	✓		✓	✓	✓	✓
Cooperative	Cheng et al. (2003)	✓			Inexact linear programming – MCDA	✓	✓	✓		✓	✓	✓	✓
Cooperative	Jørgensen (2010)		✓		Dynamic cooperative game theory	✓					✓		
Cooperative	Moretti (2004)		✓	✓	Cooperative game theory – Shapley value	✓					✓		✓
Cooperative	(Erkut et al., 2008b)	✓			Lexicographic mini-max approach	✓				✓	✓		
Cooperative	Karmperis et al. (2013)*			✓	Waste management bargaining game	✓		✓		✓	✓		✓
Competitive	Davila et al., (2005)	✓			Grey integer programming – Zero-sum game	✓			✓	✓	✓		

2.5 Summary

This study proposes an integrated decision support framework to help multiple stakeholders reach an agreement on a sustainable waste treatment option and share the associated costs and benefits in a fair and mutually acceptable way. This research aims to fill the gap in the literature on choosing the most sustainable and pragmatic waste treatment option when stakeholders have conflicting priorities and hierarchy among them.

Chapter 3 Decision Support Framework for Multi-stakeholder Decisions

This chapter is based on a journal publication titled "Selecting sustainable waste treatment options for municipal solid waste: A game theory approach for group decision-making" (Soltani et al., 2015c).

This chapter proposes a decision support framework to address the challenges of choosing a sustainable waste treatment strategy when the main stakeholders have conflicting preferences. This decision support framework aims to help the main stakeholders, municipality and industry, to reach a mutual agreement on a sustainable and pragmatic waste treatment option. In this framework, game theory complements AHP, LCA, and LCC to model the dialogues among stakeholders and guide them to reach a sustainable solution. Figure 3.1 presents the schematic of the proposed framework.

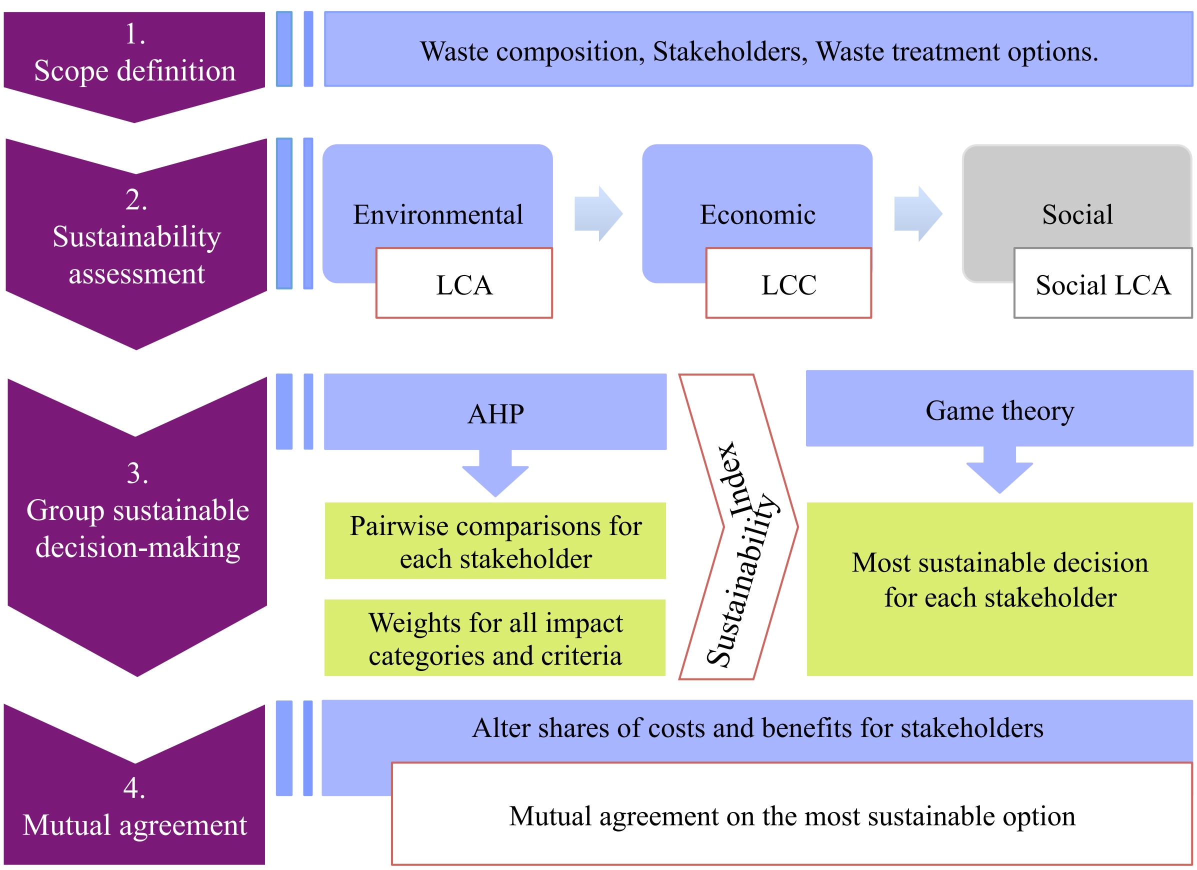

Figure 3.1 The schematic of the decision support framework

3.1 Scope Definition

The first step in the proposed framework is to define the scope of the study, namely the objectives and scenarios. The objective of this study is to compare the available waste treatment options in municipalities and then guide the interested stakeholders to mutually agree on a sustainable and pragmatic option. In addition, the scenarios are often built according to the available and proposed waste treatment options, the composition of disposed waste, and involved stakeholders.

3.2 Sustainability Assessment

LCA and LCC are used as sustainability assessment tools to evaluate the impacts of selected waste treatment options on each stakeholder. In the LCA of waste treatment options, a cradle-to-gate system boundary is more appropriate. The cradle-to-gate assessment considers all the activities from disposal of MSW in the waste treatment plant; however, it excludes the activities after the recovered material and energy or produced compost are delivered to the end-point users, and the remained waste is buried in the landfill (except for when landfill itself is assessed). Therefore, the system boundary is defined to include all activities from the disposal of waste at treatment plants or landfill to mechanical treatment, incineration, and the recovery of materials. The transportation of recovered material and energy to the destination point is not considered. Functional unit, which is usually a quantity of disposed MSW for consistent assessment, is selected as 1 kg of MSW.

The next step is to develop LCI for the available waste treatment options as follows:

- A map of the inputs and outputs of waste treatment options in the system boundary is first developed (Figure 3.2). The available options are in two categories of WTE technologies and landfilling. The inputs include any energy resources such as fossil fuels, land, and water, while the outputs are often emissions, or recovered material and energy.

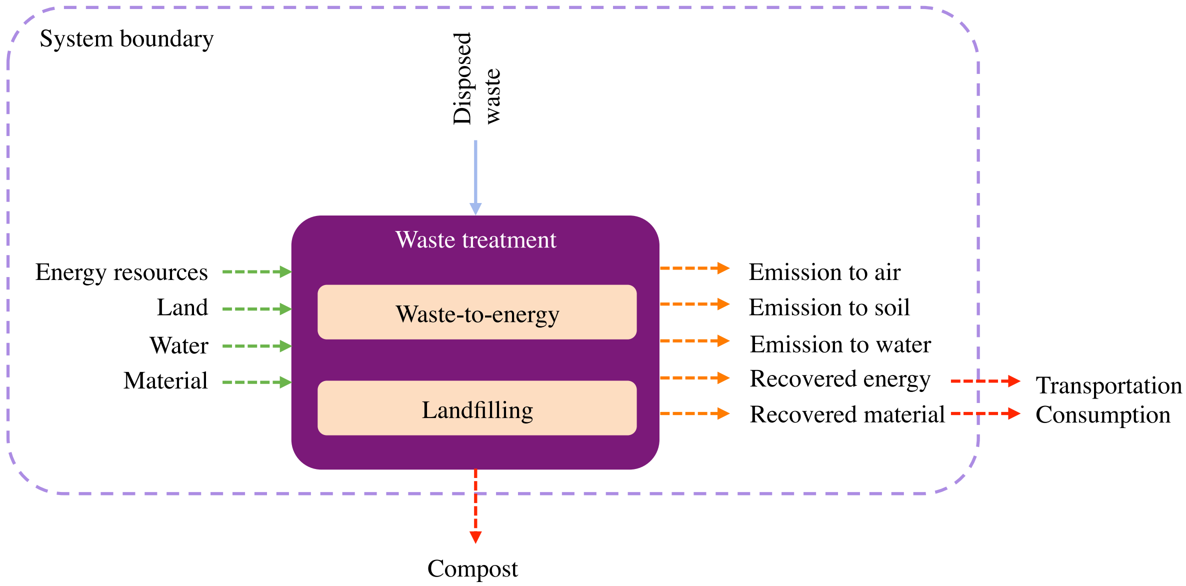

Figure 3.2 System boundaries in selecting a sustainable waste treatment

- A data collection plan is organized to identify the purpose of the LCI, geographic scope of the data, and data collection methods. SimaPro 8.0 can access various databases with information on landfilling and WTE and can help to plan LCI. The reason behind selecting SimaPro is its comprehensive presentation of assessments and outcomes.
- Data is collected as a combination of research, expert contacts, and LCA software of SimaPro. European Life Cycle Database (ELCD) in SimaPro 8.0 software is used in this study. ELCD gathers data on average waste treatment plants and landfills with leachate control in Europe. The inventories are derived for incineration and landfilling of 1 kg of waste components such as paper and plastic in an average treatment plant or landfill in Europe. Inventories are then adapted to waste composition of the region under study.
- The input and output data is documented and the contributions of each stage is evaluated.

In the next step, to perform the LCIA, the following steps are followed:

- The impact categories are selected. As a default, the most common impact categories in waste treatment studies considered in LCIA are ozone depletion, global warming, smog, acidification, eutrophication, carcinogens, non-carcinogens, and ecotoxicity.

- LCI results are classified under the relevant impact category according to their mid-point impacts on humans and the environment.
- Impacts under each category are then characterized to develop unified impact indicators. RECIPE method for mid-point impacts is used as a default in SimaPro 8.0 to aggregate the impacts under each mid-point impact category. These values are then unified and presented for each treatment option.
- Weighting and aggregating impact indicators is the last step of LCIA; however, the framework develops weights in the next step to consider stakeholders' conflicting preferences in the group decisions. In conclusion, LCA results are presented as impact indicators for all considered impact categories.

The LCC is performed to present the economic impacts of waste treatment options. In the LCC, it is key to define a scope coherent with the scope of LCA. A scheme of all costs and benefits within the scope of study is formed and values per functional unit are estimated in dollars. For this assessment, previous data on similar waste treatment plants, expert's knowledge, and published literature and reports are used to generate the estimates. Costs and benefits considered in this framework are presented in Table 3.1. Opportunity cost is in fact the benefit that is not achieved as a result of a decision. Carbon tax is the tax that some governments assign to the productions and services with high levels of greenhouse gas emission. Operation and maintenance costs are the values that businesses pay monthly or annually to achieve a desired level of productivity and includes salaries, rent, maintenance of building and equipment. Depending on the project under study, the transportation cost can include the costs of trucks and gas from the disposal station to the treatment plant. Building, equipment, and land costs are paid at the beginning of the production process as an investment. Stakeholders earn revenue by selling the recovered material and energy (as electricity, gas, etc.). If the recovered energy substitutes fossil fuels, the price of the substituted fossil fuels can be considered as a benefit. Sunk costs or costs that have already been paid are not considered.

Table 3.1 Costs and benefits considered in proposed framework

Costs	Benefits
Opportunity cost	Fossil fuel saving
Carbon tax	Recovered materials revenue
Operation and maintenance cost	Electricity sale
Transportation cost	Energy revenue
Land costs	
Building and equipment costs,	

EAV and NPV methods are used to aggregate the selected costs and benefits. In NPV, all future monetary values are discounted into a present value (equation [3.1]). In EAV, all future or present costs and benefits (recurrent or one-time) are discounted to annual values using equation (equation [3.2]). These methods help experts to consider the time value of money in long-term projects. Wherever the time value of money is not significant (low interest rate and/or low inflation rate), present and future costs and benefits are divided by the number of years in the project to calculate annual values for convenient assessment. Future values in NPV and EAV are often a current expense or a projection of an expense, while present value is often the value paid at time zero or the start of the project.

$$NPV = \sum_{t=0}^{n} NFV\,(1+r)^{-t} \qquad [3.1]$$

$$EAV = NPV\,\frac{r}{1-(1+r)^{-n}} \qquad [3.2]$$

where NPV is the present value of net economic cost, NFV is net future costs, r is real interest rate, t is time, and n is the total number of periods.

Once the EAV of all costs and benefits are calculated, the net cost of all available options are calculated (Equation [3.3]). Net economic cost of each treatment option is calculated for each stakeholder and then presented in dollar value. Social impacts are not addressed in this framework. Although in many investment decisions, social factors are often ignored by the industry, including municipality as the main stakeholder with veto power on the final decision helps the social impacts to be part of the decision, even though quantifying social impacts are often very hard.

$$Net\ cost = EAV(costs) - EAV(benefits) \quad [3.3]$$

3.3 Decision-Making for Sustainable Waste Treatment

Once the magnitude of impacts is quantified, AHP method is used to assign weights to environmental and economic criteria. The combination of the magnitude of impact and the significance of the criteria of impact will result in a sustainability index for each option. AHP is chosen among MCDA techniques because it is the most common MCDA method in the MSWM problems. AHP compares alternatives based on their performance in each criterion as well as decision-maker(s)' preferences over those criteria (Linkov et al., 2004). Hence, it can help experts assign weights to sustainability criteria, aggregate impacts from those criteria, and compare MSW treatment options, accordingly.

The hierarchy system of AHP simplifies various objectives and goals into a single score and chooses the alternative with the highest score for the decision-makers. AHP has the advantage of generating an inconsistency index to show decision-maker's inconsistent decisions (Pohekar & Ramachandran, 2004), but its simplifying method may come at the risk of losing some information along the way. Uncertainty assessment helps AHP to minimize the missing information and the subjectivity of weights. There are five steps in AHP (Saaty, 1980):

- Present the problem in a hierarchy of goals, criteria, and available options;
- Collect data on available options and the criteria of interest;
- Generate a weighting system for criteria through pair-wise comparison;
- Rank alternatives by aggregating scores and weights; and
- Perform a sensitivity analysis to validate the data and mitigate uncertainty.

To start, the hierarchy of problem is presented in Figure 3.3. After goal, sustainability criteria and sub-criteria, the available waste treatment options are displayed. Data related to each level of hierarchy are collected from experts, municipalities, and involved industry partner. Collection methods range from research to surveys, questionnaires, literature review, etc.

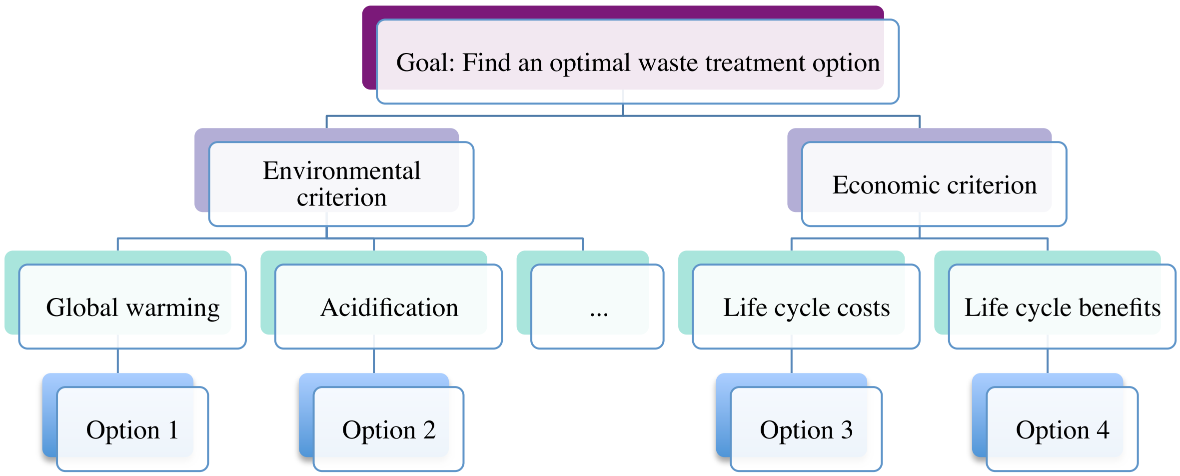

Figure 3.3 Hierarchy of the problem

In AHP, the outcomes of pairwise comparisons are presented in a priority matrix and developed into a set of "priority ratio scale" (Hossaini et al., 2014; Sadiq et al., 2003). In Matrix A (equation [3.4]), each entry a_{ij} shows on what scale criterion i is preferred to criterion j (Hossaini et al., 2014). The advantages of the pairwise comparison technique include its ease of use and understandability for non-expert users. Saaty's 9-scale is often used to compare the criteria, verbally (Table 3.2). It is important to be consistent with the scale in pairwise comparisons.

$$A = \begin{bmatrix} 1 & \dots & a_{1n} \\ \dots & 1 & \dots \\ a_{n1} & \dots & 1 \end{bmatrix} \qquad [3.4]$$

Table 3.2 Importance scale (Saaty, 1988)

Saaty Scale	Verbal definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong or demonstrated dominance
9	Extreme importance or strongest affirmation
2,4,6,8	Intermediate values

AHP develops weights for two levels of criteria and sub-criteria. The first priority matrix shows the numerical results of the pairwise comparisons of the environmental impact categories with each other. These pairwise comparisons are based on the significance of impacts on humans and the environment. There are many approaches to compare these impacts; one of them is to use pre-approved and globally acceptable weighting systems. These weighting systems are often developed by environmental experts and have general application in different environmental decision-making problems.

The United States Environmental Protection Agency (US EPA) gathered a well-mixed group of experts, industry, and municipalities to develop a tool, known as Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), which is one of the most respected and common tools for this purpose (Bare, 2002). TRACI was developed to prepare comprehensive assessments for all the potential environmental impacts and conduct impact assessment with the best applicable methodologies within each category (Bare, 2011). TRACI uses EPA's taxonomy study of possible impacts and downsizes it to a more manageable list of impact categories (Bare and Gloria, 2008; Bare, 2011). LCA tools such as GaBi and SimaPro are integrated with TRACI. TRACI provides three weighting systems of BEES panel based on Environmental Preferable Purchasing (EPP) program, US EPA Science Advisory Board, and Harvard Kennedy School of Government (Table 3.3) (Gloria, Lippiatt, & Cooper, 2007). In each of these weighting systems a different group of experts are gathered and asked to compare the importance of impact categories. AHP is then used to develop the weights from these comparisons. The suggested weighting system in the framework is EPP, as it compares the importance of impacts in short, medium, and long term. While stakeholders can still compare the impact categories using AHP, TRACI provides the weights in the framework as a default.

In the second level of hierarchy, stakeholders are asked to compare the environmental burdens with the economic costs. Later, the comparative values are put in the upper triangular section of the second priority matrix and their reciprocal values are put in the lower triangular section (Figure 3.4).

Table 3.3 Weighting systems for environmental impact categories (Gloria et al., 2007)

Impact category	Weights		
	BEES (EPP)	**Science advisory**	**Harvard**
Global Warming	29.3	16	11
Fossil Fuel Depletion	9.7	5	7
Criteria Air Pollutants	8.9	6	10
Water Intake	7.8	3	9
Human Health Cancerous	7.6	11	6
Human Health noncancerous	5.3		
Ecological toxicity	7.5	11	6
Eutrophication	6.2	5	9
Habitat alteration	6.1	16	6
Smog	3.5	6	9
Indoor air quality	3.3	11	7
Acidification	3.0	5	9
Ozone depletion	2.1	5	11
Total	**100**	**100**	**100**

Priority matrix 1 (If required)				
Origin: TRACI or stakeholders				
Environmental impact categories				
Sub-criteria	s_1	s_2	…	s_n
s_1	1			
s_2		1		
…			…	
s_n				1

Priority matrix 2		
Origin: Stakeholders		
Criteria	Environmental	Economic
Environmental	1	
Economic		1

Figure 3.4 Priority matrices for each stakeholder

Weights are developed from the priority matrix using various mathematical approaches such as eigenvector, geometric mean, and arithmetic mean, which are believed to present similar results and not to be significantly different (Hossaini et al., 2014). Eigenvector is calculated from equation [3.5]. Eigenvalue is dependent to the scale of matrix. In the arithmetic mean process, the share of values in each column out of the summation of all those values are calculated and then the weights are estimated from the arithmetic average of rows in the priority matrix. In the geometric mean approach, the geometric average substitutes the arithmetic mean.

$$AX=\lambda X \quad [3.5]$$

where λ is eigenvalue and X is eigenvector.

AHP uses the priority matrix 2 and mathematical solutions to calculate weights for the two criteria. Arithmetic or geometric means methods are easy to use for this purpose. Once weights are developed, their consistency should be examined. The values in a matrix are consistent where each entry $a_{ij} = \frac{w_i}{w_j}$ (Tesfamariam & Sadiq, 2006). In this formula, w_i is the weight of criterion or sub-criterion i ($\sum_{i=1}^{n} w_i = 1$).

Afterwards, sustainability indexes are developed from the overall weights (significance of criteria and sub-criteria) and impacts (magnitude of burdens or costs) using equation [3.6]. Each waste treatment option has a distinctive sustainability index for each stakeholder. In this framework, a lower sustainability index means that the waste treatment option is more sustainable for the stakeholder.

$$Environmental\ Burden\ (EB) = Weight\ of\ environmental\ impact\ category \times impact \quad [3.6]$$
$$Sustainability\ index\ (SI) = Weight\ of\ criterion \times EB\ or\ economic\ net\ cost$$

At this point, for life cycle sustainability goals to be achieved, stakeholders should settle on a fair distribution of costs and benefits and reach an agreement on their shares from the recovered material and energy. Game theory is capable of addressing both 'fairness' and group 'sustainability' goals in a MSWM decision-making process (Karmperis et al., 2013). What makes game theory versatile is its use of mathematical modeling to understand human interactions. Game theory is based on the fact that stakeholders make rational decisions based on their information and preferences but also their prospects of other stakeholders' actions (Osborne & Rubinstein, 1994).

In this step, a game and model that can represent the problem is arranged and presented. Game is a portrayal of interactions between stakeholders that describes all the actions they *can* play and their interests in those actions, but not the actions they *do* play (Osborne & Rubinstein, 1994). The developed framework uses game theory to model the dialogues among stakeholders and predict the best option for each stakeholder. Since more than one stakeholder is affecting the selection of waste treatment strategy, looking for an optimal option for each stakeholder has no meaning, anymore; the actions of all stakeholders impact the optimal decision (Shoham & Leyton-Brown, 2008). In this framework, a two-player game is designed for municipality and industry to simultaneously decide on their most sustainable options.

The games are formed from following elements (Osborne & Rubinstein, 1994):

- $\boldsymbol{A}$ $(\boldsymbol{a}_1, \ldots, \boldsymbol{a}_i)$ is a set of actions available to decision makers;
- $\boldsymbol{C}$ $(\boldsymbol{c}_1, \ldots, \boldsymbol{c}_i)$ is a set of possible consequences for the actions in **A**;
- $\boldsymbol{g}: \boldsymbol{A} \rightarrow \boldsymbol{C}$ is a consequence function which relates each consequence to an action;
- $\geq$ is a preference relation defined on the set **C**;
- $\boldsymbol{U}: \boldsymbol{C} \rightarrow \boldsymbol{R}$ is utility function, a specific preference relation with the condition of $\boldsymbol{x} \geq \boldsymbol{y}$ iff $\mathbf{U}(\boldsymbol{x}) \geq \mathbf{U}(\boldsymbol{y})$. Utility functions are used to show preferences of stakeholders.

Given these elements, a rational decision-maker generally chooses a feasible and optimal action $\boldsymbol{a}^*$ by maximizing $\boldsymbol{U}(\boldsymbol{g}(\boldsymbol{a}))$. In the proposed framework, these elements are defined in a similar approach:

- A is the set of waste treatment options,.
- C is the set of sustainability indexes that show the outcome of selecting and implementing each option on each stakeholder.
- g shows how elements in the C are consequences of elements in A.
- The lower sustainability index is more sustainable and satisfactory to stakeholders.
- Utility function is portrayed as sustainability index, so waste treatment option a_1 is preferred to a_2, when the $SI(a_1) < SI(a_2)$.

Strategic games are game theory models that consider every player's utility in every mutual state of the world (system) and allow players to choose simultaneously. A definition for finite 2-player normal form game in this framework is presented as a tuple (2, A, SI) and relations in equation [3.7] (Shoham & Leyton-Brown, 2008). A presentation of a strategic game for 2 players with 3 mutual actions is shown in Table 2.4.

$$\boldsymbol{A} = \boldsymbol{A}_1 \times \boldsymbol{A}_2 \text{ and } \boldsymbol{SI} = (\boldsymbol{SI}_1, \boldsymbol{SI}_2) \quad [3.7]$$

where $\mathbf{A}_i$ is a finite set of actions available to player i. Each vector $\mathbf{a} = (\mathbf{a}_1, \ldots, \mathbf{a}_n) \in \mathbf{A}$ is called an action profile. Actions can be different for each stakeholder. $\mathbf{SI}_i : \mathbf{A} \rightarrow \mathbf{R}$ is sustainability index function which represents a real utility (or payoff) function for player i.

In this framework, strategic games are used to model the simultaneous decision-making problem. It is assumed that stakeholders are announcing their decisions to a third-party or mediator, who will later announce the final outcome. In these games, stakeholders have full information about each other and the available actions. The game is portrayed in a matrix form with stakeholder 1 in rows and stakeholder 2 in columns. Values in the matrix are sustainability indexes for available and proposed waste treatment options (Table 3.4).

Table 3.4 Example of a two-player normal game theory model

Stakeholder 2

Stakeholder 1	**Option a**	**Option b**	**Option c**
Option 1	SI_{11}, SI_{2a}*	SI_{11}, SI_{2b}	SI_{11}, SI_{2c}
Option 2	SI_{12}, SI_{2b}	SI_{12}, SI_{2b}	SI_{12}, SI_{2c}
Option 3	SI_{13}, SI_{2c}	SI_{13}, SI_{2b}	SI_{13}, SI_{2c}

* SI_{ij} is sustainability index of option j for stakeholder i

To find the solution(s) to the game, the framework looks for Nash equilibrium(s). Nash equilibrium is reached when both players identify an action set as best answer. Meanwhile, Nash equilibrium in strategic games is defined as a steady state profile of actions where no player will benefit from deviation, given the other players' actions (Osborne & Rubinstein, 1994). Therefore, best answers from player 2 to each action of player 1 (and vice versa) are identified. Nash (1951) verified that "every game with a finite number of players and action profiles has at least one Nash equilibrium".

Since often one waste treatment option is the topic of the discussion, the pure strategy is the more common than mixed strategy in this framework. Pure strategy selects the most sustainable waste treatment option for each stakeholder. Nash equilibriums are stable; hence, stakeholders do not benefit from changing their choices. The result of this step is the stakeholders' decisions and best options considering all previous assumptions.

3.4 Mutual Agreement

Sometimes, if the framework predicts different sustainable options for stakeholders, there will not be enough waste for both options to take place. For example, if the framework chooses the landfilling for the municipality and a WTE technology for the selected industry, industry will not have access to any waste to recover energy from. In these cases, the selected options are no more optimal as they are not pragmatic. Hence, the proposed framework takes it further to estimate fair shares of costs and benefits (i.e. a tipping fee that one stakeholder should pay to the other one) to make the WTE technology attractive to municipality and assure a mutual agreement on the most sustainable option.

The tipping fee is calculated from the differences between the sustainability indices of the selected option and the proposed option (the waste treatment option that stakeholders would like to collaborate on) and the weights of the economic criterion for stakeholders. Equation [3.8] shows this process, if stakeholder 1 is paying the tipping fee to stakeholder 2.

$$x: \{x \subseteq (0, \infty) | (x * c > a) \cup (x * d < b)\} \qquad [3.8]$$

where a is (stakeholder 1's sustainability index of the selected option – sustainability index of the proposed option), b is (stakeholder 2's sustainability index of the selected/proposed option – sustainability index of the option selected by stakeholder 1), c is stakeholder 1's developed weight for the economic criterion, d is stakeholder 2's developed weight for the economic criterion, and x is the tipping fee per kg MSW. It is essential to implement this framework to fully understand the process and the significance of the outcomes in group decision-making on waste treatment. An excel-based tool is developed to effectively integrate all the stages in this framework. Snapshots of the tool are presented in Appendix.

3.5 **Summary**

In this chapter, a decision support framework is developed that can help two stakeholders with conflicting preferences reach a mutual decision on a sustainable MSW treatment strategy. AHP is used to help stakeholders compare the importance of environmental and economic impacts and then game theory is used to model the dialogues among stakeholders. To help the stakeholders reach a mutual agreement, their shares of costs and benefits are defined in a way that they both benefit from the same MSW treatment option.

Chapter 4 Refuse-Derived Fuel production and utilization

This chapter is based on two journal publications titled "Selecting sustainable waste treatment options for municipal solid waste: A game theory approach for group decision-making" (Soltani et al., 2015b) and "Environmental and economic aspects of production and utilization of RDF as alternative fuel in cement plants: A case study of Metro Vancouver Waste Management" (Reza et al., 2013).

The goal of this case study is to implement the developed framework for Metro Vancouver's proposal to produce RDF and utilize it in cement kilns. Apart from providing a proof-of-concept for the developed framework, this chapter attempts to guide Metro Vancouver and cement industry as stakeholders to evaluate their fair shares of costs and benefits following RDF utilization and reach a mutual agreement on RDF. Metro Vancouver is a regional district in the province of BC, Canada that consists of 21 municipalities. In this study, Metro Vancouver is referred to as municipality.

4.1 **Scope Definition for MSWM in Metro Vancouver**

In 2008, Canada's local governments spent $2.6 billion, while earned $1.8 billion on waste management. Nova Scotia and BC spent the highest per person ($30) on waste treatment and operation, about twice the national average value (Statistics Canada, 2011). Metro Vancouver aims to reduce waste management's environmental impacts and costs, and generate earnings for the municipality. Therefore, pursuing sustainable waste treatment is consistent with their long-term MSWM objectives.

Metro Vancouver's MSWM plan includes recycling and re-using of waste materials, producing energy from waste, and disposing the rest in landfills. In 2010, around 1.4 million tonnes of solid waste were disposed in landfills or burned in the WTE plant (Metro Vancouver, 2010). Delta and Cache Creek landfills receive waste disposals from Metro Vancouver area. Current practice pursued at WTE facility in Burnaby is carried out by mass burn thermal treatment. Metro Vancouver plans to build a new WTE plant and reduce the capacity of landfills. Producing RDF from the disposed MSW is one of the proposed options for this upcoming plant (Reza et al., 2013; Metro Vancouver, 2014b). About 58% of waste is recycled now, while the target is to recycle 80% by 2020. For the 700,000 tonnes waste remained after 80% diversion, plans are to send (Metro Vancouver, 2013):

- 50,000 tonnes to Delta landfill
- 280,000 tonnes to Burnaby WTE plant
- 370,000 tonnes to the new WTE plant

In this case study, two stakeholders of Metro Vancouver and cement industry are proposing the new waste treatment option of combusting RDF in cement kilns. This waste treatment option will be compared with the existing options, namely landfilling and mass-burn WTE technology. To fully understand the scope of these scenarios, first waste composition in Metro Vancouver is presented in Table 4.1.

Table 4.1 Metro Vancouver MSW composition in 2013 (Metro Vancouver, 2014b)

MSW components	**Share (%)**
Paper	13.6
Plastic	14.4
Compostable organics	36.2
Wood	2.7
Textile	2.7
Rubber	2.7
Leather/multiple composite	2.7
Metals	3.2
Glass	1.6
Building material	8.4
Electronic waste	1.1
Household hazardous	0.9
Household hygiene	5.0
Bulky objects	4.1
Fines	0.6
Total	*100*

4.2 Sustainability Assessment

For LCA, inputs and outputs (e.g., materials, energy, and emissions) from landfilling and incineration of each component of waste were collected from SimaPro 8.0 and then adapted to Vancouver's waste composition (Table 4.2). Based on the waste composition, only 51-53% of materials are recovered for the production of RDF. Three different scenarios were considered for treatment of the disposed waste, in this study:

- Landfilling of the disposed waste. The composition of mixed MSW in Vancouver is used for estimation of landfilling impacts.
- Mass-combustion of the disposed waste. The composition of mixed MSW in 2013 is used for the calculation of impacts.
- Co-combustion of RDF in cement kilns in Vancouver. Cement kilns are assumed to be close to potential cement manufacturers. In previous studies, RDF production recovered 20-50% of the disposed MSW (Nithikul, 2007; Rotter et al., 2004; Gendebien et al., 2003). In this study, 40% of the disposed MSW (e.g., paper, plastic, wood, textile, rubber, and leather) is recovered for RDF production and co-combustion in cement kilns.

Table 4.2 Environmental impact assessment for Metro Vancouver case study

Impact category	**Unit**	**Landfill**	**WTE (mass-burn)**	**Co-combustion of RDF in cement kilns**
Ozone depletion	*kg CFC-11 eq*	2.26E-09	-3.77E-08	-4.49E-08
Global warming	*kg CO2 eq*	2.23E-01	-2.11E-02	-2.55E-02
Smog	*kg O3 eq*	5.60E-03	-8.64E-03	-1.44E-02
Acidification	*mol H+ eq*	1.38E-02	-9.97E-02	-1.21E-01
Eutrophication	*kg N eq*	5.09E-04	-1.97E-05	-3.01E-05
Carcinogenics	*CTUh*	2.88E-10	-1.70E-10	-2.23E-10
Non carcinogenics	*CTUh*	5.24E-10	-6.23E-09	-8.70E-09
Respiratory effects	*kg PM10 eq*	2.90E-04	-4.05E-04	-4.46E-04
Ecotoxicity	*CTUe*	2.26E-09	-1.52E-02	-1.46E-02

To perform LCC for this case study, landfilling costs were based on the current tipping fee of \$0.108 per kg waste (City of Vancouver, 2013). Cost of landfilling for the industry is the opportunity cost of not choosing WTE or RDF, which is the cost of fossil fuels in their current practice. Price of coal was considered as $0.07 per kg coal (78$ per ton). The energy of 1 kg coal is 24.5 MJ (Reza et al., 2013) equivalent to 6.80 kWh; while the output energy for 1 kg of MSW in WTE plant in Burnaby was 15 MJ or 4.2 kWh in 2007 (TRI Environmental Consulting Inc, 2008). In addition, when landfilling is chosen as the waste treatment option, industry should pay carbon tax at the rate of $30 per tonne of CO_2 equivalent emissions (BC Ministry of Finance, 2014).

WTE profits for municipality include metal recovery and electricity sale. If WTE is chosen, industries save on fossil fuel and carbon tax. Metro Vancouver earns on average about $6 million per year from electricity produced in WTE facility (120000 MWh) and $1.4 million per year from recovered metal (Metro Vancouver, 2014a). 1 kg waste generates $0.005 revenue from 0.03 kg scrap metal and $0.022 revenue from electricity. Construction, operation, and land costs of the existing WTE facility were considered as sunk costs.

Landfill reduction of 60% was considered as a benefit for municipality, and tax saving, fuel saving, and metal recovery were considered as benefits for industry. Since stakeholders impact each other, LCC is presented to show the result of these impacts (Table 4.3). Metro Vancouver is considering 10 potential treatment plans for the future, among which two options are planning to use RDF (Metro Vancouver, 2014d). Therefore, it is assumed that Metro Vancouver can produce RDF even without cement industry and with the help of other energy-intensive industries; but the cost will be slightly higher ($0.05 per kg MSW). Also, when Metro Vancouver chooses landfilling or WTE, the costs are irrelevant to the decision of cement industry. Hence, cement industry will follow its current practice with fossil fuels, if both stakeholders are not selecting RDF.

Table 4.3 Economic net costs for case study in Metro Vancouver

Stakeholder 1- Stakeholder 2	*Stakeholder 1 – Industry* **($ per kg MSW)**	*Stakeholder 2 – Municipality* **($ per kg MSW)**
Landfill – Landfill	0.63	0.108
Landfill – WTE	0.63	-0.026*

Landfill – RDF	0.63	0.06
WTE – Landfill	0.63	0.108
WTE – WTE	0.63	-0.026
WTE – RDF	0.63	0.05
RDF – Landfill	0.63	0.108
RDF – WTE	0.63	-0.026
RDF – RDF	-0.31	0.043

* Negative value indicates earnings.

4.3 Decision-Making for Multiple Stakeholders

The developed framework creates a priority matrix to develop weights for environmental and economic criteria (Table 4.4). TRACI's BEES weighting system is used for comparing environmental impact categories. In addition, authors have made reasonable assumptions based on their expert judgements for stakeholders' priorities in comparing environmental and economic criteria. They have made assumptions about the stakeholder's priorities (i.e. whether they prefer environmental or economic criterion) and the degree of those priorities (i.e. how much they prefer one criterion over another). These judgements arrive from authors' involvement in many individual and group discussions with the Metro Vancouver and cement industry and participation in relevant conferences by Metro Vancouver. The stakeholder express their preferences through pairwise comparisons of criteria, using Saaty's 9-scale. Based on author's observations, Metro Vancouver has continuously explored sustainable waste management plans to prioritize the environment and human health; while, it is a safe assumption that cement industry would only invest in an option when it is financially sound. In addition to current assumptions, other possibilities are also explored in Chapter 5.

Table 4.4 The priority matrix for the RDF case study

	Stakeholder 1 - Industry		Stakeholder 2 - Municipality	
Criteria	Environmental	Economic	Environmental	Economic
Environmental	1.00	0.25	1.00	7.00
Economic	4.00	1.00	0.14	1.00
Sum	5.00	1.25	1.14	8.00

Weights of environmental impacts and net economic costs are estimated for each stakeholder using the arithmetic mean approach. Table 4.5 shows the overall weights for both stakeholders in the RDF case study. The results claim that economic net cost is a much greater concern for the industry as opposed to the municipality.

Table 4.5 The final weights of criteria and sub-criteria for both stakeholders

Stakeholders	*Environmental (%)*									*Economic (%)*	*Sum (%)*
Sub-criteria	*Abiotic depletion*	*Acidification*	*Eutrophication*	*Global warming 100*	*Ozone depletion*	*Human toxicity*	*Fresh aquatic ecotoxicity*	*Terrestrial ecotoxicity*	*Photochemical oxidation*		
1. Industry	2	1	2	8	1	2	2	2	1	80	100
2. Municipality	7	4	7	35	3	9	9	9	4	13	100

In the next step, game theory's normal game is used to predict the best decisions for stakeholders. The framework suggests that WTE and RDF are the best options for Metro Vancouver and for cement industry, respectively (Table 4.6). This solution is reached from a pure strategy. RDF is a dominant strategy for the industry, while WTE is a strictly dominant strategy for the municipality. It is apparent in the game that the municipality has more of the hierarchy power as it has ownership of the disposed waste. When the municipality chooses any other option other than RDF, the industry cannot produce or utilize RDF. Therefor, the industry should now pay a tipping fee to make a balance between the financial and environmental attractiveness of RDF for the municipality or to convince the municipality to select the RDF option.

4.4 Mutual Agreement on the RDF Option

The tipping fee should be an amount that will make RDF more sustainable than WTE, while keeping RDF the most sustainable option for the industry. The developed framework suggests that if the cement industry pays a tipping fee of \$0.11-0.9 per kg waste to Metro

Vancouver, both stakeholders will benefit from a proposed new RDF plant in Vancouver, BC [4.1]. This value is calculated based on previous assumptions and is not making any strong suggestions; but it shows how the framework can help stakeholders make offers that are fair and satisfactory for everyone.

$$-\$0.25+0.8\,x< \$0.5 \rightarrow x<\$0.9 \qquad [4.1]$$
$$-\$0.006-0.13\,x< -\$0.02\rightarrow x>\$0.11$$

where x is a positive tipping fee per kg MSW.

Table 4.6 Game theory results for Metro Vancouver case study

Stakeholder 2
Metro Vancouver

Stakeholder 1
Cement industry

	Landfilling	*WTE*	*RDF*
Landfilling	0.52 0.09	0.5 -0.02	0.47 -0.004
WTE	0.52 0.09	0.5 -0.02	0.47 -0.004
RDF	0.52 0.09	0.5 -0.02	-0.25 -0.006

4.5 Summary

In this chapter, the proposal of co-combusting RDF in cement kilns is analyzed. The framework suggests that if the industry pays $0.11-0.9 tipping fee to Metro Vancouver (with current assumptions), RDF can be selected as a sustainable MSW treatment option. The developed framework helps stakeholders apply this sustainable decision.

Chapter 5 Uncertainty analysis

This chapter includes portions of a study submitted to the journal of *Environmental Modeling and Software* with the title "Studying the impacts of uncertainty in group decision-making setting: strategizing municipal solid waste treatment" (Soltani et al. 2015d).

The developed decision support framework is further complicated as available information is mostly uncertain because of imprecise data and subjective weighting schemes which may lead to unreliable outcomes. In this chapter, uncertainties in each step of the framework are assessed and clearly presented. Later, the ones that are the direct results of the process selected in this framework are reduced or their impacts on the outcomes are evaluated. Finally, the uncertainty assessment methods are implemented for the case study of RDF production and utilization.

5.1 Definition of Uncertainty

Uncertainty is often classified into vagueness and ambiguity (Klir & Yuan, 1995). Vagueness discusses the lack of distinct values and ambiguity refers to the existence of more than one value or option (Sadiq & Tesfamariam, 2009). Heijungs & Huijbregts (2004) describe data, relationships, or choices as uncertain when they belong to one of the following groups:

- No value, equation, or option is available
- An imprecise or inappropriate value, equation, or option is available
- Multiple values, equations, or options are available

It should be noted that uncertainty is different from variability. While uncertainty is about missing or incorrect values, relationships, and choices, variability is about the heterogeneous nature of the data when values are different on case by case basis (Heijungs & Huijbregts, 2004).

Sources of uncertainty are categorized as parameter, model, and scenario uncertainty (Lloyd & Ries, 2007). Parameter uncertainty refers to errors or negligence in the values of input data when their measurements are unavailable, unreliable, biased, or imprecise, or when they are variable or arbitrary in nature but presented as a constant value (Lloyd & Ries, 2007). Model uncertainty refers to inaccurate predictions due to the lack of appropriate scientific hypotheses, such as the general structure and the relation among factors in the model (USEPA, 2013). Scenario uncertainty refers to the ambiguity in using one scenario over another. Using scenarios is the result of assumptions about geographical, temporal and technological conditions and changes in a system (Walker et al. 2003).

The goal of uncertainty analysis is to first predict the robustness of outcomes of an assessment, and later predict how outcomes will change if the robustness was not acceptable. There are four general approaches to address uncertainty (Figure 5.1) (Heijungs & Huijbregts, 2004):

- The scientific approach designs more experiments and research for more information.
- The group discussion approach uses experts' judgments.
- The official approach relies on accredited values developed by authoritative institutions, such as ISO.
- The statistical approach uses numerical and probabilistic methods or soft computing techniques such as fuzzy set theory.

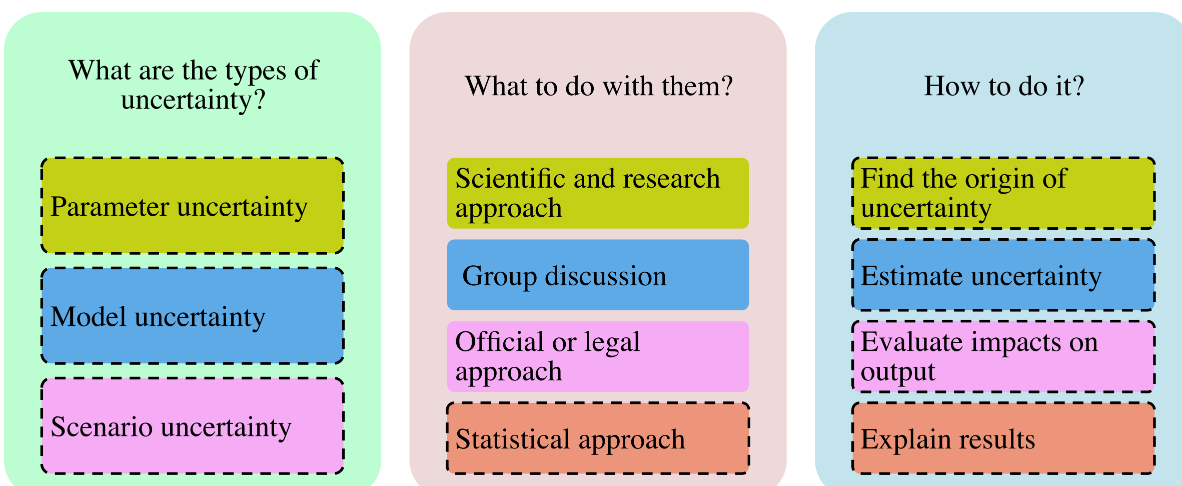

Figure 5.1 The process of addressing uncertainty

While the first three approaches look for ways to reduce uncertainty, the last approach aims to investigate uncertainty's impacts on the outcome (Heijungs & Huijbregts, 2004). There are three steps in addressing uncertainties using these approaches (Figure 5.1):

- Finding the origin of uncertainties and estimating them,
- Evaluating the impacts of uncertainties on outputs, and
- Explaining and presenting the results.

In the proposed framework, many uncertainties may impact the final result. A substantial uncertainty can cost stakeholders thousands or even millions of dollars. In this study, the uncertainties that are directly related to stakeholders and group decision-making are studied in more details. Ultimately, it is decision-makers' responsibility to improve the quality of the data or just be aware when implying from the framework's outcome.

5.2 Sources of Uncertainty

In Table 5.1, the relevant uncertainties in the developed framework are identified. The types of uncertainty and actions to deal with them are also presented. Where action is not taken, a brief explanation is provided.

Table 5.1 Sources of uncertainties in the proposed framework

Sources of uncertainty	Type	Actions taken/ Explanations
	Sustainability assessment - LCA	
Imprecise emission measurement	Parameter	LCA software's assumption
Uncertain life of substances	Parameter	Most common life assumed
Disregarded or inaccurate normalization weights	Parameter	LCA method's uncertainty
Imprecise and incomplete waste composition*	Parameter	**Sensitivity analysis 5-10%**
Different human exposure parameters in Human Health Risk Assessment	Parameter	Most common characteristics assumed
Linear functions instead of non-linear	Model	LCA method's uncertainty
Disregarded or unknown impact categories	Model	Similar impact categories for all options
Uncertain characterization factors	Model	LCA method's uncertainty

Sources of uncertainty	Type	Actions taken/ Explanations
	Sustainability assessment - LCA	
Temporal differences in yearly values (inventories, waste composition, temperature, etc.)	Scenario	Average values assumed
Spatial differences between source and actual waste plant (inventories, importance of impact categories)	Scenario	Information lacking for the same region in the case study
Choice of certain waste treatment options	Scenario	Different for each region
Choice of functional unit	Scenario	Complicated to consider
	Sustainability assessment - LCC	
Values of costs and benefits	Parameter	**Sensitivity analysis 5-10%**
Linear functions for aggregation of costs and benefits (more of some materials can increase costs or benefits non-linearly)	Model	Not significant
Temporal changes in the interest rate for present values	Scenario	An average considered
Choice of some costs and benefits	Scenario	Consult with experts
Functional unit	Scenario	Same as LCA
	Weighting - AHP	
Values in the selected weighting systems	Parameter	**Fuzzy AHP for environmental impact categories**
Not considering vagueness in verbal comparison	Parameter	**Fuzzy AHP for environmental and economic criteria**
Use of one methodology over another in developing matrix	Model	**Different methods used**
Criteria selection for decision-making	Scenario	**Sustainability criteria chosen**
Ignoring social impacts	Scenario	Lack of information and qualitative nature of the impacts
Individual differences in group preferences	Scenario	Inside group decisions not addressed in this framework
Choosing one weighting system over another	Scenario	**Other methods used and compared**

Sources of uncertainty	Type	Actions taken/ Explanations
Group decision-making – Game theory		
Modeling the negotiations (game) as simultaneous decision-making other than a sequence of decisions and not considering re-negotiations.	Model	Decision-making process in this framework is simultaneous.
Unknown attitude towards risk	Model	Complicated utility functions
Stakeholder's incomplete information about each other's type and objective	Model	**Bayesian game**
Number of stakeholders	Model	Framework only designed for two player problems
Choosing the stakeholders' level of information about each other	Scenario	**Bayesian game**

* Bold sources of uncertainty are explored further in this study

5.3 Uncertainty in LCA

Uncertainties are inherent in LCA, which makes extraction of reliable outcomes more challenging. Although LCA is very helpful in environmental decision-making, it is important to be mindful of its limitations and state them clearly. Uncertainty assessment of LCA results is not about criticizing the method, but about being aware of what can be expected. The quality of the results can be improved by investigating and focusing on the inputs that contribute the most to the uncertainty of the output (Ekvall et al., 2007). Although each case introduces its own range of uncertainties, but there are uncertainties that are common to all studies which stem from the LCA methodology itself. The structure of LCA and related uncertainties are reviewed and discussed in Heijungs & Suh (2002). Some of the main sources of uncertainties in group MSWM are discussed below.

First common type of uncertainty encountered in LCA is the selection of the functional unit and the system boundary. Choosing an amount of disposed waste (e.g., 1 kg of MSW) implies that the quantity of waste is not relevant in impact assessments and the waste management process (Ekvall et al., 2007). This hypothesis will also neglect to account for additional costs of expanding plants and the diminishing returns.

In addition, spatial and temporal diversity between available and real input data is often a source of uncertainty in LCA. Consideration of site-specific data is encouraged, but for many plants, site-specific data are not available. Using Environmental Impact Assessment (EIA) is one of the approaches to incorporate site-specific data in environmental studies (Ekvall et al., 2007). Furthermore, sensitivity analysis of available waste composition data can help stakeholders to be aware of the role that available data plays in the outcomes. The temporal aspect of environmental impacts can also change the outcomes (e.g., life of global warming impact can be 20, 100, or 500 years). Thus, the timing of input data should be consistent and when applicable, multiple options should be used in parallel.

Moreover, LCA's linear models on the calculations of cause-effects and related risks are often criticized (Guinée et al., 2002). Various factors, from waste composition to fuel consumption, affect LCA results linearly, while in fact relationships are better shown with non-linear functions (Guinée et al., 2002). This will limit reliability and usability of LCA in waste treatment studies. That being said, using non-linear models requires high quality input data that is expensive, hard to collect, or even unavailable (Guinée et al., 2002).
Lastly, the marginal effects of WTE technologies on other markets are often ignored in LCA. Production of electricity and steam, and recovery of metals and bottom ash will increase their supply, and will subsequently affect their markets (Ekvall et al., 2007; Ekvall & Weidema, 2004). This consideration is extremely complex and requires various data.

5.4 **Uncertainty in LCC**

In addition to the environmental impacts, waste treatment technologies/ strategies impact financial and social resources. The most significant uncertainties in LCC of waste treatment options are:

- Inclusion of some costs and benefits and overlooking others,
- Using current estimations for the future, and

- Uncertainty in the values of costs and benefits.

The selection of some costs and benefits for assessment is a methodological choice rather than an uncertainty. Stakeholders or trusted experts select the influential costs and benefits to consider in the LCC of waste treatments. As previously mentioned, the time required for collecting data should be financially and rationally reasonable.

Moreover, time is not directly priced, but its opportunity cost should be considered in the LCC. The discount rate shows the opportunity cost of borrowed money or future benefits; this rate changes based on the riskiness of projects and the source of borrowed money (Layard & Glaister, 1994). Most of the costs and benefits considered in the LCC of waste treatment options or similar engineering projects are recurring costs/benefits (monthly or annually). Other costs and benefits are investments that are paid at the beginning of the first year. Monthly costs are often turned into annual values using compound interest rates. Equivalent annual costs of investments are added to recurring costs (equation [5.1]).

$$\boldsymbol{Investment} \times \boldsymbol{Capital\ recovery\ factor} = \boldsymbol{P} \times \left[\frac{\boldsymbol{i\,(1+i)^n}}{\boldsymbol{(1+i)^n - 1}}\right] \qquad [5.1]$$

where *i* is interest rate and *n* is the number of years.

In addition, the LCC procedure and calculations follow ‘normative neoclassical economic theory’, which believes that stakeholders maximize their utilities or profits with full access to relevant information and follow a consistent and rational thought process (Gluch & Baumann, 2004). In real life, the stakeholders may be uncertain about their choices and impacts of their choices on the market and themselves. The LCC method over-simplifies economic impacts, ignores non-monetary impacts, and discounts future costs according to the current economy and overlooks market fluctuations (Gluch & Baumann, 2004). Uncertainties about the future can be mitigated using various methods, such as Monte Carlo simulation, sensitivity analysis, regression analysis, scenario forecasting, probability analysis, and decision trees.

Finally, uncertainties emerge in the LCC as a result of discrete decisions, when using cost and benefit values. Costs and benefits estimations are sometimes incomplete or carry errors. Carlsson Reich (2005) suggests using sensitivity analysis to study this uncertainty. Sensitivity analysis changes the values of costs and benefits in a 5-10% range and studies its impacts on the outcome.

5.5 Uncertainty in Assigning Weights

Using a weighting system to combine non-commensurate environmental impacts to create a single index can be scientifically challenged. In addition, the aggregation of results from economic and environmental assessments can also result in the loss of valuable information. However, weighting systems are unavoidable when different options need to be compared (Carlsson Reich, 2005). That being said, they should be transparent and follow rational and scientific reasoning.

The first critique of the weighting systems is their subjectivity. Various mathematical tools are used to help in the decision-making process; however, if the policy-makers wait for unarguable and precise scientific results from these tools before they act, their wait may never come to an end (Ekvall et al., 2007). The subjectivity of developed weights can be diminished by using weighting system tools such as TRACI that is generated from a well-balanced group of experts (USEPA, 2012). Meanwhile, pairwise comparisons in MCDA techniques such as AHP are subjective and hence carry uncertainty (Tesfamariam & Sadiq, 2006). As a general rule, wherever involved stakeholders provide pairwise comparisons according to their own priorities, subjectivity is unavoidable.

Another type of uncertainty in weighting systems is related to stakeholders' opinions/ preferences when they are comparing criteria. In the proposed framework, AHP helps stakeholders assign weights to criteria, but the stakeholders are not always able to express their exact preference over the environmental and economic criteria. This uncertainty cannot be reduced by further research (Layard & Glaister, 1994). Therefore, methods such as fuzzy set theory, Dempster-Shafer, and other probabilistic methods can be used with conventional

AHP to capture uncertainty in the weighting scheme. However, fuzzy set theory is found to be the most common method used to address uncertainties in AHP (Sadiq & Tesfamariam, 2009). A fuzzy set represents a collection of uncertain values x_i with membership functions of μ_x that show the degree of x_i being a member of the fuzzy set (equation [5.2]) (Sadiq & Tesfamariam, 2009).

$$\mu_x: X \to [0,1] \quad x \in X \tag{5.2}$$

Finally, the uncertainty of weighting systems increases when multiple stakeholders with different levels of credibility and confidence are involved (Tesfamariam et al., 2010). Credibility factor is usually a function of the stakeholders' years of experience and knowledge on the topic of decision (Tesfamariam et al., 2010). In addition, belief factor is a probability function that shows the confidence of stakeholders in their choices and the availability of evidence for verifying them (Tesfamariam et al., 2010). Although belief factor is subjective and hard to assess, credibility factor can help fuzzy AHP in developing more robust results.

Fuzzy AHP is performed in the following sequence:

1. Design a hierarchical structure similar to the AHP with goal, sustainability criteria and sub-criteria, and waste treatment options in each level.
2. Develop a priority matrix through pairwise comparison of elements in each level of hierarchy. Pairwise comparisons show the importance of criteria based on their impact on sustainability level of the system. In fuzzy AHP, triangular fuzzy numbers substitute crisp numbers in Saaty's 9-level table, but the ranges between [1, 9] (Table 5.2).

3. Calculate the Consistency index (CI) and consistency ratio (CR) of the developed priority matrix; if CR is under 0.1, stakeholders are consistent (Equation [5.3]). This step is sometimes challenging for studies with more than one stakeholder involved. For fuzzy values, the most likely values are often chosen to calculate consistency indices. If comparisons are inconsistent, the stakeholder are guided to effectively reconsider the inconsistent comparison (Tesfamariam & Sadiq, 2006).

$CI = (\lambda_{max} - n)/(n - 1)$ [5.3]

$CR = \frac{CI}{RI}$

where RI is a random index.

Table 5.2 Importance scale with fuzzification factor (Δ = 0.5)

Saaty's Crisp Scale (Saaty, 1988)	**Fuzzy Scale** *(min, most likely, max)* (Tesfamariam & Sadiq, 2006)	**Linguistic definition**
1	(1, 1, 1.5)	Equal importance
3	(2.5, 3, 3.5)	Moderate importance
5	(4.5, 5, 5.5)	Strong importance
7	(6.5, 7, 7.5)	Very strong
9	(8.5, 9, 9)	Extreme importance
2,4,6, and 8 intervals	Other numbers in between	Intermediate values
Lower triangle scales	$\frac{1}{x_{ji}+\Delta}, \frac{1}{x_{ji}}, \frac{1}{x_{ji}-\Delta}$	x_{ij} are scales in the upper triangle of matrix

4. Use the arithmetic fuzzy operation rules to develop weights. Submission and multiplication operations in fuzzy logic are shown in Table 5.3. Any method from arithmetic and geometric mean to eigenvector can be used at this stage, considering their results are not significantly different (Tesfamariam & Sadiq, 2006; Hossaini, Reza, Akhtar, Sadiq, & Hewage, 2014). In geometric mean approach, the geometric mean of fuzzy values in each row is calculated by equation [5.4] (Tesfamariam & Sadiq, 2006; Meixner, 2009). The process is repeated for both levels of hierarchy in fuzzy AHP: 1. Environmental impact categories. 2. Environmental and economic criteria.

$G_i = ((x_{min}, x_{most\ likely}, x_{\max})_{i1} \otimes \ ... \otimes (x_{min}, x_{most\ likely}, x_{\max})_{in})^{1/n}$

[5.4]

$W_i = G_i \otimes (G_1 \oplus \ ... \oplus G_n)^{-1}$

$G^{-1} = (\frac{1}{x_{\max}}, \frac{1}{x_{\text{most likely}}}, \frac{1}{x_{\min}})$

5. Evaluate the impact of fuzzy numbers on final outcomes and decisions.

Table 5.3 Some of the arithmetic operations in fuzzy AHP

Arithmetic operation	Result
Addition A + B	C = $\{x_A + x_B, min\,(\mu_A\,(x), \mu_B\,(x)) \mid x \in X\}$
Multiplication A × B	C = $\{x_A . x_B, min\,(\mu_A\,(x), \mu_B\,(x)) \mid x \in X\}$

5.6 Uncertainty in Group Decision-Making

Proposed framework uses game theory to model the decision-making process when stakeholders impact each other's decisions. As mentioned previously, game theory offers various models and solutions for different types of problems. In decision-making section of a waste management problem between municipality and industry, uncertainties can occur in multiple forms:

1. Uncertainty about stakeholders deciding simultaneously or consecutively. Simultaneous actions in strategic games represent a situation where stakeholders have complete information about each other's available actions and payoffs and then a mediator (person or computer program) receives stakeholder's choices and announces them at the same time (Osborne & Rubinstein, 1994). In extensive games, stakeholders decide after observing the other stakeholder's action.

2. Uncertainty about the extent of stakeholders' information about the payoffs of the other stakeholder.

3. Uncertainty in stakeholders' behaviors toward risk. A stakeholder can be risk avert, risk neutral, or risk lover, which means that his utility is a function of risk involved in actions in addition to the payoff of actions.

4. Uncertainty about other stakeholders' types.

Since the proposed framework attempts to reduce stakeholders' time of negotiation by providing them with fair and applicable solutions, it models the situation better with simultaneous decision-making and risk-neutral groups. Stakeholders also have almost full information about each other's pay-offs; hence, the first three uncertainties are not discussed further in this thesis. In MSWM, stakeholders might not be aware of the each other's preference among sustainability criteria (i.e. types). Bayesian games assign each type a probability, which is formed from a combination of stakeholders' posterior beliefs and observations (Osborne & Rubinstein, 1994). In this situation, stakeholders cannot in fact tell a difference between two possible games that the opponent is playing. While stakeholders are uncertain, nature is aware of what games will be played (hence the probabilities). In this study, industry is assumed to not know the municipality's type (interim utility), while municipality knows the industry's preference (ex-poste utility).

5.7 **Implementation and Results**

The discussed uncertainties in the inputs and their impacts on the reliability of the outcomes are investigated below. Once the uncertainties are introduced and quantified, the framework's suggestions and stakeholders' decisions might change. The purpose of this section is only to demonstrate the framework and proposed uncertainty assessments. Hence, certain assumptions have been made and not necessarily validated. All the steps in the framework are followed while being cautious of the uncertainties.

5.7.1 Uncertainty in Waste Composition

For Metro Vancouver to efficiently plan future MSWM strategies, the relationship between RDF's SI and waste composition was assessed. Waste composition carry parameter uncertainty due to unavailability of complete and precise data. Therefore, waste composition components and economic net cost versus final SI for RDF was graphed (economic net cost was included for reference). Figure 5.2 shows that in producing RDF, economic net cost has the highest impact on SI of the cement industry; while plastic has the highest positive impact on SI of Metro Vancouver. At all times, SI of the cement industry from RDF is higher than that of Metro Vancouver.

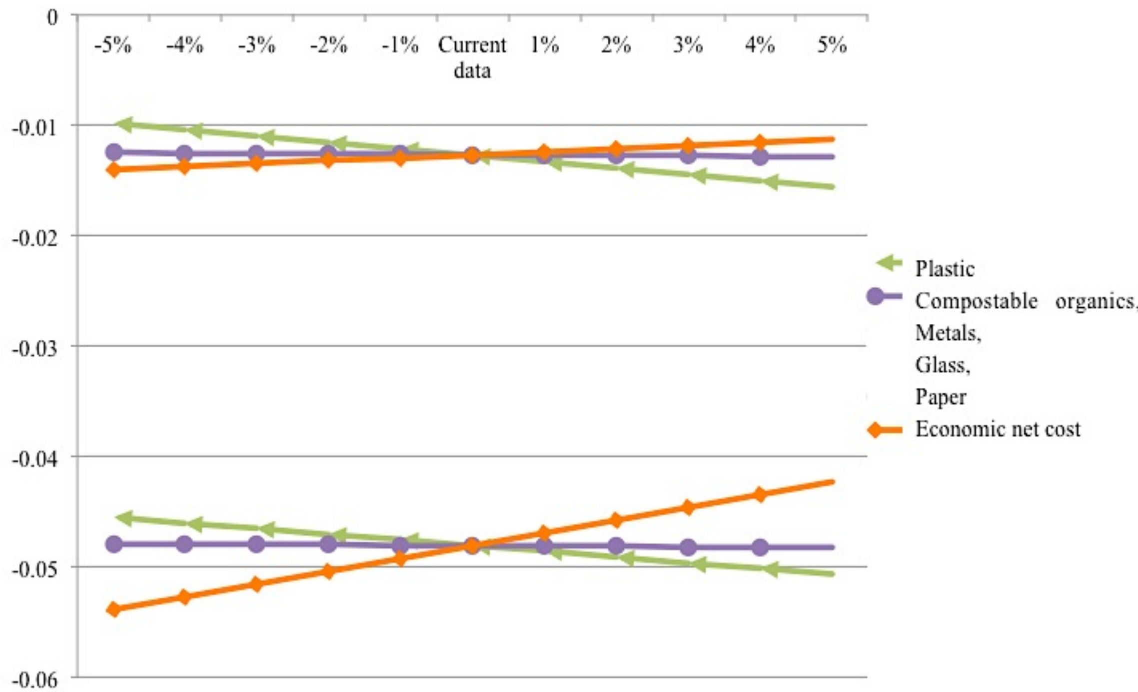

Figure 5.2 Parameter uncertainty of RDF in Metro Vancouver case study

5.7.2 Uncertainties in the LCA and LCC

In the LCA, sensitivity analysis is used to study the uncertainty in the waste composition in Vancouver and assess the impact on the final results. A variation of waste composition by 5% and 10% is assumed in the analysis. The outcome of this analysis shows that the industry's sustainability indices do not change, while the municipality becomes indifferent between RDF and WTE.

In the LCC, the time value of money is considered for future values of costs and benefits. With an average of 2% interest rate, a \$1 investment is worth \$1.5 in 20 years (an average life of a treatment plant). Annuity equivalent of a \$1 present value is around \$0.06. Therefore, considering time value of money will increase annual costs or benefits by \$0.01 or 1% (simplified method of dividing \$1 by 20 years gives an annual cost of \$0.05), which is insignificant. Investments are considered as costs for proposed waste treatment options and as sunk cost (Already paid) in existing plants. Moreover, the uncertainty of cost and benefit values is studied by performing sensitivity analysis on LCC results. For example, Table 5.4 shows how changes in the net costs of each waste treatment option can change the stakeholders' most sustainable options at the final stage. The results of this assessment are explained below:

- When the net cost of landfilling is less than -0.79 (benefit is \$0.79 more than costs), stakeholders can both agree on landfilling.
- When the net cost of WTE is less than -0.31, stakeholders can both agree on WTE.
- When the net cost of RDF is less than -0.05, stakeholders can both agree on RDF.

Table 5.4 Sensitivity analysis: results of uncertain costs and benefits

<table>
<tr><td>Options</td><td>Stakeholders
/Net costs</td><td>-0.79</td><td>-0.35</td><td>-0.31</td><td>-0.05</td><td>0.06</td><td>0.63</td><td>0.66</td></tr>
<tr><td rowspan="2">Landfill</td><td>Municipality</td><td>L, W</td><td colspan="6">W</td></tr>
<tr><td>Industry</td><td>L</td><td>L, W</td><td colspan="5">R</td></tr>
<tr><td rowspan="2">WTE</td><td>Municipality</td><td colspan="4">W</td><td>W, R</td><td colspan="2">R</td></tr>
<tr><td>Industry</td><td colspan="2">W</td><td>W, R</td><td colspan="4">R</td></tr>
<tr><td rowspan="2">RDF</td><td>Municipality</td><td colspan="3">R</td><td>R, W</td><td colspan="3">W</td></tr>
<tr><td>Industry</td><td colspan="5">R</td><td>R, W</td><td>W</td></tr>
</table>

5.7.3 Uncertainty Assessment for Weighting Scheme

The fuzzy AHP method is used to propagate the uncertainty of weighting systems in the framework. First, the uncertainty of experts when developing the EPP weights is addressed. In developing the fuzzy priority matrix, diagonal entries are defined as 1, which means minimum and maximum values are also taken as 1. Values in the upper triangle are derived from the EPP weighting system in TRACI. Later, values in the lower triangle are calculated as reciprocal of the associated values in the upper triangle. All values in the matrix are normalized to be in between 1 and 9. The results are shown in Table 5.5 with fuzzification numbers 0.5 and 1.

Table 5.5 Geometric mean values in F-AHP

Fuzzification factor (Δ) = 0.05			
Values/ Membership degrees	***Minimum / 0***	***Most likely / 1***	***Maximum / 0***
Abiotic depletion	5%	5%	7%
Acidification	3%	3%	4%
Eutrophication	6%	7%	8%
Global warming 100	28%	34%	39%
Ozone depletion	2%	3%	4%
Human toxicity	10%	12%	15%
Fresh aquatic ecotoxicity	11%	14%	17%
Terrestrial ecotoxicity	12%	15%	18%
Photochemical oxidation	7%	8%	9%
Fuzzification factor (Δ) = 0.1			
Abiotic depletion	4%	5%	8%
Acidification	2%	3%	5%
Eutrophication	5%	7%	10%
Global warming 100	23%	34%	43%
Ozone depletion	2%	3%	4%
Human toxicity	8%	12%	18%
Fresh aquatic ecotoxicity	10%	14%	20%
Terrestrial ecotoxicity	10%	15%	22%
Photochemical oxidation	6%	8%	10%

Consequently, the impacts of these changes on the final sustainability indices have been determined. The results show that industry's sustainability indices and hence their decisions do not change, but municipality's sustainability indices change moderately with the changes in the weights of the environmental impacts. However, this change does not change municipality's best option and related decision. In Figure 5.3, the fuzzy weights of environmental impacts are shown and provide a comparison. Global warming, human toxicity, and fresh aquatic and terrestrial ecotoxicity are the impact categories with the largest fuzzy weights and biggest ranges, with global warming being the most significant one.

Trapping greenhouse gases in the atmosphere causes global warming. Global warming potential is often calculated in terms of carbon dioxide equivalent and measures the amount of heat that is trapped for a certain amount of time, namely 20, 100, or 500 years.

Stakeholders should spend more time on discussing what amount of time horizon is more suitable for the project under discussion due to the significance of the impact.

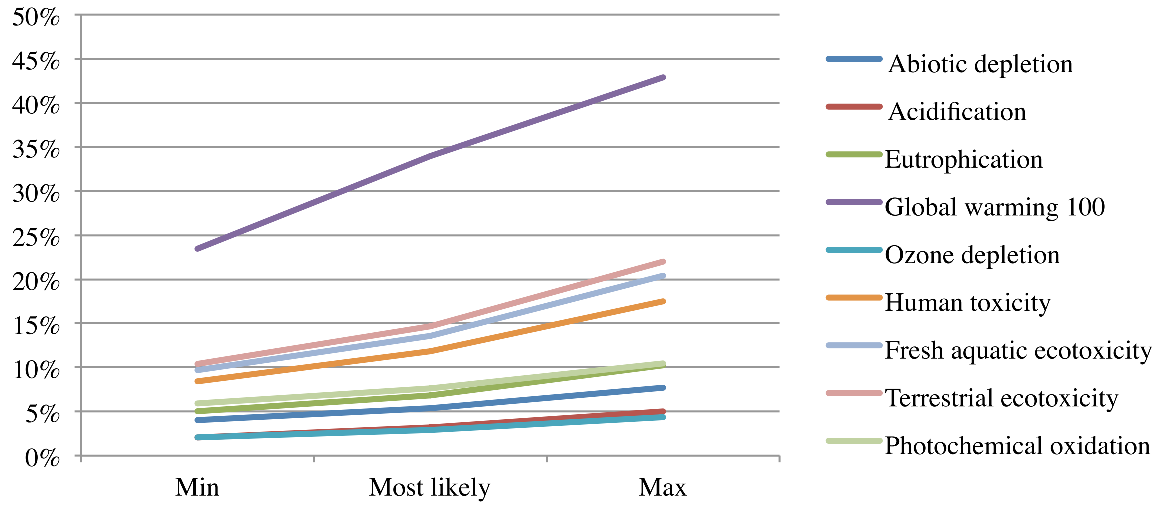

Figure 5.3 Fuzzy weights (for Δ 10%)

Second, the uncertainty of choosing one weighting system in TRACI (i.e. EPP) over another is studied. As a default, EPP weighting system is used in the developed framework. If science advisory weighting system is used, landfill and WTE become same for the industry, while sustainability indices of WTE and landfill get closer for municipality. Using Harvard weighting system instead of EPP does not change the outcomes significantly.

The fuzzy weights for environmental and economic criteria are calculated for each stakeholder. These weights show the uncertainty of stakeholders in expressing their preferences. Although they often know which criterion they prefer, sometimes they cannot verbalize how much. The proposed framework initially assumed that industry will prefer economic benefits, somehow strongly, while municipality will prefer environmental benefits, very strongly. Fuzzy weights are presented in Table 5.6.

Table 5.6 Fuzzy weights for the sustainability criteria

	Stakeholder 1 – Industry		
Criteria/ Membership degrees	**Minimum**	**Most likely**	**Maximum**
Environmental	16%	20%	24%
Economic	66%	80%	98%
	Stakeholder 2 – Municipality		
Environmental	76%	88%	100%
Economic	11%	13%	15%

Once the weights of environmental and economic criteria are presented as fuzzy sets, sustainability indices should also be considered as fuzzy values. The analysis shows that the final decisions of stakeholders stay the same even with fuzzy values. The results show that WTE is a "better" option for municipality at all times with the current setting in the framework (assumptions on costs and benefits, etc.); but as environmental criteria is preferred more and more, sustainability index of RDF gets closer to the one for WTE. Similarly, RDF is always preferred by industry in the current setting. As economic criterion is the most preferred by the industry, the sustainability indices of landfill and WTE become almost the same. The sustainability indices of RDF and WTE become closer in value when the industry shows more interest in the environmental benefits. The difference between sustainability index of WTE and RDF is much smaller for municipality than industry. This means that it is more probable for the municipality to be persuaded by industry and reach a mutual agreement.

Although uncertainties cannot change the final outcome with the current assumptions, they can still change the tipping fees. When municipality has extreme preference over environmental benefits, the tipping fee should increase by $0.02/ kg MSW. In this case study, Metro Vancouver is planning on sending 370,000 tonnes of MSW to its new WTE plant by the year 2020 (Metro Vancouver, 2013). With the current assumptions, municipality's uncertainty in comparing the criteria can increase the tipping fee by about $8 million. Considering the total costs of building and operating a new WTE plant, this is still a small and manageable cost.

5.7.4 Decision-Making Under Uncertainty

In the last step of the uncertainty assessment, the industry's hesitation on whether the municipality prefers the economic criterion to the environmental one is investigated. This means that the industry has observed and gathered information that supports both types of municipalities: the one that prefers economic gains and the one that prefers environmental benefits. Municipality, on the other hand, knows about industry's preference. Bayesian game models this problem. The framework suggests the same decisions when Bayesian game substitutes normal game; but still the tipping fee will change. When the probability of municipality preferring environmental criterion (P) is 87%, municipality's type is irrelevant in the outcome of the framework (Table 5.7).

Table 5.7 Bayesian game for uncertainty on municipality's type

	Industry			
Municipality	Waste treatment options	Landfill	WTE	RDF ↓
		Strongly prefers environmental criterion (P)		
	Landfill	0.09, 0.52	0.09, 0.52	0.09, 0.52
	WTE →	-0.02, 0.5	-0.02, 0.5	-0.02, 0.5
	RDF	-0.004, 0.47	-0.004, 0.47	-0.006, -0.25
		Strongly prefers economic criterion (1-P)		
	Landfill	0.11, 0.52	0.11, 0.52	0.11, 0.52
	WTE →	-0.02, 0.5	-0.02, 0.5	-0.02, 0.5
	RDF	0.06, 0.47	0.06, 0.47	0.04, -0.25

5.8 Summary

In this chapter, major uncertainties that can impact the reliability of the developed framework are observed and analyzed. The statistical approaches of sensitivity analysis, fuzzy set theory, and Bayesian games are used to analyze the impact of the uncertainties. The analysis is demonstrated using the case study of RDF, showing that the stakeholders' uncertainty about each other's preferences and their difficulty in expressing their own preferences, and uncertainty in the values of costs and benefits have the most significant impacts on the outcome of the framework.

Chapter 6 Conclusions and Recommendations

6.1 Summary and Conclusions

Selection of waste treatment options is the core of MSWM because of related environmental and economic impacts. An optimal waste treatment option attempts to find a reasonable balance between environmental and economic - and when known social - impacts of available choices. Choosing a sustainable waste treatment strategy requires assessment of various criteria from the point of view of multiple stakeholders.

This research critically reviewed the MSWM studies with MCDA-based frameworks from 1991 to 2013 and analyzed the trends in the MSWM problems. The analysis of trends showed that the number of studies with consideration of multiple stakeholders have tremendously increased in the past decade. Most studies identified government/municipalities and experts as parts of multi-stakeholder decision-making problems. Moreover, AHP was found to be the most commonly applied MCDA method. But, the existing studies fall short on considering competing relations and hierarchy among stakeholders in MSW treatment problems.

To choose and apply a sustainable waste treatment option, municipalities generally develop partnerships with other stakeholders such as industries. When a new WTE technology is proposed, stakeholders are competing for lesser contribution of costs. In addition, municipality's responsibility toward MSW, results in unequal voting powers among stakeholders. If both stakeholders do not mutually agree on a WTE technology, the project will not be applicable and none of the stakeholders will benefit. Hence, they negotiate their shares of costs and benefits to reach a mutually agreeable decision. Reaching an agreement for multiple stakeholders with conflicting priorities is often a complicated affair.

This study proposes a decision framework to assist two stakeholders with conflicting priorities to choose a sustainable waste treatment option. In addition, it estimates their fair shares of costs and benefits, which helps them to reach a mutual agreement on a single optimal option that is environmentally superior and economically feasible. The developed framework uses LCA, LCC, and AHP to help stakeholders to compare various options based on their individual preferences. It then applies game theory to model stakeholder's actions, conflicts, and dialogues and share the costs in a fair and acceptable way.

The application of the developed framework was also validated with a case study of RDF in Vancouver. Two stakeholders, Metro Vancouver and the cement industry, compared the sustainability impacts of landfilling, mass-burn WTE, and RDF to evaluate the possibility of collaborating on a new RDF treatment plant. The developed framework estimated that a tipping fee of \$0.11-\$0.9 per kg MSW should be paid by the cement industry to Metro Vancouver, so that RDF can be applied as Metro Vancouver's new waste treatment option.

The developed framework used various state-of-the-art tools/ methods and diverse data from different sources, so uncertainty is unavoidable in the assessments. The sources of uncertainties are mainly related to input data, model/methodology, and the stakeholders' preferences. To address and reduce uncertainties, sensitivity analysis, fuzzy AHP, and Bayesian games have been employed. Uncertainty analysis was performed on waste composition, costs and benefits of waste treatment options, weighting systems, and group decision-making for the RDF case study. Most uncertainties considered in the case study did not change the stakeholder's decisions; but they changed the tipping fee required for stakeholders to reach an agreement. Among the assessed uncertainties, the ones with the greatest impacts on the reliability of the outcomes in the framework are: the uncertainty of the cost and benefit values, the selection of time horizon of greenhouse gases in global warming potential, stakeholder's difficulty with verbalizing their preferences on sustainability criteria, and stakeholders' imperfect information about each other's preferences or types.

6.2 Originality and Contribution

Previous studies on MSWM acknowledged the importance of considering multiple stakeholders in decision-making, but they fell short on discussing group decision-making problems with both competitions and hierarchy among stakeholders. In choosing a WTE technology for waste treatment, municipalities often require industrial partners. Since both stakeholders are self-interested and prefer to pay less of the costs and gain more of the benefits, reaching a mutual agreement on a sustainable option is complicated. In such decision-making problems, various criteria and stakeholders' conflicting preferences should be considered. This study performed a critical review on MSWM studies and developed a comprehensive framework that can help stakeholders to reach a mutual agreement on a sustainable option. This framework makes the outcome of the group decision-making pragmatic by fairly sharing the costs and benefits among stakeholders. The developed framework is unique in the problem it is addressing and the set of stakeholders it is discussing. This study will also analyze the impacts of uncertain data and models on the outcome of the framework.

6.3 **Applications**

The results of this framework will help municipalities to explore more advanced and sustainable treatment options such as WTE technologies and also avoid free riding. The free riding problem occurs when one stakeholder pays for a product from which multiple stakeholders benefit. This framework will also help stakeholders make informed decisions in group settings. The developed framework has a capability to deal with other engineering problems where multi-stakeholder involvement is inevitable in decision-making process.

This framework indirectly promotes technologies that re-use and recover useful material and energy from disposed MSW. In fact, it provides solutions for the involved stakeholders to cooperate and apply these technologies. If a mutual agreement is not reached, stakeholders will not benefit from the proposed options. It should be mentioned that the objective of this study is not to compromise environmental benefits by offering more financial benefits, but rather to help stakeholders share the costs among themselves so that they can conserve more natural resources for future generations.

6.4 Limitations and Recommendations

Based on this study, the following limitations are observed. As a result some recommendations are made for future studies (Table 6.1):

Table 6.1 Limitations and recommendations in this study

No.	Limitation	Recommendation
	Overall framework	
1	The framework uses certain methods to address a group decision-making problem, while in fact other approaches might be available.	Other methods of group decision-making problems such as Delphi methods can be approached, although the process might be less efficient.
	Sustainability assessment section	
2	Social impacts are often ignored in sustainability assessment of waste streams or are blended with economic assessment. One of the reasons for such omission is the difficulty associated with assessing social factors and their subjective nature.	Pursuit of social life cycle assessment (s-LCA) in the context of MSWM problems can improve the decision-making process. There are various quantitative and qualitative methods for evaluating social impacts independently (Refer to a review by Chhipi-Shrestha, Hewage, & Sadiq, 2014). Based on literature review, the following sub-criteria can be considered for social assessment of waste treatment options for future studies: - Proximity to residential area (e.g., Noise, Odor (den Boer et al., 2007)) - Workers' and neighborhood's safety (Sheppard & Meitner, 2005) - Employment (den Boer et al., 2007) - Affordability - Public acceptability - Land use (den Boer et al., 2007)

No.	Limitation	Recommendation
	Sustainability assessment	
3	Apart from the most general costs and benefits considered in this framework and the case study of RDF, other costs and benefits can impact the sustainability assessment results.	Consideration of more costs and benefits will make the results of assessments more reliable and precise. Among them is the cost of technology changes in the production line of the industry to combust fuels other than fossil fuels.
4	Environmental impacts were assumed to be similar for all stakeholders as LCA often considers a hand-full of impacts; but there are individual impacts that are often ignored in LCA.	The consideration of other impacts requires an extensive Human Health Risk Assessment on all stakeholders according to the routes of exposure to hazardous materials and frequency of those exposures. In such study, workers at the site, residents in the neighborhood of plants, and occasional visitors would face different levels of exposures.
5	The assessments are done using only the SimaPro software. SimaPro has access to data on European MSW treatment plants, and should be adapted to be used for North American projects.	There are other sustainability assessment tools, such as GaBi. The results of GaBi are compare with SimaPro for this study and SimaPro's better presentation of outcomes is the reason for its selection. Using various tools in parallel will also help the experts to better estimate the impacts.
6	The most challenging part of this study was providing accurate data and real scenarios or making assumptions that truthfully represented the waste treatment scenarios and stakeholders.	To improve the scenarios, municipalities and industry should be actively involved in the study.

No.	Limitation	Recommendation
	Weighting systems	
7	In this study, reasonable assumptions were made for pairwise comparisons of the sustainability criteria.	Using real stakeholders for these comparisons is recommended for the future studies.
	Game theory	
8	Inclusion of more than two stakeholders in the framework will require complex programming and modeling in the decision-making sections. Normal games are very complicated for n-player games.	This framework can expand to incorporate n-player games with n>2 using appropriate programming tools.
9	This study only discusses the normal games. The case study also had sufficient evidence that the stakeholders have complete information about the actions and decide simultaneously; therefore, other possibilities were only mentioned as uncertainties.	Extensive games can be incorporated into the framework for other group decision-making problems. In these models, stakeholders get to observe each other's actions in each round. This process can repeat for a limited number of rounds or until stakeholders reach the same decision.
10	Only pure strategy Nash equilibriums are mentioned as solutions to the games.	Solutions to the games can also be mixed strategy Nash equilibrium. These results will provide an optimal combination of the available options.
	Uncertainty analysis	
11	Uncertainty in the LCA methodology is not discussed in depth.	Other statistical methods (where applicable) can be used for comparison of the results. The uncertainty in the LCA methodology can be explored further.

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Appendix

The snapshots of the developed Excel tool are presented here.

Table A.1 Step 1 sheet

STEP 1 WASTE COMPOSITION

	Landfill	RDF	WTE
STEP 1	**Waste composition percentage for each alternative**		
Waste composition	Alternative 1	Alternative 2	Alternative 3
Paper	0.136	0.136	0.136
Plastic	0.144	0.144	0.144
Compostable organics	0.362	0	0.362
Wood	0.027	0.027	0.027
Textiles	0.027	0.027	0.027
Rubber	0.027	0.027	0.027
Leather	0.027	0.027	0.027
Metals	0.032	0	0.032
Glass	0.016	0	0.016
Building material	0.084	0	0.084
Electronic waste	0.011	0	0.011
Household hazardous	0.009	0	0.009
Household hygiene	0.05	0	0.05
Bulky objects	0.041	0	0.041
Fines	0.006	0.006	0.006
Sum	100.0%	39.4%	100.0%
	74%	33.4%	0.744

Table A.2 Step 2 sheet

STEP 2 LCA per fraction of waste

Alternative 1 - Landfilling

Per kg MSW

STEP 2 **LCA of each fraction of waste in each alternative**

Impact categories	Paper	Plastic	Compostable	Wood	Textile	Metals	Glass
Abiotic depletion	0	0	0	0	0	0	0
Acidification	0.02381856	0.01305474	0.01943333	0.02986431	0.02416508	0.00319427	0.004790547
Eutrophication	0.00028466	0.00021137	0.0010655	0.00082736	0.00110759	2.34E-05	9.51755E-05
Global warming 100	0.54195856	0.00920452	0.29340673	0.96237069	0.5615248	0.00364073	0.000544834
Ozone depletion	3.2301E-09	3.23E-09	3.23E-09	3.2301E-09	3.2301E-09	3.3773E-10	3.51912E-10
Human toxicity	1.6693E-10	6.5691E-10	8.5861E-11	5.475E-11	5.6178E-10	3.4293E-09	8.51843E-10
Fresh aquatic ecotoxicity	0.00494065	0.01679092	0.00318472	0.00265074	0.01000785	0.14362555	0.009403923
Terrestrial ecotoxicity	0.00494065	0.01679092	0.00318472	0.00265074	0.01000785	0.14362555	0.009403923
Photochemical oxidation	0.0105413	0.00394073	0.00784926	0.01430408	0.01074793	0.00149357	0.001773477

Table A.3 Step 3 sheet

STEP 3 Sustainability performance

STEP 3		**Sustainability performances**		
		Landfill	WTE	RDF
Impact categories	Units	Alternative 1	Alternative 2	Alternative 3
Abiotic depletion	Kg Sb eq	0	0	0
Acidification	Kg SO2-eq	0.013791733	-0.099711193	-0.08837934
Eutrophication	Kg PO43+-eq	0.000509378	-1.97144E-05	-2.17746E-05
Global warming 100	Kg CO2-eq	0.22251545	-0.02108101	-0.018710626
Ozone depletion	Kg CFC-11 eq	2.26455E-09	-3.76567E-08	-3.29881E-08
Human toxicity	CPUh	2.88392E-10	-1.69924E-10	-1.62178E-10
Fresh aquatic ecotoxicity	Kg 1,4-DB	0.009330953	-1.69924E-10	-1.62178E-10
Terrestrial ecotoxicity	Kg 1,4-DB	0.009330953	-0.015210503	-0.010596828
Photochemical oxidation	Kg C2H4-eq	0.005595088	-0.008640403	-0.010301992
Economic net cost Stakeholder 1	$	0.63	0.63	-0.31
Economic net cost Stakeholder 2	$	0.108	-0.026	0.043

Table A.4 Step 4 sheet

STEP 4 Criteria weights

				Global weights
	Environmental	Economic		Weights
Environmental	1.00	0.25		2%
Economic	4.00	1.00		1%
sum	5.00	1.25		2%
				8%
Environmental	0.2	0.2	20%	1%
Economic	0.8	0.8	80%	2%
				2%
				2%
				1%
				80%
			Total	100%

Table A.5 Step 5 sheet

STEP 5 Game theory

	Stakeholder 2		Municipality				
		Landfill		WTE		RDF	
Stakeholder 1 Industry	Landfill	0.52	0.09	0.52	-0.02	0.52	-0.006
	WTE	0.50	0.09	0.50	-0.02	0.50	-0.006
	RDF	-0.25	0.09	-0.25	-0.02	-0.25	-0.006