Development of a Decision Making Framework for Solid Waste Management Using GIS-based Site Selection and an Economic Comparison

by

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Abstract

The management of municipal solid waste (MSW) is one of the major challenging issues for various global jurisdictions. MSW generation and disposal rates are increasing worldwide along with increased population and urbanization. Limited landfill capacity and long-term environmental issues associated with landfilling (e.g., landfill gas emission and leachate generation) have led to a need to consider sustainable alternatives for MSW use and disposal.

Two of the most important issues associated with waste conversion facility building are optimal site location and economic feasibility. The overall objective of this research is to: (1) develop a methodology for waste conversion facility site selection and (2) create a generic decision-making model that can be used by county planners to make waste conversion facility decisions incorporating economic and social parameters. Siting a solid waste-to-energy (WTE) facility requires an assessment of solid waste availability as well as compliance with environmental, social, and economic factors. There are some important parameters (e.g., location and amount of available waste, soil type, etc.) that should be considered when siting WTE facilities. These parameters do not have equal weight. In the first part of this study, six different waste management scenarios were studied with three different weights used. The analytic hierarchy process (AHP) was used to assign weights to the parameters. Both waste availability amount-dependent and waste availability amount-independent studies were carried out. The purpose of the second part of this study is to develop a framework to help compare the costs of different waste management scenarios. A user-friendly model was developed that allows the user to input different waste availability details and other variables (i.e., cost of biofuel, cost of electricity, etc.). Ten waste management scenarios were compared based on either gate fee or internal rate of return. These scenarios are: (i) gasification (producing biofuel), (ii) gasification (producing electricity), (iii) anaerobic digestion, (iv) composting, (v) new landfill, (vi) gasification (producing biofuel) integrated with anaerobic digestion, (vii) gasification (producing electricity) integrated with anaerobic digestion, (viii) gasification (producing biofuel) integrated with composting, and (ix) gasification (producing electricity) integrated with composting. A sensitivity analysis was conducted to assess the impact of changes in the values of different parameters.

For this research, a case study of Parkland County was conducted. For this case study, at 10% IRR and a waste availability of 25,000-50,000 tonne/year, composting is the cheapest solution (77 -86 $/tonne gate fee), and for a waste availability of 50,000-150,000 tonne/year, a gasification (producing electricity) facility integrated with composting is the cheapest solution with a gate fee of 42 -77 $/tonne. Moreover, as incentives (from government or other parties) increase for waste-to-energy scenarios, these scenarios become cheaper. As capital investment incentives increase, the facility owner's capital investment decreases.

Preface

This thesis is an original work by Md. Mohib-Ul-Haque Khan under the supervision of Dr. Amit Kumar. Chapter 3 of this thesis is to be submitted as Khan, M.M., Sultana, A., Kumar, A., "Optimal siting of solid waste conversion facilities using a GIS-based assessment", to *Waste Management*. Chapter 4 of this thesis has been submitted as Khan, M.M., Jain, S., Vaezi, M., Kumar, A., "Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways", to *Waste Management* in 2015. I was responsible for the data collection, modelling and validation, and manuscript composition. A. Sultana, M. Vaezi and S. Jain contributed to model validation and manuscript edits. A. Kumar was the supervisory author and was involved with concept formulation, evaluation, model development and validation, and manuscript edits.

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List of abbreviations

AD	Anaerobic digestion
AHP	Analytic Hierarchy Process
BDT	Bone dry tonne
CO_2	Carbon dioxide
CO_2-eq	Equivalent carbon dioxide
ESA	Environmentally sensitive areas
FUNNEL-Cost-MSW	**FUN**damental E**N**gineering Principl**E**s-based Mode**L** for Estimation of **Cost** of Energy and Fuels from **MSW**
GHG	Greenhouse gas
GIS	Geographic information system
IRR	Internal rate of return
kWh	Kilowatt hour
MSW	Municipal solid waste
OPEX	Operating expenditure
WA	Waste availability
WTE	Waste-to-energy

Chapter 1: Introduction

1.1. Background

Municipal Solid waste (MSW) is produced as a result of human activities and varies with population size, urbanization, and living standards. The management of MSW is a big concern today for city authorities and planners due to increasing population, urbanization, and limited land space. Sustainable Management of MSW is one of the major challenges (Javaheri et al., 2006), and the traditional treatment and dumping of MSW come with some significant environmental issues such as leachate generation and air pollution (Ojha et al., 2007). Such environmental challenges, combined with political, social, and economic issues, as well as the availability of land, are major concerns to be addressed in land evaluation and management (Lein, 1990). Moreover, increasing population leads to increased fossil fuel consumption and corresponding increases in energy and fuel demands. Converting MSW to energy could provide an environmentally friendly means not only for producing cleaner energy, but also for offsetting GHG emissions.

In 2010, 19 out of 32 European countries (EU-27 member states, Croatia, Iceland, Norway, Switzerland, and Turkey) landfilled more than 50% of their municipal solid waste (European Environment Agency, 2013). In 2004, 172 million tonnes of solid waste was generated in China (Shekdar, 2009), and India generates around 45 million tonnes of waste every year (Shekdar, 2009). These two countries openly dump 50% and 90% of their total MSW, respectively (Visvanathan and Trankler, 2003). In the United States, most MSW went to the dump until 1975, and currently many landfills have either reached or nearly reached their capacity (Palmer, 2011). In Canada, most waste ends up at landfills as well. In 2010, 30% of Canada's landfills either reached or surpassed their capacity (PPP Canada, 2014). These landfills produce a sizable portion (about 25%) of Canada's methane emissions (Environment Canada, 2012). It is necessary to develop and implement more environmentally friendly waste management options to divert waste from landfills. The details on MSW estimate for Canada and Alberta is discussed in Chapter 2.

There are many studies on solid waste utilization techniques. A few studies focus on an energy and economic assessment for specific technologies (Bonk et al., 2015; Emery et al, 2007). Others provide current solid waste scenarios and future possibilities for some specific regions (Boukelia and Mecibah, 2012; Hossain et al., 2014; Kimambo and Subramanian, 2014). Environmental impacts and life cycle assessments (LCA) are the focus of many other studies, e.g., Fruergaard and Astrup (2011) and Bozorgirad et al (2013). A number of studies use geographic information system (GIS) to find suitable locations for solid waste disposal (Sener et al. 2011; Yesilnacara et al. 2012; Gorsevski et al. 2012). However, the available information for site selection of MSW conversion facility is not comprehensive. Furthermore, although some location-specific and technology-specific waste-to-energy (WTE) techno-economic studies have been conducted (Lemea et al. 2014; Bonk et al. 2015), there is no techno-economic study on solid waste use that considers the spatial variation of solid waste and the use of a real road network and compares waste conversion technologies for a wide range of waste availability.

The main aim of solid WTE or fuel facilities is to reuse most of the waste materials received through simple transformations or complex biological and thermal processes. Each solid WTE plant has its own specifications, and MSW incinerators are considered to be a source of pollution (Arena , 2012; Tavares et al., 2011), hence this study focuses on the siting of WTE or fuel facilities based on thermal processes (e.g., gasification, pyrolysis) and biological conversion (e.g., anaerobic digestion) rather than incineration. MSW treatment plants usually fall into the group of obnoxious or undesirable facilities (Aragones-Beltran et al, 2010). Siting WTE facilities in optimal locations at optimal capacities is a complex task involving many challenges and constraints. For example, social opposition such as community reactions, sometimes known as a NIMBY (not in my backyard) mentality, is one of the major challenges (Aragones-Beltran et al, 2010).

When considering the complete disposal of waste, a waste management plan should include landfilling along with waste treatment processes because landfilling is still the ultimate destination for the waste that cannot be treated by prevailing waste treatment processes. However, if all waste (after recycling) goes to the landfill, the landfill's remaining life will decrease rapidly, and land scarcity is already a key barrier in waste management. A Zero Waste approach could fulfill environmental objectives but is not economically feasible. On the other hand, landfilling all waste would comply with all economic criteria but would not contribute to environmental goals and expressed public desire. A suitable plan balances the two extremes – Zero Waste and landfill-only – and combines prevailing resources in a planned way to make the best fit for a feasible solution. Such a plan is dependent on several factors: it must be economical, environmentally and socially acceptable, and in compliance with remaining landfill life and landfill spaces. There have been some studies in this domain (Kambo et. al, 1991; Song et al., 2012), but a comprehensive framework for development of such a plan is very limited.

1.2. Research Motivation

The motivation of this research is drawn from a number of factors.

- Landfills in some cities and counties are nearing the end of their life, and space for new landfills is increasingly scarce. Some small towns and counties do not have their own landfill and so transport their waste out of the county or town, which increases waste disposal costs. Moreover, landfilled waste generates GHGs and leachates. The combination of increasing population with increasing urbanization and economically developed lifestyles leads to increased waste generation and increased demand for fossil fuels. The reasons stated above trigger the need for waste conversion facility development. The key barriers to waste conversion facility development are proper site selection, financing of the facilities, and public perception towards waste-to-energy.
- Siting waste disposal facilities (i.e., landfills) with GIS-based assessment is well established. But, there is little research in the area of siting waste conversion facilities using GIS and spatial analysis. In order to locate a waste conversion facility complying environmental, social and economic factors, it is necessary to conduct a GIS-based comprehensive site selection study for waste conversion facilities.
- The decision to switch from landfilling to waste conversion facility depends on several factors such as waste availability, financing, difficulty in getting a new landfill permit, remaining landfill life, available spaces for new landfills, and existing vested interests. Since economic feasibility is one of the key factors, it is important to develop a model based on economic comparison of different waste conversion pathways.

- In order to find out the major controlling economic parameters to make the waste conversion facility more feasible, it is necessary to understand the sensitivity of economic parameters on the gate fee and internal rate of return of the waste conversion scenarios.

1.3. Objectives

The overall objective of this research is to develop a modelling framework which could help the decision makers in suitable use of the MSW in a particular jurisdiction. The specific objectives of this study are to:

- Create a decision-making model based on economic, environmental, and other parameters to select optimal waste disposal option
- Develop a site selection methodology for waste-to-energy facility development with a GIS-based assessment specific to Alberta
- Calculate transportation cost using a real road network that incorporates GIS and other attributes (road speed limits, direction of traffic, etc.)
- Determine the optimum size and location of an MSW processing facility for a particular municipality
- Compare waste conversion technologies over a wide range of waste availability to provide a clear idea about the cheapest technology for a certain amount of waste availability and the minimum amount of waste availability required to implement a certain technology for a specific region
- Conduct a specific case study for Alberta's Parkland County to determine the optimal waste disposal option for the county.

1.4. Scope and Limitation of the Thesis

- This study developed a GIS-based methodology for waste conversion facility site selection and applied this methodology to the province of Alberta. Some of the environmental and social parameters considered in this study are specific to Alberta and may be different for other places. The developed methodology can be applied to any other places by changing the corresponding parameters' values.
- This study compares ten waste management scenarios and contains default economic values for these ten scenarios. If, any different waste management scenario is needed to be compared, the economic details of that scenario are needed to be input in the model.

1.5. Organization of the Thesis

This thesis consists of five chapters as well as a table of contents, a list of tables, a list of figures, three appendices, and a list of references. The thesis is based on paper-based format. Hence, each chapter represents a paper which is expected to be published in peer-reviewed journals. Since each chapter is intended to be read independently, there is some repetition of concepts, data and assumptions.

Chapter 1 provides the background, research motivation, objectives, and organization of the thesis. The current chapter gives a brief summary of current waste management scenario worldwide and in the Background and Research Motivation sections why this type of study and modelling are necessary. In the Objectives and Organization of thesis sections, this chapter gives a succinct overview of the whole study.

Chapter 2 describes the MSW potential and current waste management scenario in Canada and Alberta.

Chapter 3 describes the development of a GIS model used to locate optimal sites for solid WTE facilities. The developed site selection methodology has been applied to the province of Alberta. Results for six different scenarios are included in the Results and Discussion section and are compared in Conclusion.

Chapter 4 introduces the developed framework and demonstrates the application of an economic comparison model designed to help county and municipal decision-makers develop waste-to-energy facilities. The developed framework compares ten waste management scenarios based on different conversion technologies and their combinations including landfilling and composting. A GIS model has been used in this study to determine suitable locations for WTE facilities and landfills considering environmental, social, and economic factors. Finally, a case study on Parkland County and its surrounding counties was conducted and a sensitivity analysis was performed to assess the influence of various key parameters on the calculated gate fees.

Chapter 5 makes conclusions and recommendations for future work.

Appendices are provided at the end of the thesis and contain related information, diagram and codes.

Chapter 2: Current Management of MSW and its Potential in Canada and Alberta

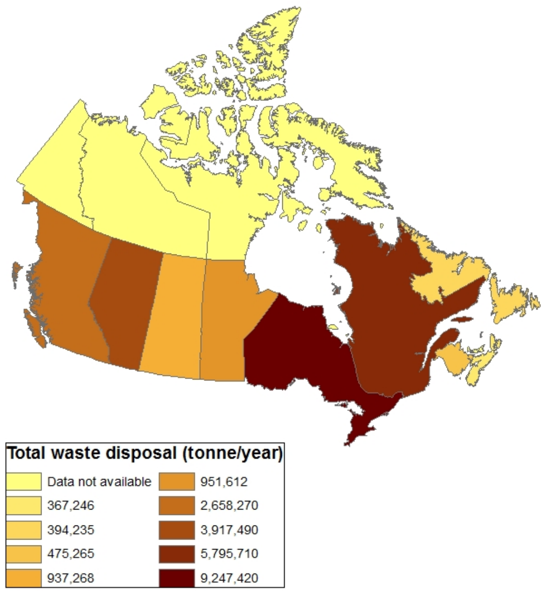
2.1. Introduction

Canada's MSW generation is increasing and as a result its disposal issue is also becoming more challenging. As mentioned in chapter 1, 30% of Canada's landfills either surpassed or reached their capacity in 2010 (PPP Canada, 2014). Moreover, around 20% of Canada's total methane emissions are produced in landfills (Environment Canada, 2014). Hence it has become necessary to increase the diversion rate of MSW from landfills and, it follows, to study MSW potential and current MSW management scenarios to make a sustainable waste management strategy. This chapter discusses recent waste disposal rates, waste diversion rates, and costs associated with MSW management for each province and territories in Canada. This chapter also provides a waste availability assessment for the province of Alberta.

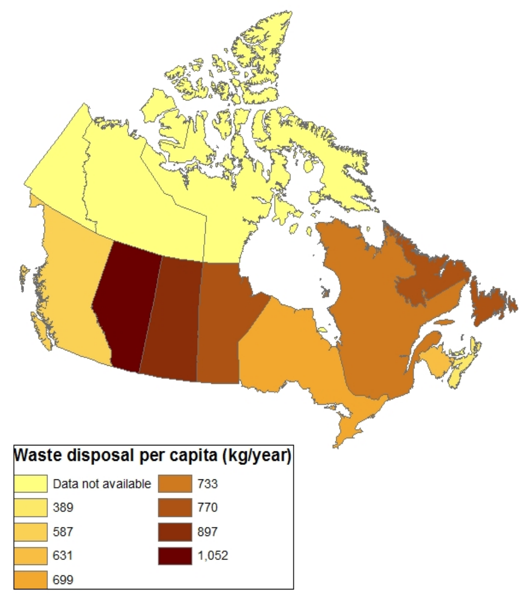
2.2. Current Management of MSW in Canada

Canada had a population of almost 35.5 million in 2014 (Statistics Canada, 2014) and approximately 25 million tonnes of non-hazardous waste disposal in 2010 (Statistics Canada, 2010). Figures 1(a) and 1(b) show the disposal of waste in each province in 2010. In this thesis, waste disposal data for Nuvanut, Yukon, Prince Edward Island, and the Northwest Territories could not be included due to scarcity of data on waste availability in the public domain. Ontario, Quebec, Alberta, and British Columbia were the four provinces with the highest waste disposal; waste disposal in these provinces were 9.2, 5.79, 3.9, and 2.65 million tonnes/year, respectively (Statistics Canada, 2010). On a per capita basis, 729 kg per capita waste was disposed in Canada.

Alberta and Saskatchewan had the highest per capita waste disposal, 1,052 and 897 kg, respectively (Statistics Canada, 2010).



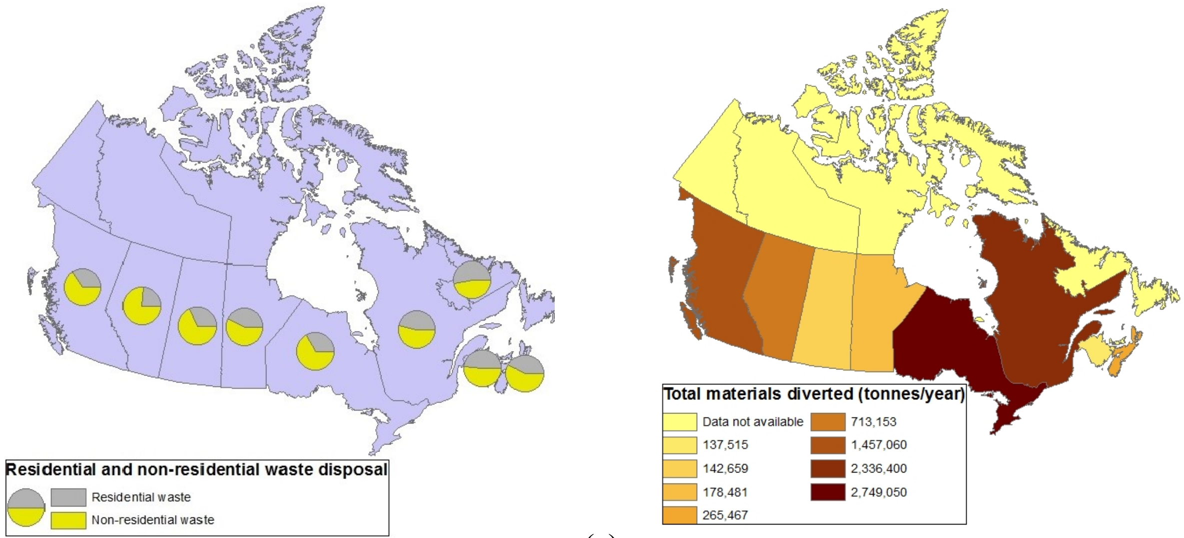
(a)



(b)

Figure 1: **(a) Total waste disposal, (b) waste disposal per capita by province**

Figure 2(a) gives an idea of the residential and non-residential portions of the total waste disposal in Canadian provinces in 2008. Here, residential waste disposal includes both the waste self-hauled from residential sources and the waste collected by the municipality. The non-residential waste stream includes industrial, commercial, and institutional (ICI) waste and construction and demolition (C&D) waste. In 2008, Canada had almost 9.35 and 16.55 million tonnes of residential and non-residential waste, respectively (Statistics Canada, 2010). On a per capita basis, in 2010, Canada had 271 kg and 458 kg of residential and non-residential waste, respectively (Statistics Canada, 2010). Every province had more non-residential than residential waste. Almost 75% of Alberta's disposed waste came from non-residential sources (Statistics Canada, 2010).



(a) (b)

Figure 2: (a) Residential and non-residential waste disposal percentage, (b) total materials diverted in each province in 2010

Figure 2(b) shows total materials diverted in each province in 2010. Canada had approximately 8 million tonnes of waste diverted from landfilling, which is around 24% of the total generated waste (Statistics Canada, 2010). Most of the diverted waste was in Ontario, Quebec, and British Columbia; wastes diverted by these provinces were 2.7, 2.3, and 1.5 million tonnes, respectively (Statistics Canada, 2010).

Figure 3 shows the per capita expenditure made by local governments in 2010 on different waste management activities. On a per capita basis, local governments spent approximately \$15[1], \$5, and \$2 on the operation of disposal facilities, recycling facilities, and organics processing facilities (Statistics Canada, 2010). Collection and transportation costs, disposal facility operational costs, tipping fees, and recycling facility operational costs represent the major

[1] All currency figures in this chapter are expressed in Canadian dollar (CAD) and the base year is 2010 unless otherwise noted.

portion of the total expenditure. Figure 4 shows each province's expenditures for these four cost components.

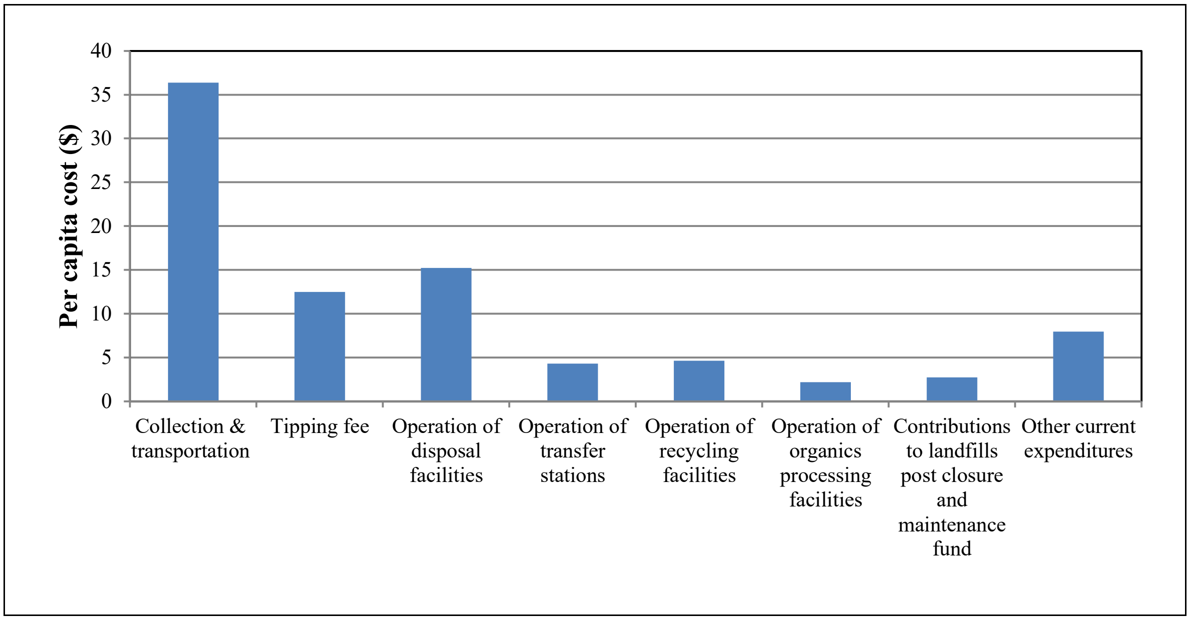


Figure 3: Per capita costs spent by local governments on waste management activities

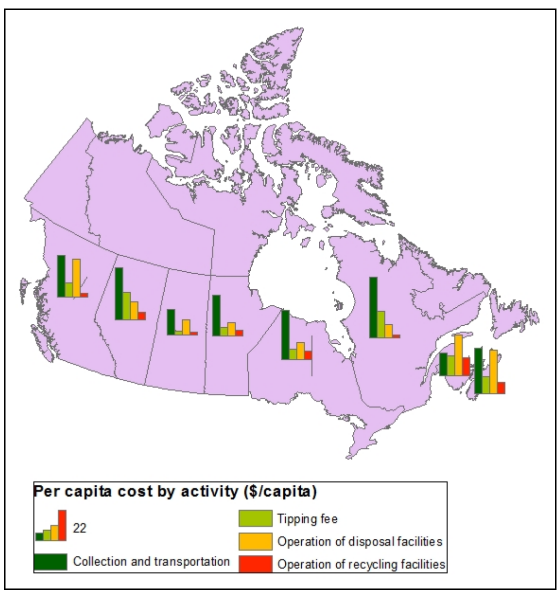


Figure 4: Per capita costs spent by local governments on the four main waste management activities for each province

Figure 5 depicts a proportional relationship between per capita waste diverted and per capita total current expenditure for waste management. In 2010, Canada had national averages of $16, $86, and 236 kg of per capita capital expenditures, per capita operating expenditures, and per capita diverted waste materials (Statistics Canada, 2010). Alberta, Nova Scotia, and British Columbia surpassed the national per capita capital and operating expenditure. British Columbia, Quebec, and Nova Scotia had higher per capita waste diverted than the national average (Statistics Canada, 2010).

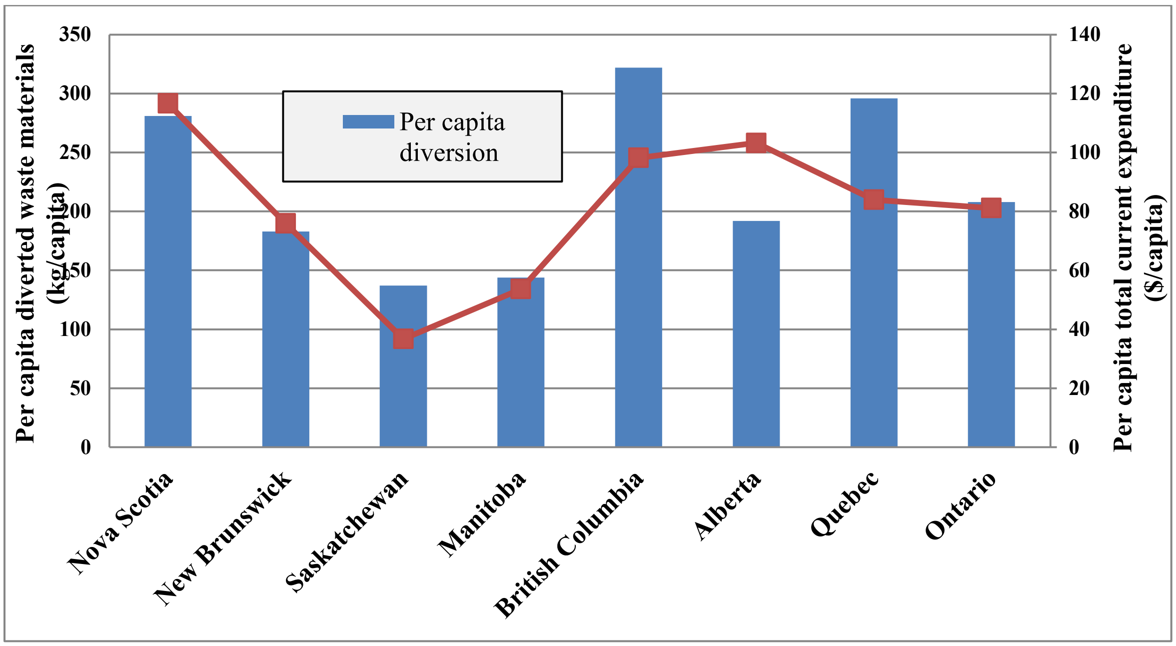


Figure 5: Per capita waste diverted and local current expenditures for each province in 2010

2.3. Current MSW Scenario and MSW Characteristics in Alberta

The province of Alberta covers 661,185 square kilometers. It had a total population of 3,699,939 in 2012 (Government of Alberta, 2012a). Alberta's waste management hierarchy is Reduce, Reuse, Recycle, Recover (Alberta Environment, 2006). "Reduce" means to reduce the generation of waste; “reuse” is to use materials again for the same or different purposes; “recycling” is a process to change waste materials into new products; and “recovery” is a process of extracting energy from waste materials.

In Alberta, waste disposal from residential and non-residential sources was 970,422 tonnes and 2,947,070 tonnes, respectively, in 2010 (Statistics Canada, 2010). Approximately 33% of the total waste generated in Alberta is from the residential sector, while 40% comes from the ICI (industrial, commercial, and institutional) sector and 27% from the C&D (construction and demolition) sector (Alberta Environment, 2010). Residential waste collected in Edmonton typically contains up to 29% of yard waste, 23% food waste, and 17% is paper and cardboard. Around 30% of the ICI waste collected in Alberta is in the form of organics (City of Edmonton, 2010), and 29.7% is paper. Wood (26.5%) is the predominant component of the C&D waste stream collected in Alberta followed by paper (14%) (City of Edmonton, 2010).

Since a portion of the total waste generated in Alberta goes to recycling and composting facilities, this study uses “waste by disposal” data instead of “waste by generation” data to find out waste availability for waste-to-energy facilities. Though significant efforts are made to reduce, reuse, and recycle waste, landfilling still remains the most common method of waste disposal in Alberta (Government of Alberta, 2014). There are three types of landfills in Alberta: hazardous waste (class I), non-hazardous waste (class II), and inert waste (class III) landfill. Landfill data were collected from Alberta Environment (Page, 2013) and landfill personnel.

Figure 6 shows Alberta’s landfill location and waste availability. The figure includes both residential and non-residential waste. However, some industrial landfills were unwilling to share their landfill data and for some other landfills, real measured data were not available. Waste availability data were assumed for some of the class II landfills with no measured data based on the per capita of the nearest landfill.

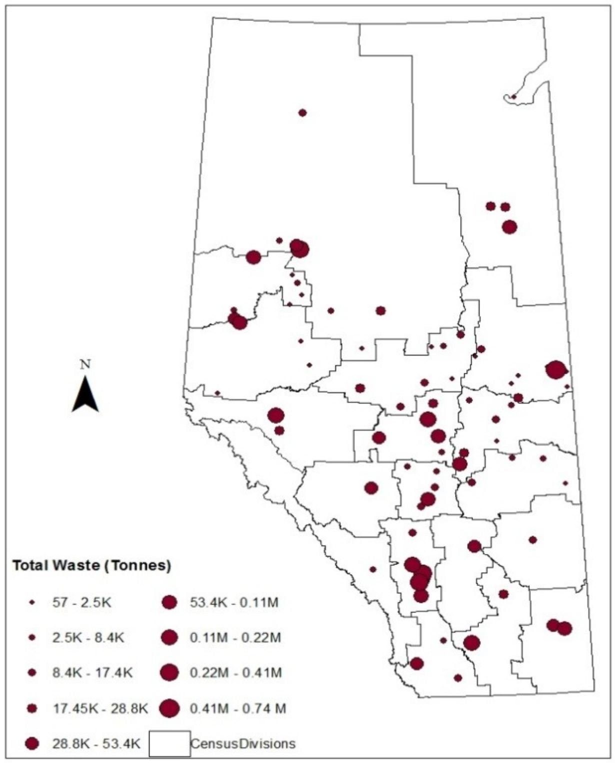


Figure 6: Waste availability at Alberta landfills

Of the total estimated waste, 66% is from class II and class III landfills and 34% is from industrial landfills. Waste availability at class II, class III, and industrial landfills is shown in Table 1.

Table 1: Waste availability at different types of landfills

Type of Landfill	Waste (tonne/year)
Waste from industrial landfills	1,371,708
Waste from class II and class III landfills	2,705,806
Total waste considered	4,077,514

Extracted energy from industrial waste varies widely for different kinds of waste; moreover, it is more difficult to treat and gasify industrial waste than residential waste (Lynch, 2014; Yassin et al., 2009). Thus for simplicity this study considers waste from only class II and class III landfills.

2.4. Waste Transportation Framework

Figure 7 depicts anticipated and proposed waste transportation frameworks considered in this study for waste-to-energy facilities in Alberta.

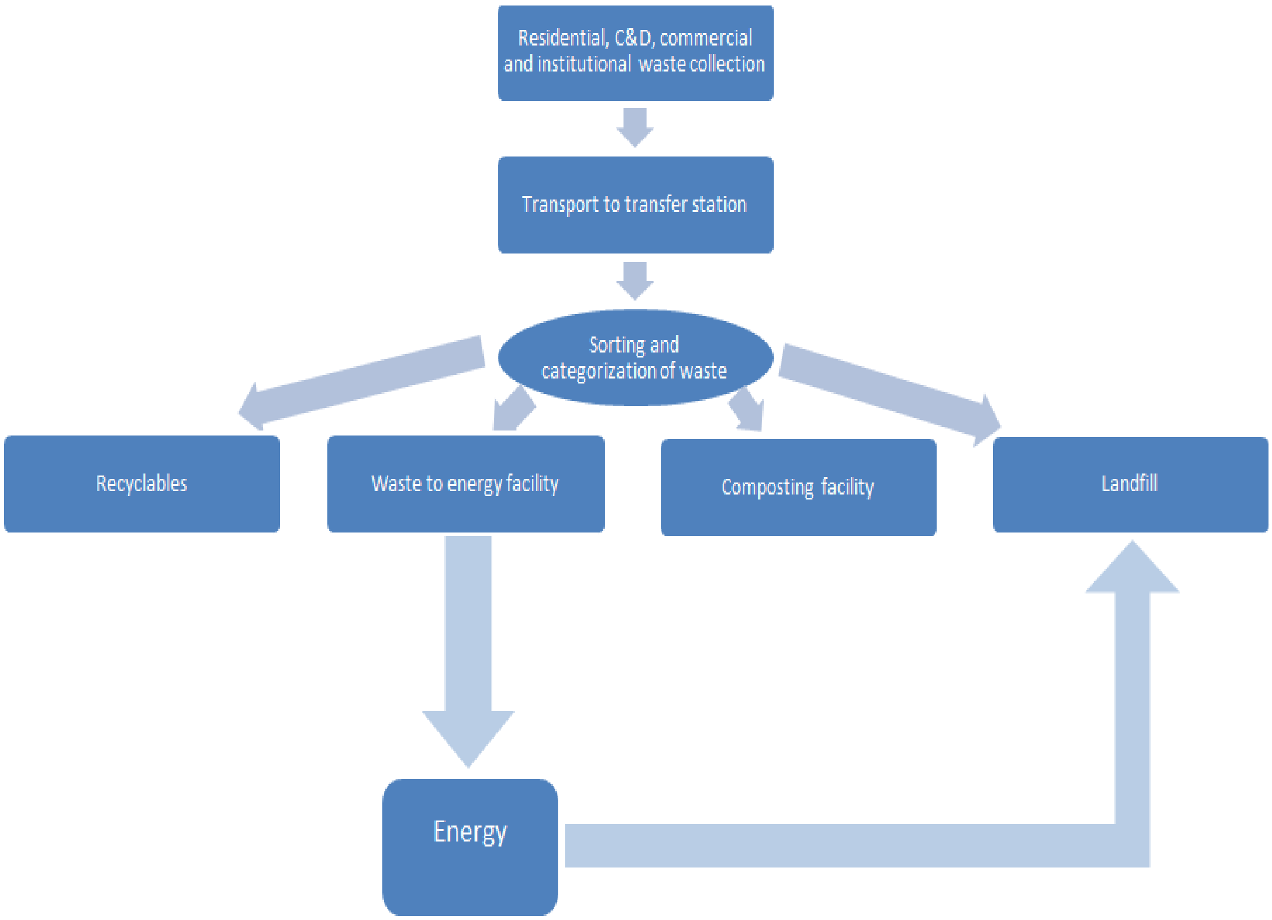


Figure 7: Waste transportation framework

In this framework, waste is sorted and categorized at the transfer stations. The recyclable portion goes to recycling facilities, waste with high organic content goes to composting facilities, waste with low energy content goes to landfills, and waste with moderate and high energy content goes to waste-to-energy facilities. After waste is treated at the WTE facilities, ash goes to the landfills. Most transfer sites in Alberta are not equipped with waste sorting facilities.

2.5. Waste at Transfer Stations

A solid waste transfer station receives waste material from a community and the waste is consolidated, tranferred to a large vehicle, and transported to a distant waste disposal facility. In

Alberta, transfer stations are typically used to collect and transport waste economically to landfills, increase collection efficiency, provide convenient drop-off locations, and decrease traffic volume at landfills (Solid Waste Association North America, 2008). A general rule of thumb is that transfer stations are more economical if the hauling distance is greater than 35 km (Solid Waste Association of North America, 2008). However, this depends on the technology for waste conversion and the product being produced.

Since in the anticipated waste transportation framework waste is transported from a transfer station to waste-to-energy facilities, it is critical to know how much waste is available at the transfer stations. In Alberta's current waste management system, waste availability at transfer sites is not measured accurately. For this study, waste disposal at landfills within each census division was estimated and then waste availability in each census division was calculated. Waste availability per unit area was calculated for each census division. Areas served by transfer sites were calculated by dividing the whole area into proximal zones (i.e., zones representing the full area where any location within the zone is closer to its associated transfer station than to any other transfer station) and the position of the tranfer sites. Waste availability at each transfer station was estimated by multiplying the area served by the corresponding transfer site and waste availability per unit area of the corresponding census division. Figure 8 shows the location and estimated solid waste availability at existing waste transfer sites.

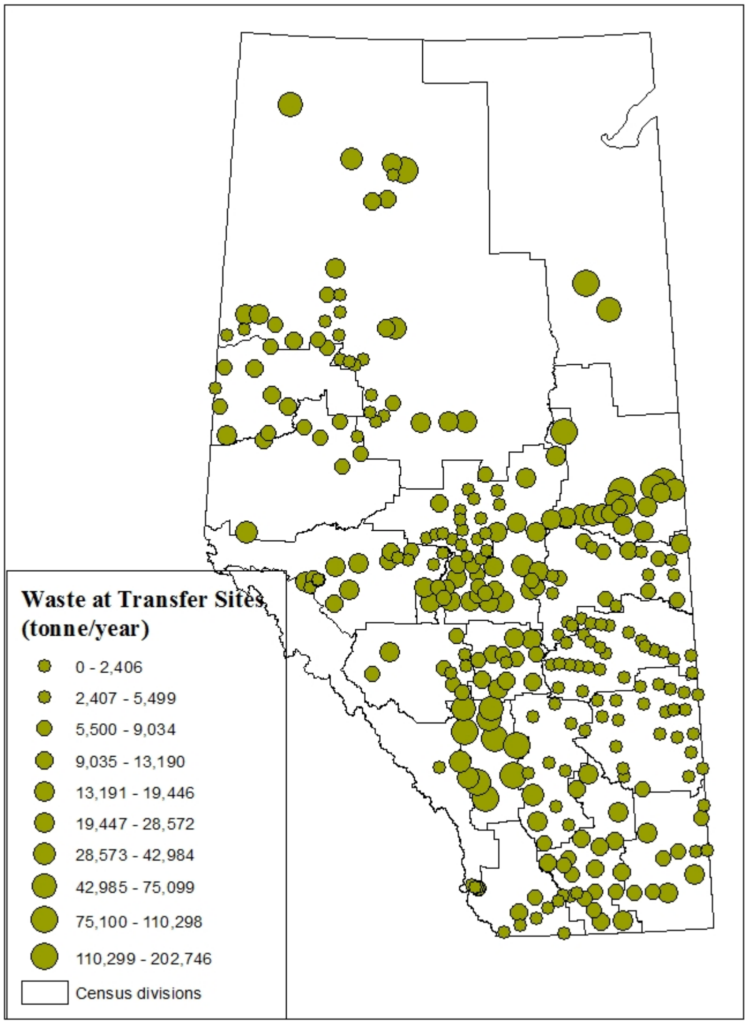


Figure 8: Waste availability at different transfer stations in Alberta

2.6. Conclusion

The necessity of waste diversion from landfilling is becoming increasingly recognized in almost every province and territory in Canada. In 2010, recycling and composting diverted 24% of the total waste generated from landfilling; the remaining 76% of MSW was disposed at the landfills (Statistics Canada, 2010). High per capita MSW generation accompanied by rapidly decreasing landfill life leads to further waste diversion from landfilling through the conversion of waste to value-added products. In 2010, Canada had a national average of $36 per capita collection and transportation cost expenditures (Statistics Canada, 2010). This high collection and transportation cost indicates the need to optimize waste management facility site selection.

Apart from the country-wide MSW management study, this chapter also focused on a waste availability assessment for Alberta. Waste availability was assessed by collecting waste disposal data from 79 landfills. The total available waste considered in this study was 4,077,514 tonnes/year for Alberta's 19 census divisions (CDs). Of this total, 1,371,708 tonnes/year were available at industrial landfills. The waste availability at transfer stations was estimated using ArcGIS proximal zones.

Chapter 3: Optimal Siting of Solid Waste Conversion Facilities Using a GIS-Based Assessment[2]

3.1. Introduction

The rapidly increasing waste generation and land scarcity engendered from fast growing world population prompt the implementation of a sustainable waste management strategy. A sustainable municipal solid waste (MSW) management system is a combination of different techniques aiming to reduce waste generation, to increase recycling of waste materials to new products and to convert waste material to value-added products with the use of recovering technologies (Demesouka et al., 2014; Kontos et al., 2005). The site selection of both waste conversion and waste disposal facilities is counted as one of the crucial tasks of the MSW management system due to environmental, social, and economical concerns (Sultana and Kumar, 2012; Tchobanoglous et al., 1993).

Several landfill siting techniques can be found in various existing literatures (Delgado et al., 2008; Gemitzi et al., 2006; Geneletti, 2010; Karagüzel, 2007; Kontos et al., 2005; Mutlutürk and Sumathi et al., 2008; Nas et al., 2010; Şener et al., 2006; Wang et al., 2009). These publications mostly develop approaches for suitable landfill site selection using the synergy of geographic information system (GIS) and multiple criteria decision analysis (MCDA) techniques (Malczewski, 1999). According to Sener et al. (2011), the GIS-supported landfill site selection process is consisted of two steps: screening out of unsuitable lands from the study area and

[2] A version of this chapter is to be submitted as Khan, M.M., Sultana, A., Kumar, A., Optimal siting of solid waste conversion facilities using a GIS-based assessment, to *Waste Management* in 2015

ranking of the remaining area. While GIS provides powerful handling and visualization of the data, MCDA ranks candidate sites by providing weights to various criteria.

As mentioned above, a large number of studies have been conducted on landfill siting in the last three decades. However, in this study a methodology was developed for siting a waste conversion facility. Moreover, the impact of the evaluation criteria (mentioned in section 3.2.2) was also studied through investigating six scenarios in this research. Afterwards, this developed methodology was applied to the province of Alberta.

This chapter introduces an approach to siting a solid waste conversion facility. Siting a solid waste conversion facility requires an assessment of solid waste availability as well as compliance with environmental, social, and economic factors. A geographic information system (GIS) spatial analysis was used primarily to screen out unsuitable land from the study area and then to identify the most suitable areas based on the availability of waste and other criteria. The analytic hierarchy process (AHP) was used with the GIS spatial analysis for a multi-criteria evaluation of relative preferences of suitable locations for waste-to-energy and bio-product facilities taking environmental and social factors into account. The main aim of this study was to develop a methodology to identify suitable locations for waste-to-energy (WTE) or biofuel facilities considering environmental and social constraints. Six scenarios were analyzed to determine the most suitable places. Waste availability (both location and amount) - dependent and waste availability location-dependent analyses were conducted. This site selection methodology was applied to the province of Alberta.

3.2. Methodology

The GIS software ArcGIS 10 (ESRI, 2015a), developed by the Environmental Systems Research Institute (ESRI), was used in this study. GIS is a handy tool for a land use suitability analysis. It has the capability to store and handle ample spatial data; it also has the ability to combine different types of numeric and descriptive values with spatial data and develop a simulation model (Al-hanbali et al., 2011). For a multi-criteria decision analysis (MCDA), several criteria are considered and values are assigned to each to find out the relative weighted value of the criteria. An analytic hierarchy process (AHP) is a widely accepted multi-criteria decision-making analysis method (Saaty, 2000). This decision support tool (DST) uses a pairwise comparison of multiple criteria and a multi-level hierarchical structure to obtain the relative weight of each individual criterion. The combination of GIS and AHP is an efficient tool to solve the waste management facility site selection issue (Basağaoğlu et al., 1997; Sener et al., 2006).In this study, an AHP-integrated GIS was used to find suitable locations for WTE facilities.

Geospatial information for this analysis was collected in both vector[3] and raster format[4] from several sources including Geobase Portal (Geobase Portal, 2013) and AltaLIS (AltaLIS, 2013). A two-step approach was used. First, an exclusion analysis[5] considering social and environmental constraints was performed to screen out unsuitable lands from the study area. Then a preference analysis[6] was conducted to find out the relative preference of different regions

[3] Vector data format uses points, lines, and polygons for representation of a model. This format is useful for storing data with discrete boundaries (ArcGIS Desktop Help, 2005).

[4] Raster data format uses regular grid of cells for representation of a model. This format is useful for storing data that varies continuously (ArcGIS Desktop Help, 2005).

[5] Exclusion analysis screens out unsuitable lands from the study area considering environmental and social criteria (Sultana and Kumar, 2012).

[6] Preference analysis ranks the remaining area considering some factors and by applying MCDA to assign weights to these factors (Sener et al., 2011).

of the study area. All maps were converted to raster maps with a 30m x 30m cell size, with each cell containing an interpretable value. This relative preference of different regions was combined with the exclusion analysis data to find the land suitability model (LSM)[7]. The detailed methodology considered for the suitability analysis is shown in Fig. 9.

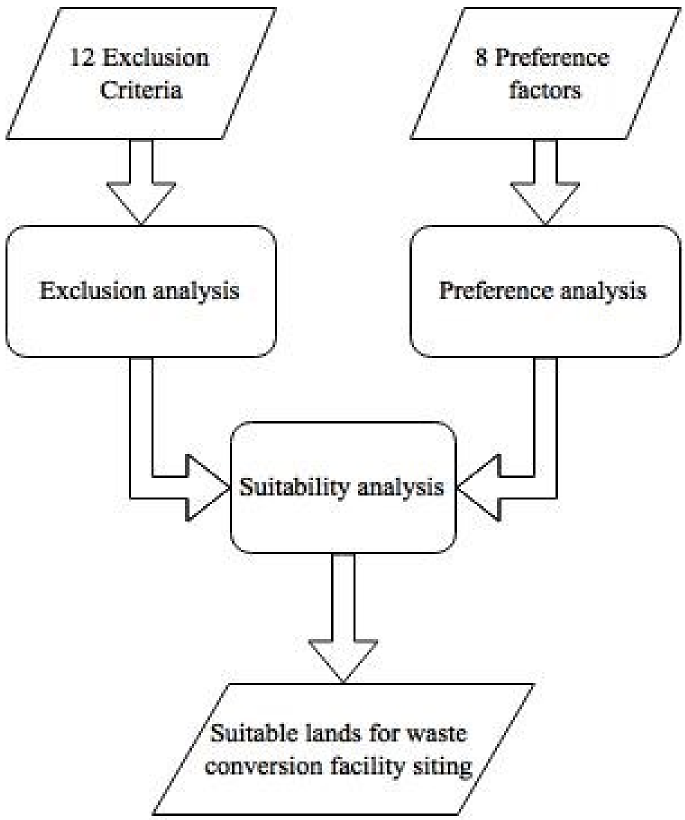


Figure 9: Flowchart of the suitability analysis methodology

3.2.1. Exclusion Analysis

To find optimal sites for waste-to-energy or biofuel facilities, an exclusion analysis was done that considered environmental, social, and economic factors (hereafter known as "constraints") in order to screen out unsuitable areas from the study area.

[7] A land suitability model (LSM) is developed by combining a constraint map and the suitability layers from preference analysis. This model represents the rank of land suitability for different regions (Sultana and Kumar, 2012).

A WTE facility needs to be placed in a safe and at a definite distance from critical environmental areas (e.g., flood plains, roads, residential areas, airports, etc.) and away from power systems (e.g. transmission lines, substations, etc.) due to safety concerns. Areas with steep slopes (greater than 15%) were also removed from the study area. Constraints identified and considered in this study are tabulated in Table 2.

Table 2: Identified constraints and corresponding buffer zones

Criteria	Specifications	Source/ Reference
Rivers, lakes, and other water bodies	More than 300 m from water bodies	(Government of Alberta, 2010a)
Rural and urban areas	More than 1 km from residential and urban areas	(Eskandari et al., 2012; Ma et al., 2005)
Airports and heliports	More than 8 km from international airports and 3 km from local airports	(Southern Alberta Energy-From-Waste Alliance, 2012; Ma et al., 2005),
Industrial and mining zones	More than 1 km from industrial and mining zones	(Sultana and Kumar, 2012)
Environmentally sensitive areas (ESA) (flood plains, conservation areas, habitat sites)	More than 1 km from ESAs	(Eskandari et al., 2012)
Natural gas pipelines	More than 100 m from natural gas pipelines	(Sultana and Kumar, 2012; Ma et al., 2005),
Park and recreational areas	More than 500 m from these sites	(Sultana and Kumar, 2012)
Wetlands	More than 200 m	(Sultana and Kumar, 2012)
Roads	More than 30 m	(Sultana and Kumar, 2012)
Power plants and substations	More than 100 m	(Sultana and Kumar, 2012)
Transmission lines	More than 100 m	(Sultana and Kumar, 2012)
Land surface gradient	Areas with slopes larger than 15% are screened out	(Sultana and Kumar, 2012)

In the exclusion analysis, buffer zones were created for each constraint. Areas inside the buffer zones were excluded from the study area. “Standards for Landfills in Alberta” (Government of

Alberta, 2010a), the *Alberta Transfer Station Technical Guidance Manual* (Solid Waste Association North America, 2008), and other material on siting landfills were used to determine the buffer extents. A binary map was developed for each of the constraints, with "0" referring to being within the buffer area and "1" referring to being outside the buffer area. All these binary maps were multiplied to produce the final constraint map. In the final constraint map (shown in Fig. 20), cells with the value "0" represent unsuitable locations and cells with the value "1" represent places potentially available for waste-to-energy facilities. The value of the i^{th} cell of the final constraint map is calculated as follows:

$$C_{E,i} = \prod_{k=1}^{n} C_{i,k} \tag{1}$$

where $C_{E,i}$ is the Boolean (0,1) cell value of the ith cell of the final constraint map, $C_{i,k}$ is the Boolean cell value of i^{th} cell in the k^{th} constraint grid layer, and n is the number of constraints considered in the study. Multiplication of all the constraint grid layers results in the final constraint map. A value of "0" in any cell results in a value of "0" for the corresponding cell of the final constraint map. Cells with a value of "1" in the constraint grid layer result in a value of "1" for the corresponding cells of the final constraint map. Figure 10 (a) gives a brief overview of the exclusion analysis.

3.2.2. Preference Analysis

The preference analysis shows relative preference for different regions of the study area. Eight factors were considered in order to identify the most preferable sites for maximum energy and economic benefits. These factors have been used in other research (Sultana and Kumar, 2012; Eskandari et al., 2012; Ma et al., 2005) and are as follows:

i) Waste availability

ii) Urban area

iii) Water availability

iv) Roads

v) Transmission lines

vi) Power substations

vii) Land cover and

viii) Slope

Buffer extents were set with in discussion with the experts from environmental agencies (e.g., Alberta Environment). For almost all of the factors, multiple buffers were generated around the corresponding factor. Each of the buffer rings was then assigned a grading value. Since factors are not all of equal importance, the AHP was used to assign appropriate weights to each factor.

The analytic hierarchy process is a widely accepted multi-criteria decision-making method. Through this method a weightage factor from a pairwise comparison can be derived. Paired elements are compared, and each element is assigned a value on a 9-point scale derived from Saaty (Saaty, 2000). The fundamental scale of relative importance is shown in Table 3.

Table 3: The fundamental scale of relative importance in the AHP (Sultana and Kumar, 2012; Ma et al., 2005)

Definition	Relative importance
Equal importance	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values to reflect compromise	2, 4, 6, 8

The first step is to make a hierarchy of the considered influencing factors that provides an overall view of the complex relationship between the factors. After defining the structure, for each pair of criteria, rating on the basis of relative priority is done by assigning a weight between “1” (equally important) and “9” (extremely more important). An $n\ x\ n$ matrix “A” is developed where $a_{i,j}$ is the extent of preferring factor i to factor j and $a_{j,i} = \frac{1}{a_{i,j}}$. Then the sum of each column in the matrix is calculated and each matrix element is divided by its corresponding column sum. Finally, relative weight is calculated by taking the average across each row.

The final steps of the AHP are to calculate the consistency ratio (CR) and to check the consistency of the pairwise comparison. The consistency ratio is calculated using the following mathematical relation:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

where CR= Consistency Ratio, RI= Mean/Average consistency index, and CI= Consistency Index. The consistency index is calculated using the following relation:

$$CI = \frac{\lambda max - n}{n - 1} \tag{3}$$

where n= Order of matrix and λ_{max}= maximum eigenvalue of the matrix.

For the i^{th} cell of the final preference map, its value was calculated as

$$C_{P,i} = \sum_{j=1}^{m} w_j C_{i,j} \quad ; \quad 0 \leq w_j \leq 1 \tag{4}$$

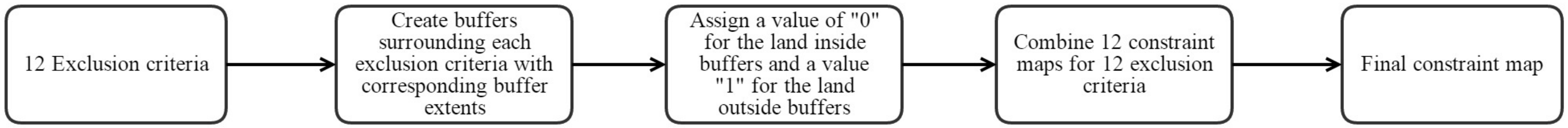
where $C_{P,i}$ is the value of i^{th} cell of the final preference map, $C_{i,j}$ is the value of ith cell for jth preference factor, m is the number of preference factor considered for this study, and w_j is the weight assigned to the j^{th} preference factor. Figure 10 (b) gives a brief overview of the preference analysis.

The land suitability map is created by using a final constraint map from an exclusion analysis and a final preference map from a preference analysis. The suitability index (SI)[8] is calculated using Eqn. 5.

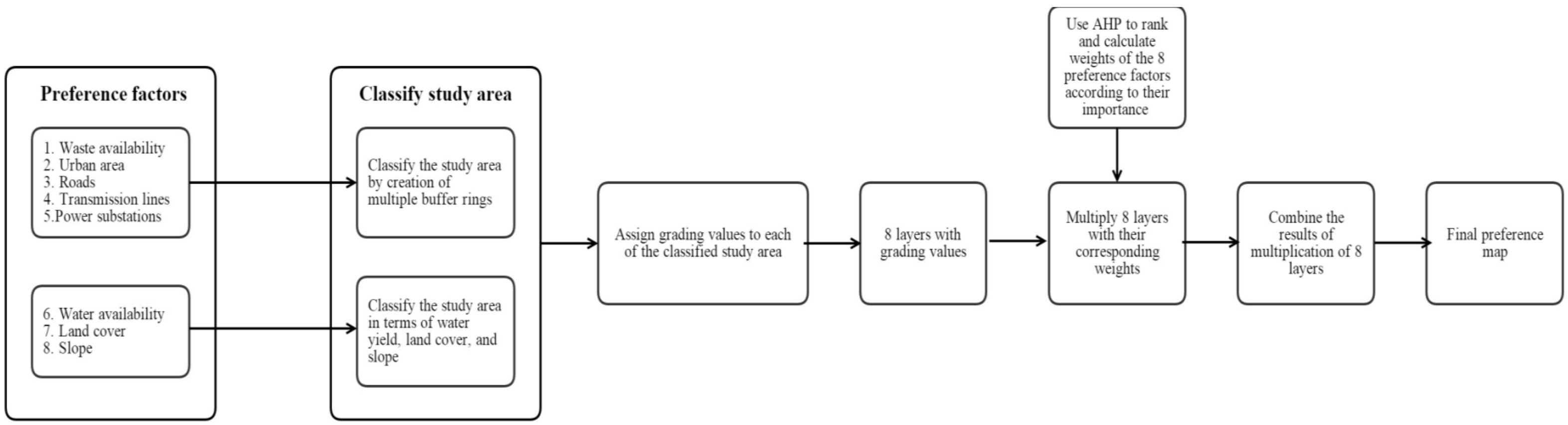
$$SI_i = C_{E,i} \times C_{p,i} \tag{5}$$

A sample calculation of suitability index values has been shown in Appendix A.

[8] The suitability index is the number that is used in a land suitability map (LSM) to indicate how suitable the location is. The higher the suitability index, the more suitable the location is.



(a)



(b)

Figure 10: **(a) Overview of exclusion analysis, (b) overview of preference analysis**

3.2.2.1. Distance from Transfer Stations

Waste transportation is a major criterion in WTE facility siting because of transportation costs and environmental problems (e.g., odor, nuisance). Thus it is essential to locate WTE facilities at minimum distance from waste transfer sites. In this analysis, multiple buffer rings were created for each of the transfer stations and grading values were assigned to each buffer with different distances as shown in Table 4. Here the distances from transfer stations for assigning grading values have been calculated by using Jenks' natural break classification method; this method is based on groupings inherent in the data (ArcGIS Resources, 2012). Class breaks are identified in such a way that they group similar data by reducing variance within classes and maximize difference between classes by maximizing the variance between classes. After classifying the distance into 10 classes, 1-10 grading values were assigned to these classes; grading values were assigned in such a way that higher grading values represent lesser distance and lower grading values represent greater distances.

Table 4: Grading values for buffers with particular extents (distance from transfer stations)

Distance from transfer stations	Grading value
< 25 km	10
from 25 km to 50 km	9
from 50 km to 79 km	8
from 79 km to 110 km	7
from 110 km to 142 km	6
from 142 km to 179 km	5

Distance from transfer stations	Grading value
from 179 km to 219 km	4
from 219 km to 260 km	3
from 260 km to 302 km	2
from 302 km to 361 km	1

Figure 11 shows the grading values assigned to different areas based on their distance from transfer stations.

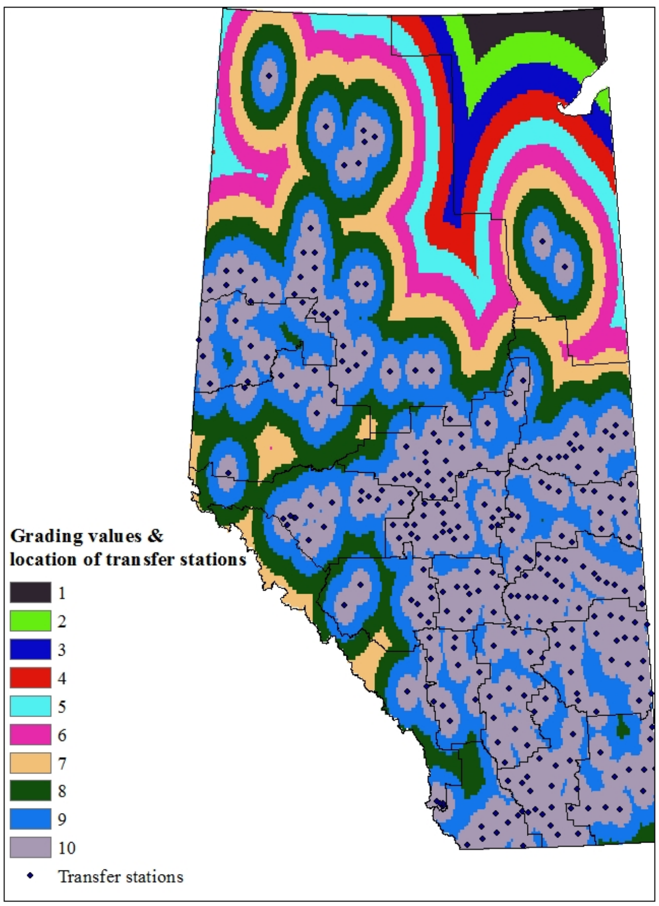


Figure 11: Map showing grading values for distance from transfer stations

Six scenarios were analyzed in this study:

- Scenario 1 - Waste availability (WA) location-dependent preference analysis with WA=0.44 (calculated using AHP)[9]
- Scenario 2 - Waste availability location-dependent preference analysis with WA=0.36 (calculated using AHP)
- Scenario 3 - Waste availability location-dependent preference analysis with WA=0.28 (calculated using AHP)
- Scenario 4 - Waste availability (both location- and amount-) dependent preference analysis with WA=0.44
- Scenario 5 - Waste availability (both location- and amount-) dependent preference analysis with WA=0.36
- Scenario 6 - Waste availability (both location- and amount-) dependent preference analysis with WA=0.28

In the preference analysis for scenario 1 (waste availability location-dependent analysis with WA=0.44), scenario 2 (waste availability location-dependent analysis with WA=0.36) and scenario 3 (waste availability location-dependent analysis with WA=0.28), while considering land suitability around transfer stations, grading values decreased with an increase in distance from the transfer stations; but grading values were kept independent of the amount of waste

[9] Waste availability (WA) is one of the eight preference factors considered for preference analysis. All eight preference factors were ranked using AHP. The details of AHP are described in Appendix A. Through the ranking procedure, preference factors were assigned weights considering their relative importance. In this study, three different weights were assigned to the preference factors by using three different relative importances. The intention behind using three different relative importances was to observe the impact of change in weights of the preference factors on suitability analysis.
Here, WA=0.44 means, waste availability was assigned 44% weight among all the preference factors.

availability in the transfer stations. Preference analyses dependent on both waste availability and distance from transfer stations were done for scenarios 4, 5, and 6.

3.2.2.2. Distance from Water

In siting any waste-based facility, surface water contamination is a major consideration. In this study, a restricted buffer zone of 300 meters was considered for water bodies in order to eliminate the chance of surface water contamination (Government of Alberta, 2010a). Figure 12 shows grading values assigned to different areas beyond the restricted buffer zone based on water availability at those areas. Water availability for all regions was classified into 10 classes using Jenk's natural break classification method (ArcGIS Resources, 2012). Grading values (1-10) were assigned in such a way that, grading values increase with increase in water availability.

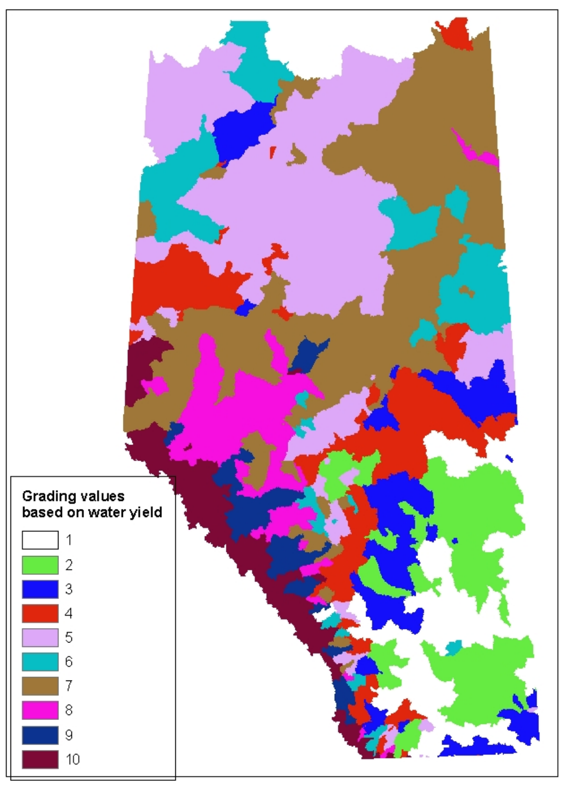


Figure 12: Map showing grading values for water yield

Suitability grading values assigned to different zones based on water yield for those areas are shown in Table 5.

Table 5: Grading values for water yield

Water availability	Grading value
from 291 dm3/km2/yr to 645 dm3/km2/yr	10
from 193 dm3/km2/yr to 291 dm3/km2/yr	9
from 147 dm3/km2/yr to 193 dm3/km2/yr	8
from 98 dm3/km2/yr to 147 dm3/km2/yr	7
from 71 dm3/km2/yr to 98 dm3/km2/yr	6
from 45 dm3/km2/yr to 71 dm3/km2/yr	5
from 23 dm3/km2/yr to 45 dm3/km2/yr	4
from 13 dm3/km2/yr to 23 dm3/km2/yr	3
from 0 dm3/km2/yr to 13 dm3/km2/yr	2
0 dm3/km2/yr	1

3.2.2.3. Distance from Urban Areas

Studies show that public opposition to landfills decreases exponentially with the increase in the distance from residential areas (Bah and Tsiko, 2012; Lober and Green, 1994). Different countries have different laws to specify the distance of noxious facilities from urban and built-up areas. In this study a restricted buffer zone of 1 km was considered for each urban area in order to minimize odor and view (Eskandari et al., 2012; Ma et al., 2005). Multiple buffer rings were created surrounding the urban areas and grading values were assigned to these buffer rings in such a way that grading values increase with increase in distance from urban areas. Al-hanbali et al. (2011), Kontos et al. (2005), and Sultana and Kumar (2012) were used to decide on the multiple buffer ring extents and the grading values for urban areas. These grading values along with the corresponding distances have been tabulated in Table 6.

Table 6: Grading values for distance from urban areas

Distance from urban areas	**Grading Value**
>4000 m from urban areas	10
from 3000 m to 4000 m	8
from 2000 m to 3000 m	6
from 1000 m to 2000 m	4
<1000 m	0

Figure 13 shows the grading values assigned to different areas based on their distance from urban areas.

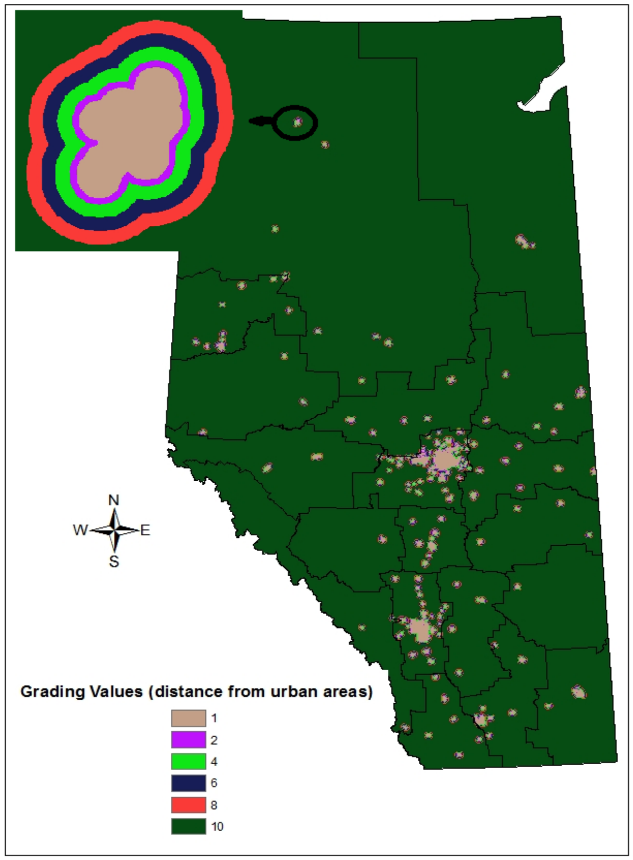


Figure 13: Areas with grading values for distance from urban areas

3.2.2.4. Distance from Roads

Distance from existing roads is an important factor in locating WTE facilities. A restricted buffer zone was considered in this study in order to minimize odor and view. Beyond this restricted buffer zone, the facility location must be close to a road network in order to reduce transportation costs. Multiple buffer rings were created surrounding the roads and grading values were assigned to these buffer rings in such a way that grading values increase with decrease in distance from roads. Al-hanbali et al. (2011), Kontos et al. (2005), and Sultana and Kumar (2012) were used to decide on the multiple buffer ring extents and the grading values for roads. Grading values for different areas based on their distance from roads are tabulated in Table 7.

Table 7: Grading values for distance from roads

Distance from roads	Grading value
<30 m	0
from 30 m to 200 m	10
from 200 m to 500 m	8
from 500 m to 1000 m	6
from 1000 m to 2000 m	4
> 2000 m	2

Figure 14 shows the grading values assigned to different areas based on their distance from roads.

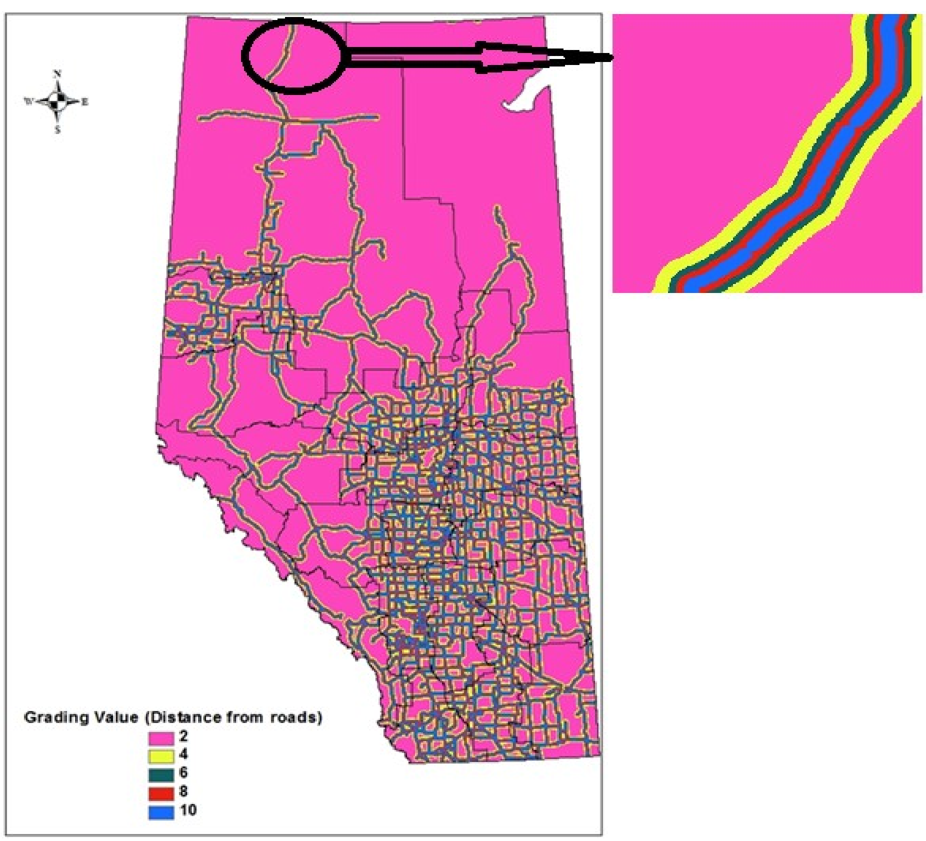


Figure 14: Grading values for distances from roads

3.2.2.5. Distance from Transmission Lines and Substations

In this study a restricted buffer zone of 100 m around each transmission line was considered for safety reasons. Beyond the restricted buffer zone, the closer the facilities are to the transmission lines the better, in order to save costs. Ma et al. (2005) and Sultana and Kumar (2012) were used to decide on the multiple buffer ring extents and the grading values for transmission lines.

Grading values of places for distance from transmission lines are tabulated in Table 8.

Table 8: Grading values for distance from transmission lines

Distance from transmission lines	Grading value
< 100 m	0
from 100 m to 1000 m	10
from 1000 m to 2000 m	8
from 2000 m to 3000 m	6
from 3000 m to 5000 m	4
>5000 m	2

Figure 15 shows the grading values assigned to different areas based on their distance from transmission lines.

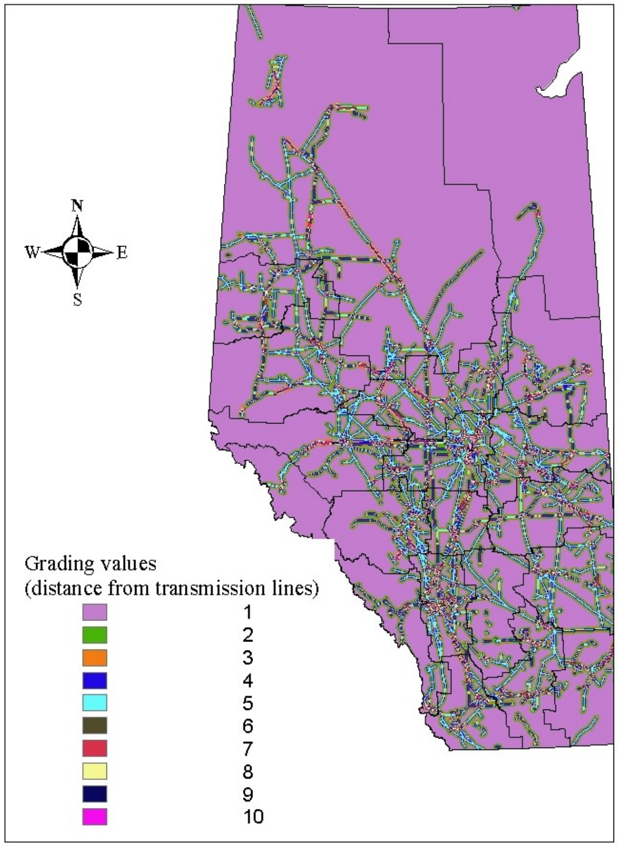


Figure 15: Grading values for distances from transmission lines

As with transmission lines, a restricted buffer zone of 100 m was considered for substations, for safety reasons. Beyond the restricted buffer zone, the closer the facilities are to substations the better, in order to save costs. Ma et al. (2005) and Sultana and Kumar (2012) were used to decide on the multiple buffer ring extents and the grading values for substations. Grading values of places for distance from substations are tabulated in Table 9.

Table 9: Grading values for distance from substations

Distance from substations	Grading value
< 100 m	0
from 100 m to 1000 m	10
from 1000 m to 2000 m	8
from 2000 m to 3000 m	6
from 3000 m to 4000 m	4
from 4000 m to 5000 m	2
>5000 m	1

Figure 16 shows the grading values assigned to different areas based on their distance from substations.

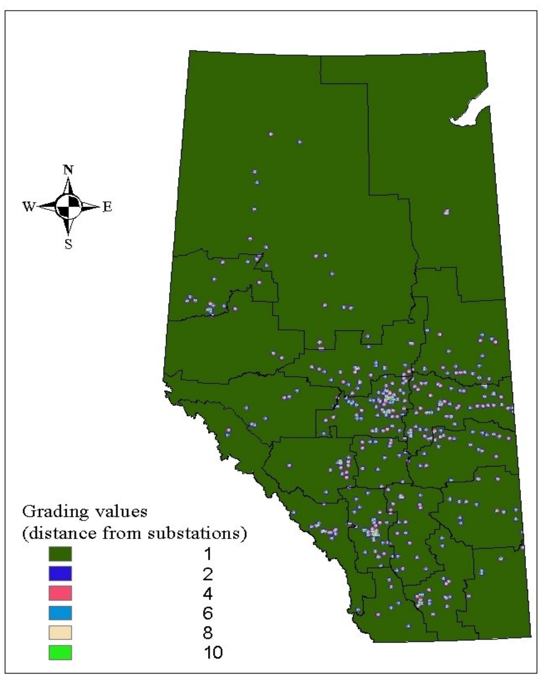


Figure 16: Grading values for distances from substations

3.2.2.6. Slope and Land Cover

Since there is a cost to level slopes, it is important to site the WTE facility in a place with minimal slope. According to previous literature on siting landfills (Lin and Kao, 1998; Lin and Kao, 1999), a slope with a grade of more than 8% and less than 12% would be appropriate for a landfill site. In this study, areas with slopes of a grade of more than 15% were screened out. Areas with slopes greater than 15% were assigned a value "0" and areas with slopes of 15% of less were assigned a value of "1." Figure 17 shows regions with values of "0" and values of "1" with different colors.

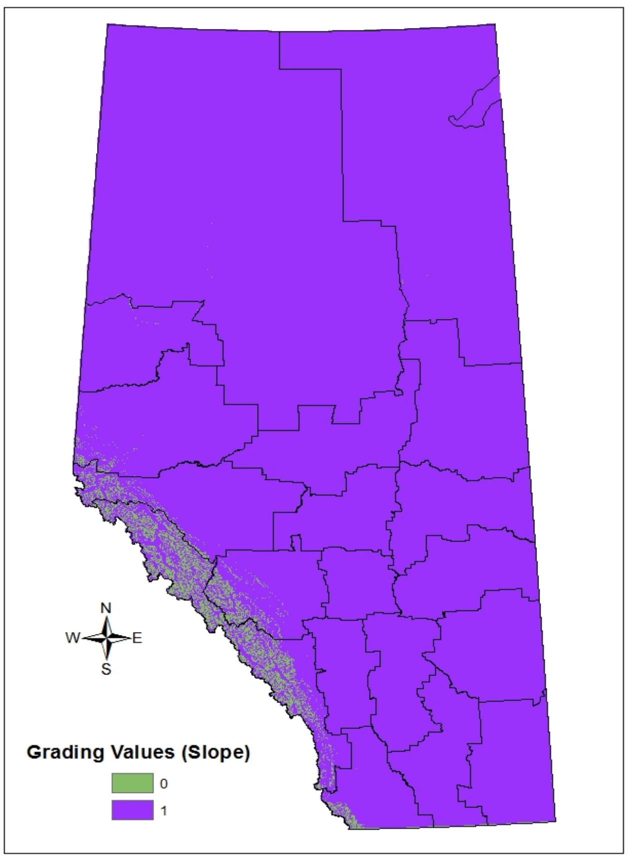


Figure 17: Grading values for slopes

Figure 18 shows the grading values assigned to different areas based on types of land cover (e.g., agricultural land, forest areas, grassland, etc.). Grading values were assigned to different kinds of land cover. Alberta Biodiversity Monitoring Institute (2014) and Sultana and Kumar (2012) were used to decide on the classification of land cover types and the grading values for these classes of land covers. Grading values for different types of land cover are tabulated in Table 10.

Table 10: Grading values for landcover

Types of landcover	Grading value
Water, snow/ice, coniferous forest, broad forest	0
Mixed forest	1
Rock/rubble	2
Roads, railways	5
Agricultural land	6
Shrubland	7
Developed land	8
Exposed land	8
Grassland	10

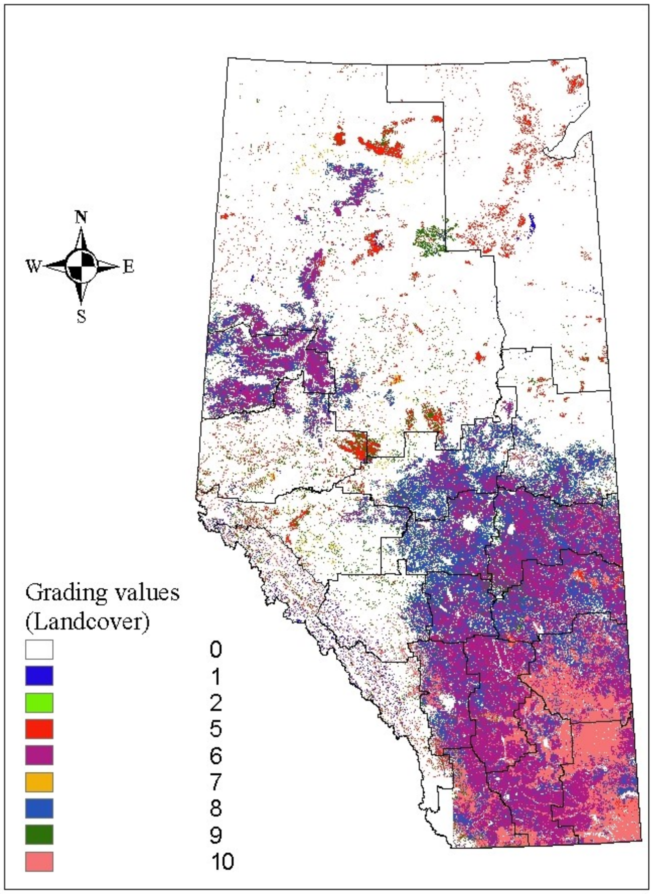


Figure 18: Map showing land cover grading values

The weightage factor was calculated for each of the eight influencing factors using the analytic hierarchy process (AHP). The method is explained in detail in Appendix A.

For this study, “distance from transfer station” was the most important factor to minimize odor issues and to minimize transportation cost. After “distance from transfer station,” “distance from urban areas” was considered the next important factor. Therefore, “distance from transfer station” was rated moderately more important than “distance from urban areas.” “Distance from transfer station” was also rated strongly more important than “distance from water bodies.” “Distance from roads” and “distance from transmission lines” are the next important factors followed by “distance from substations,” “distance from land cover,” and “area with slope.” This assumption on relative importance has been made based on Ma et al. (2005), Sultana and Kumar (2012), and Tavares et al. (2011).

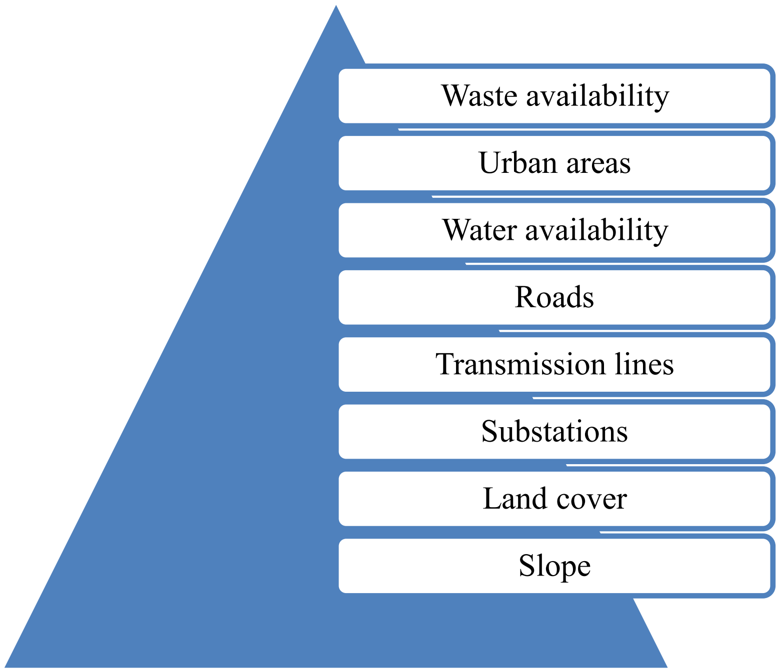


Figure 19: Relative importance of the preference factors

The pairwise comparison matrix and weights of preference factors are tabulated in Table 11 (for scenarios 1 and 4), Table 12 (scenarios 2 and 5) and Table 13 (scenarios 3 and 6). The land surface area required for a waste conversion plant is assumed to be 10 acres (Lynch, 2014).

3.3. Results and Discussion

Superposing the raster layers from the exclusion and preference analyses yields a final siting suitability map. Figure 20 shows the result of the exclusion analysis, with useful and excluded areas shown by different colors.

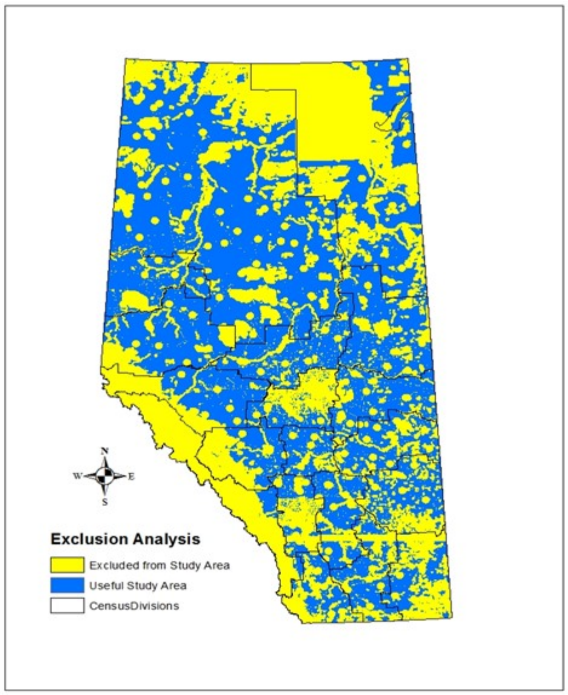


Figure 20: Result of exclusion analysis

In this study, the exclusion analysis screened out 45.7% of the total study area and thereby reduced it to 54.3%.

Six final siting suitability maps were developed for six scenarios and these maps were analyzed and compared.

3.3.1. Scenario 1: Waste Availability Location-Dependent Analysis with WA=0.44

The pairwise comparison matrix and weight of preference factors (used for scenarios 1 and 4) are tabulated in Table 11.

Table 11: Pairwise comparison matrix and weights of preference factors with AHP (used in scenarios 1 and 4)

Preference factors	WA	Urban	Water	Roads	Transmission	Substation	Land cover	Slope	Weight
WA	1	3	5	7	8	9	9	9	0.44
Urban	0.33	1	2.00	3.00	4	4	5	6	0.19
Water	0.20	0.50	1	2.00	3	3	4	5	0.13
Roads	0.14	0.33	0.50	1	2	2	3	3	0.08
Transmission	0.13	0.25	0.33	0.50	1	1	2	2	0.05
Substation	0.11	0.25	0.33	0.50	1	1	2	2	0.05
Land cover	0.11	0.20	0.25	0.33	0.5	0.5	1	1	0.03
Slope	0.11	0.17	0.20	0.33	0.5	0.5	1	1	0.03

The consistency ratio[10] for this pairwise comparison matrix was found to be 0.017; anything lower than 0.1 is acceptable (Saaty, 2000).

A waste-to-energy facility suitability index map depicting the suitability of different places for facility siting for this scenario is shown in Fig. 21. In this figure, each 30 m cell has a suitability index. The suitability index (SI) “0” represents an unsuitable cell and “9” (there is no cell with SI=10) the most suitable cell.

[10] Consistency ratio is the ratio of consistency index (CI) to mean/average consistency index (RI). This ratio is used to check the consistency of the pairwise comparison for AHP. Consistency ratio, consistency index, and mean/average consistency index have been described in Appendix A.

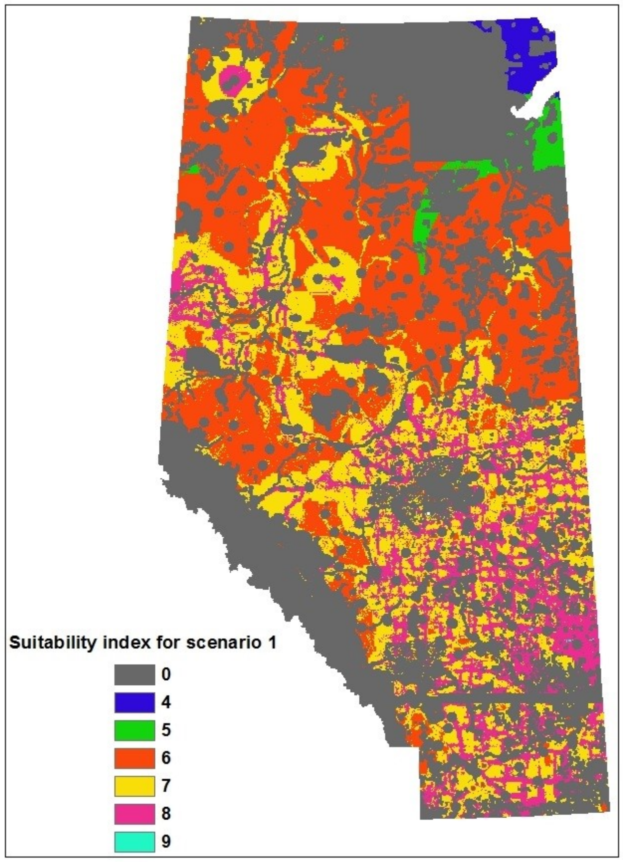


Figure 21: Land suitability model (LSM) results for scenario 1 (WA weightage=0.44)

Areas with SI=9 were found to be mostly inside census division (CD) 4 (i.e., 42.83% of SI=9 areas were found inside CD 4) and CD 7 (i.e., 19.18% of SI=9 areas were found inside CD 7). Table 15 shows the percentages of the total SI=9, SI=8, and SI=7 areas that lie inside different census divisions. All census divisions except CD 16 and CD 18 have areas with a suitability index of 9. CD 4 and CD 17 have 12.38% and 10.36% of the total SI=8 area, respectively. 23.64% and 9.62% of the total SI=7 area lie inside CD 17 and CD 13, respectively.

To briefly summarize, for scenario 1, a considerable portion of suitable areas lies inside CD 4, CD 17, and CD 7.

3.3.2. Scenario 2: Waste Availability Location-Dependent Analysis with WA=0.36

A change in the weights of the factors may influence optimal site locations of WTE facilities. To address the effect of a change in factor weightage and to assess the reliability of the model, a preference analysis with a different ranking of importance of the factors was undertaken. In this scenario, the relative importance of water availability and urban area was increased compared to that of the factor, waste availability. The pairwise comparison matrix and weight of preference factors (used for scenarios 2 and 5 of this study) are tabulated in Table 12.

Table 12: Pairwise comparison matrix and weights of preference factors for the case with lower waste availability (WA) weightage (used in scenarios 2 and 5)

Preference factors	WA	Urban	Water	Roads	Transmission	Substation	Land cover	Slope	Weights
WA	1	2	3	4	5	7	8	9	0.36
Urban	0.5	1	2	3	4	4	5	6	0.22
Water	0.33	0.50	1.00	2.00	3	3	4	5	0.15
Roads	0.25	0.33	0.50	1.00	2	2	3	3	0.09
Transmission	0.20	0.25	0.33	0.50	1	1	2	2	0.06
Substation	0.14	0.25	0.33	0.50	1	1	2	2	0.06
Land cover	0.13	0.20	0.25	0.33	0.5	0.5	1	1	0.03
Slope	0.11	0.17	0.20	0.33	0.5	0.5	1	1	0.03

A waste-to-energy facility suitability index map depicting the suitability of different places for facility siting for this scenario is shown in Fig. 22.

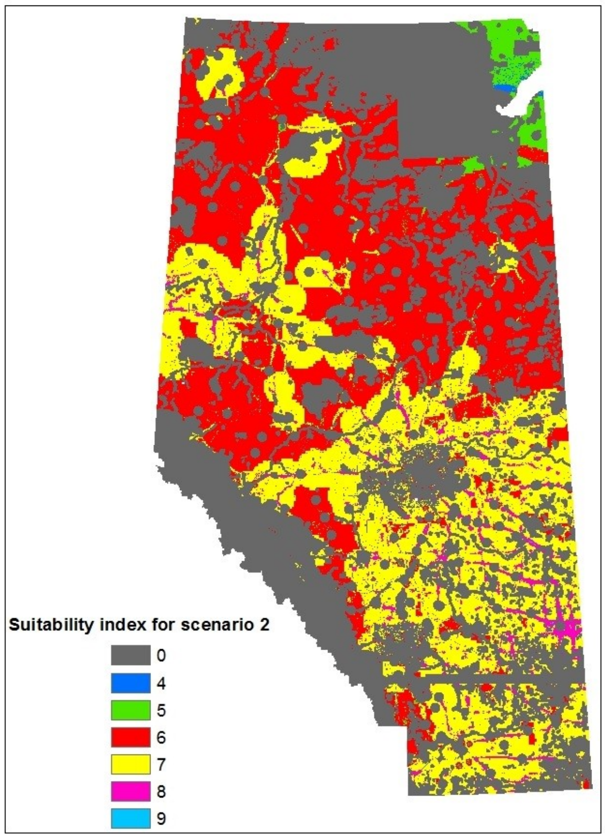


Figure 22: Land suitability model (LSM) results for the scenario 2 (WA weightage=0.36)

Increasing the relative weight of waste availability means that areas close to waste transfer stations are given more priority than other areas. As the weight of waste availability decreases from 0.44 to 0.36, areas with suitability index 7 and 8 increase but areas with suitability index 9 decrease. Table 15 shows the percentages of the total SI=9, SI=8, and SI=7 areas that lie inside different census divisions. Areas with SI=9 have been found to be mostly inside CD 4 (48.1%)

and CD 7 (28.6%). CD 4 and CD 7 have 20.98% and 10.38% of the total SI=8 area, respectively. 17.76% and 10.27% of the total SI=7 area lie inside CD 17 and CD 19, respectively.

To briefly summarize, for scenario 2, a sizable portion of the suitable areas lies inside CD 4, CD 7, and CD 17.

3.3.3. Scenario 3: Waste Availability Location-Dependent Analysis with WA=0.28

This scenario was analyzed to see the impact on suitable locations when the relative importance of transmission lines, roads, water availability, and urban areas is increased compared to that of the factor, waste availability. The pairwise comparison matrix and weight of preference factors (used for scenarios 3 and 6) are tabulated in Table 13.

Table 13: Pairwise comparison matrix and weights of preference factors for the case with lower waste availability (WA) weightage (used in scenarios 3 and 6)

Preference factors	WA	Urban	Water	Roads	Transmission	Substation	Land cover	Slope	Weights
WA	1	2	2	3	4	4	5	7	0.28
Urban	0.5	1	2	3	4	5	6	7	0.24
Water	0.50	0.50	1.00	2.00	3	4	5	6	0.17
Roads	0.33	0.33	0.50	1.00	2	3	4	5	0.12
Transmission	0.25	0.25	0.33	0.50	1	2	3	4	0.08
Substation	0.25	0.20	0.25	0.33	0.5	1	2	3	0.05
Land cover	0.20	0.17	0.20	0.25	0.33	0.50	1	2	0.03
Slope	0.14	0.14	0.17	0.20	0.25	0.33	0.5	2	0.03

A waste-to-energy facility suitability index map depicting the suitability of different places for facility siting for this scenario is shown in Fig. 23.

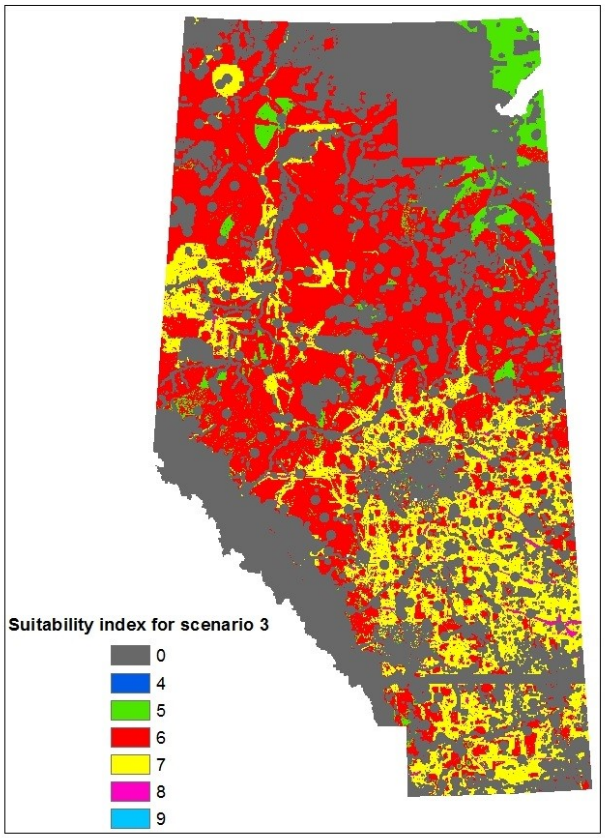


Figure 23: Land suitability model (LSM) results for scenario 3 (WA weightage=0.28)

When the relative weight of waste availability is changed, areas with a high SI decrease. Table 15 shows the percentages of the total SI=9, SI=8 and SI=7 areas that lie inside different census divisions. Areas with SI=9 have been found mostly inside of CD 4 (79.37%) and CD 7 (10.74%). CD 4 and CD 7 have 24.26% and 11.52% of the total SI=8 area, respectively. 12.11% and 8.66% of the total SI=7 area lie inside CD 17 and CD 4, respectively.

To briefly summarize, for scenario 3, a sizable portion of the suitable areas lies inside CD 4, CD 7, and CD 19.

3.3.4. Scenario 4: Waste Availability (Both Location and Amount) Dependent Analysis (with WA=0.44)

For this scenario, waste transfer stations were stratified into three groups based on waste availability; distance from these transfer stations was classified as shown in Table 14. Waste availability ranges shown in Table 14 were calculated by taking the average of the available waste at these transfer stations. At first, transfer stations with above average available waste (i.e., > 9107 tonne/yr) were considered to be in one group. However, since there was a large variety in this group (i.e., ranging from 9107 tonne/yr to 138,525 tonne/yr), these transfer stations were stratified again by taking the average (i.e., 24,945 tonne/yr). The distance ranges (multiple buffer extents) in Table 13 were calculated by using Jenks' natural break classification method (ArcGIS Resources, 2012) in a similar process mentioned in section 3.2.2.1 of this thesis.

Table 14: Extents of multiple buffer rings

Waste availability at transfer stations	Extents for multiple buffer rings
39 - 9,107 tonnes	<79 m from transfer stations
	79 km to 179 km from roads
	179 km to 302 km from transfer stations
	302 km to 361 km from transfer stations
9,107 - 24,945 tonnes	<50 m from transfer stations
	50 km to 142 km from transfer stations

Waste availability at transfer stations	Extents for multiple buffer rings
	142 km to 260 km from transfer stations
	260 km to 361 km from transfer stations
24,945 - 138,525 tonnes	<25 km from transfer stations
	25 km to 110 km from transfer stations
	110 km to 219 km from transfer stations
	219 km to 361 km from transfer stations

Multiple ring buffers with the extents shown in Table 14 were created for each transfer station. Relative preference was given to places with high waste availability and high grading values were assigned to them. Places with the highest waste availability (24,945-138,525 tonnes/year) and lowest buffer extent were assigned the highest grading value (grading value 10). Places with the lowest waste availability (39 - 9,107 tonnes/year) and the highest buffer extent (302 - 361 km from the transfer stations) were assigned the lowest grading value (grading value 1). Assigning a grading value to a buffer with a particular distance was done in a similar way as the approach used to assign values for distance from transfer stations. After reclassifying buffers with assigned grading values, a preference analysis was done by weighting overlaying preference factor layers with the weightage shown in Table 11. A waste-to-energy facility suitability index map depicting the suitability of different places for facility siting for this scenario is shown in Fig. 24.

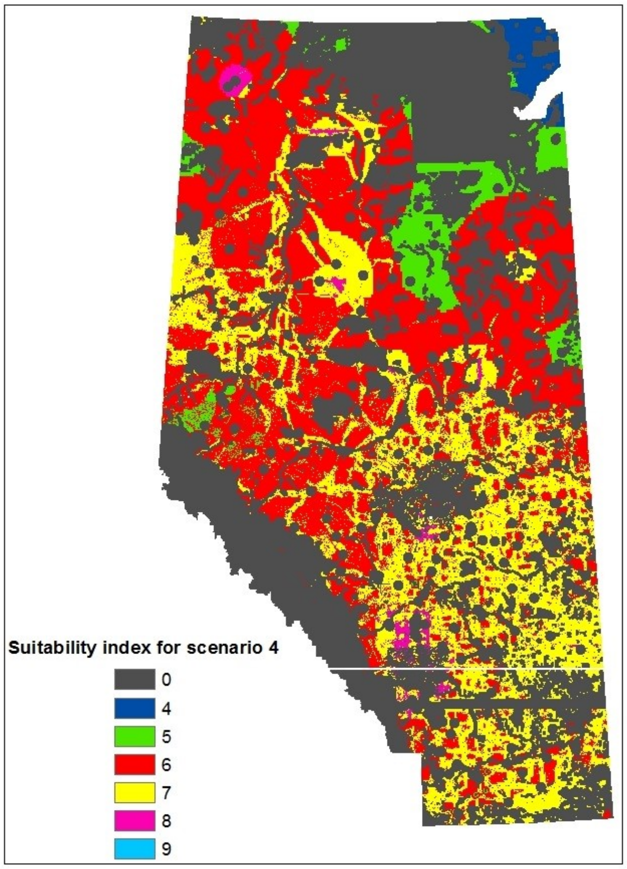


Figure 24: LSM for waste availability dependent preference analysis with WA= 0.44

Table 15 shows the percentages of the total SI=9, SI=8, and SI=7 areas that lie inside different census divisions. Areas with SI=9 were found only inside CD 5 (76.49%) and CD 6 (23.51%). CD 17 and CD 6 have 38.45% and 31.26% of the total SI=8 area, respectively. 20.61% of the total SI=7 area lies inside CD 17.

To briefly summarize, for scenario 4, a sizable portion of the suitable area lies inside CD 5, CD 6, and CD 17.

3.3.5. Scenario 5: Waste Availability (Both Location and Amount) Dependent Analysis (with WA=0.36)

For this scenario, the classification of waste transfer stations based on waste availability, multiple ring buffer formation, and assigning grading values to buffers was done in the same way as for scenario 4. A preference analysis was done by overlaying preference factor layers with the weightage shown in Table 12. A waste-to-energy facility suitability index map depicting the suitability of different places for facility siting for this scenario is shown in Fig. 25.

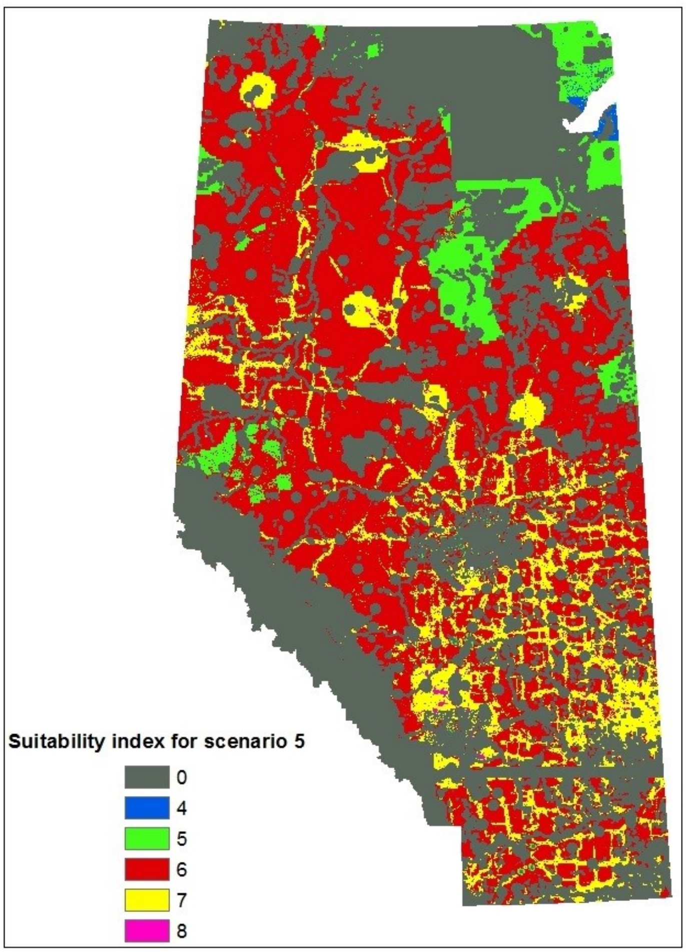


Figure 25: LSM for waste availability dependent preference analysis with WA= 0.36

Table 15 shows the percentages of the total SI=8 and SI=7 areas that lie inside different census divisions. Areas with SI=8 were found mostly inside CD 6 (36.66%) and CD 17 (19.71%). CD 17 and CD 4 have 17.53% and 10.77% of the total SI=8 area, respectively.

To briefly summarize, for scenario 5, a major portion of the suitable areas lies inside CD 6, CD 17, and CD 4.

3.3.6. Scenario 6: Waste Availability (Both Location and Amount) Dependent Analysis (with WA=0.28)

For this scenario, the classification of waste transfer stations based on waste availability, multiple ring buffer formation, and assigning grading values to buffers was done in the same way as for scenario 4. A preference analysis was done by overlaying preference factor layers with the weightage shown in Table 15. A waste-to-energy facility SI map depicting the suitability of different places for facility siting for this scenario is shown in Fig. 26.

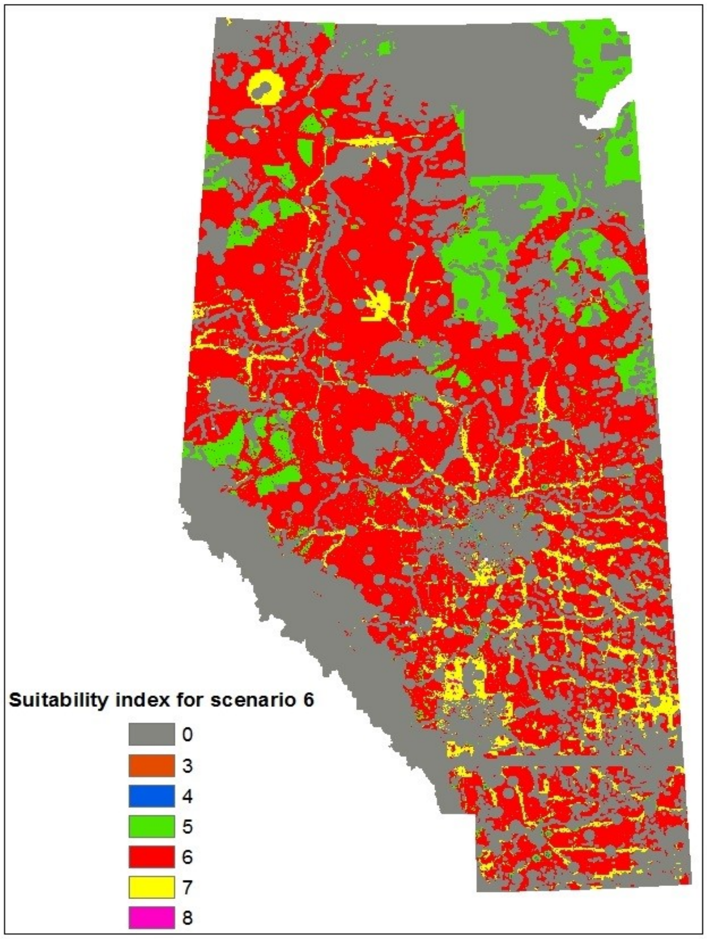


Figure 26: LSM for waste availability dependent preference analysis with WA= 0.28

Table 15 shows the percentages of the total SI=8 and SI=7 areas that lie inside different census divisions. Areas with SI=8 were found mostly inside CD 6 (30.21%) and CD 4 (18.34%). CD 17 and CD 4 have 18.81% and 11.25% of the total SI=8 area, respectively.

To briefly summarize, for scenario 6, a major portion of the suitable areas lies inside CD 6, CD 4, and CD 17.

Table 15: Comparison of area percentages of the total area with SI=7, SI=8, and SI=9 in different census divisions

Census division	Area (%)															
	Scenario 1			Scenario 2			Scenario 3			Scenario 4			Scenario 5		Scenario 6	
	SI 7	SI 8	SI 9	SI 7	SI 8	SI 9	SI 7	SI 8	SI 9	SI 7	SI 8	SI 9	SI 7	SI 8	SI 7	SI 8
CD 1	0.0	5.9	2.6	0.0	5.3	3.9	0.0	4.0	5.4	0.0	0.0	4.9	0.0	4.0	0.0	3.5
CD 2	1.0	8.0	4.0	0.0	7.2	5.6	0.0	4.0	7.3	0.0	0.1	6.4	0.2	5.5	0.5	5.1
CD 3	0.3	2.4	2.2	0.0	1.3	2.3	0.0	1.8	2.5	0.0	0.1	2.6	0.3	1.8	1.4	1.6
CD 4	42.8	12.3	2.0	48.1	20.9	4.9	79.3	24.2	8.6	0.0	2.2	7.6	8.6	10.7	18.3	11.2
CD 5	5.9	6.3	4.2	0.6	4.2	5.4	0.0	3.6	6.4	76.4	6.9	5.1	7.3	5.1	7.2	5.0
CD 6	0.2	2.6	2.3	0.0	2.4	2.6	0.0	2.6	2.6	23.5	31.2	2.0	36.6	6.1	30.2	8.1
CD 7	19.1	9.4	3.4	28.6	10.3	5.6	10.7	11.5	7.9	0.0	0.9	6.8	4.3	6.8	10.9	6.6
CD 8	5.6	4.9	2.9	5.1	4.6	3.9	0.0	4.1	4.9	0.0	3.5	4.0	4.8	4.5	3.5	4.7
CD 9	1.3	2.5	2.7	0.1	2.1	2.8	0.0	1.8	2.9	0.0	1.8	2.9	1.9	2.4	0.5	2.0
CD 10	8.4	9.3	5.5	0.1	9.5	7.1	0.0	10.8	8.9	0.0	1.3	7.8	3.2	7.5	8.0	7.5
CD 11	0.0	3.2	4.4	0.0	1.9	4.9	0.0	1.3	4.5	0.0	7.0	2.8	8.6	2.9	1.9	3.4
CD 12	3.9	4.9	5.4	6.1	4.1	5.5	0.0	3.4	5.3	0.0	0.7	5.2	0.7	5.7	1.9	4.8
CD 13	2.0	7.8	9.6	0.0	8.0	8.1	0.0	9.1	8.0	0.0	4.0	8.0	1.4	8.1	0.4	7.8
CD 14	0.2	2.4	5.8	0.3	2.8	4.8	0.0	5.0	2.9	0.0	0.0	2.8	0.0	1.7	0.6	2.0
CD 15	0.0	0.1	0.9	0.0	0.1	0.6	0.0	0.1	0.2	0.0	0.8	0.7	0.1	1.2	0.0	0.6
CD 16	0.0	0.0	0.7	0.0	0.0	0.4	0.0	0.0	0.1	0.0	0.0	0.6	0.0	1.0	0.0	0.3
CD 17	1.4	10.3	23.6	0.0	7.7	17.7	0.0	5.2	12.1	0.0	38.4	20.6	19.7	17.5	9.7	18.8
CD 18	0.0	1.0	5.5	0.0	0.6	2.9	0.0	0.1	1.4	0.0	0.0	2.7	0.0	1.5	0.0	1.2
CD 19	7.1	5.7	11.4	11.0	6.2	10.2	9.8	6.6	7.3	0.0	0.3	5.7	1.6	5.2	4.3	5.0

Table 16 shows a comparison of the six scenarios in terms of the total SI=7, SI=8, and SI=9 areas. For scenarios 2 and 3, the total area of SI=8 and SI=9 is smaller than that for scenario 1; on the other hand, the total area for SI=7 is greater for scenario 2 than that for scenario 1. This is mainly due to the lower weightage of waste availability for scenarios 2 and 3 than for scenario 1. For scenarios 4, 5, and 6, the area of SI=7, SI=8, and SI=9 is less than that of 1, 2, and 3. For scenario 4, the area for SI=9 is very small; and for scenarios 5 and 6, no area was found with SI=9.

Table 16: Comparison of total area with SI=7, SI=8, and SI=9 for six scenarios

Suitability index	Scenario 1 (ha)	Scenario 2 (ha)	Scenario 3 (ha)	Scenario 4 (ha)	Scenario 5 (ha)	Scenario 6 (ha)
7	16,558,025	20,393,906	12,482,845	11,364,045	6,527,772	3,639,816
8	7,618,053	1,402,327	333,674	520,528	82,804	29,591
9	15,189	3,098	233	67	0	0

3.4. Conclusions

Siting a new MSW conversion facility is a highly complicated task since it involves decisions based on environmental, social, technical, and economical issues. The methodology outlined in this chapter is a GIS-based approach to locate suitable sites for waste conversion facilities. Suitability indices were generated through a multi-criteria decision making analysis combined with a GIS. These indices provide information on site suitability taking into account environmental components, location of waste availability, and amount of waste available. A GIS spatial analysis was done in two steps. First, 45.7% of the area was screened out by an exclusion analysis that considered 12 constraints and second, an AHP was used to calculate the weightage of different factors.

Six scenarios were analyzed in this study. Scenarios 1, 2, and 3 depend on the locations of the waste transfer stations but are independent of the waste availability at the transfer stations. Scenarios 4, 5, and 6 are dependent on both the location of waste transfer stations and waste availability at those transfer stations. AHP was utilized three times to rank the preference factors. As a result, waste availability was assigned with three different weights, namely 0.44, 0.36, and 0.28. Among the six scenarios, scenario 1 and 4 were analyzed with a waste-availability-weightage (WA weightage) = 0.44, scenario 2 and 5 were analyzed with WA weightage= 0.36, and scenario 3 and 6 were analyzed with WA weightage= 0.28.

For scenarios 1, 2, and 3, a major chunk of the SI=9, SI=8, and SI=7 areas lies inside CD 4 and CD 17. This is mainly because many transfer stations are located within those census divisions. On the other hand, for scenarios 4, 5, and 6, a sizable portion of SI 9, SI 8, and SI 7 lies inside CD 6 and CD 17. These results depict the fact that lands with higher suitability index decreases with decrease in WA weightage. The methodology used in scenarios 4, 5, and 6 can be used if the amount of waste availability varies highly from region to region. The results can help planners find suitable sites while planning the waste management infrastructure throughout the province, considering waste availability and environmental parameters with different weights.

However, this GIS-aided siting methodology is flexible in terms of criteria (both exclusion and preference) determination. This methodology can be expanded by considering some more criteria.

The methodology presented in this chapter can serve as an efficient tool for decision makers and planners in siting waste conversion facility. However, since the final decision for siting a waste conversion facility also depends on public opinion and political decisions, participation of local community is mandatory while siting a waste conversion facility.

Chapter 4: Development of a Decision Model for Economic Comparison of Municipal Solid Waste Utilization Pathways[11]

4.1. Introduction

Economic competitiveness is one of the key factors in making decisions towards the development of waste conversion facilities and devising a sustainable waste management strategy. The goal of this study is to develop a framework, as well as to develop and demonstrate a comprehensive techno-economic model to help county and municipal decision makers in establishing waste conversion facilities. The user-friendly data-intensive model, called the **FUN**damental E**N**gineering Princip**lE**s-based Mode**L** for Estimation of **Cost** of Energy and Fuels from **MSW** (FUNNEL-Cost-MSW), compares ten different waste management scenarios, including landfilling and composting, in terms of economic parameters such as gate fees and return on investment. In addition, a geographic information system (GIS) model was developed to determine suitable locations for waste conversion facilities based on integration of environmental, social, and economic factors. Finally, a case study on Parkland County and its surrounding counties in the province of Alberta, Canada, was conducted and a sensitivity analysis was performed to assess the influence of the key technical and economic parameters on the calculated results.

4.2. Methodology

The GIS software ArcGIS 10 (ESRI, 2015a) and its geodatabase were used to find suitable locations for waste conversion facility based on environmental, social, and economic factors. A user-friendly data-intensive model called, FUNNEL-Cost-MSW, was afterwards developed. This

[11] A version of this chapter has been submitted as Khan, M.M., Jain, S., Vaezi, M., Kumar, A., Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways, to *Waste Management* in 2015.

model can compare various waste conversion technologies and landfilling approaches. The current version of FUNNEL-Cost-MSW calculates the gate fees (the payment that the waste conversion facilities take per tonne of waste received) and internal rate of return (IRR - the interest disbursed or earned on the unrecovered balance such that the net present value of the initial payment is zero) for ten waste management scenarios and helps the user to understand and compare the economic feasibility of every scenario. There are some other considerations that affect waste management decision making as well, including the remaining landfill life, available spaces for future landfills, and current rules and regulations. Nevertheless, comparison of different waste management scenarios in terms of economic assessment is considerably valuable in waste management decision making.

4.2.1. Site Selection

The suitable and optimal location of a waste conversion facility depends on some environmental, social, and economic factors and waste availability. In this study, site selection was performed in two stages through an exclusion analysis and preference analysis (Sultana and Kumar, 2012). The exclusion analysis screens out unsuitable lands from the study area based on social and environmental factors as shown on Table 2 in chapter 3. For every 12 constraints stated in Table 2, a buffer zone was created where the areas inside and outside the buffer zones were assigned value of “0” and “1”, respectively. Accordingly, a binary map was generated for every constraint. A final constraint map was developed by multiplying all the binary values from whole the maps. Figure 20 in chapter 3, shows an example of final constraint maps.

Preference analysis was performed to find the relative preference of different regions within the study area. Eight factors were considered to find the most preferable sites for a waste conversion facility building. These eight factors have been selected based on literature review and experts working in the field (Ma et al., 2005; Page and Pate, 2013; Sultana and Kumar, 2012; Tavares et al., 2011). The weights of the preference factors were calculated using the AHP (Saaty, 2000). Using AHP, the preference factors were compared with each other and each factor was assigned a value on a 9-point scale. Weight of each factor was calculated using these assigned values. AHP methodology is explained in details in section 3.2.2 of chapter 3.

Multiple buffer zones were created around each preference factor, and scores (on a scale of 0 to 10) were assigned to the buffer zones depending on their distance from the corresponding factor and afterwards multiplied by the corresponding weights to calculate the relative preference of the corresponding region of the study area. In this study, places with a suitability index (a value that indicates how suitable each location is on the map, taking into account the criteria entered into the model) of 7, 8, 9, and 10 were considered suitable sites for a waste conversion facility. Figure 27 shows an overview of the methodology of this study.

After determining the candidate sites, the final facility location can be chosen by one of the following two options:

i) Location-allocation analysis (ArcGIS Resource Center, 2012) with ArcGIS can be done using the actual road network. Location-allocation analysis was done in this study to locate the facility/facilities in such a way that waste supply from the transfer stations to the facility/facilities has the lowest transportation cost. For a location-allocation analysis, road networks, candidate facility site locations, and transfer station locations are needed as input. In this study, a “minimize impedance (P-median)” network analysis was performed in order to conduct a location-allocation analysis. For a “minimize impedance (P-median)” analysis, facilities are located such that the transportation cost between waste supply points and facilities is minimized (ArcGIS Resource Center, 2012).

ii) A spreadsheet-based model was used to determine the actual driving distance travelled from the transfer station to the candidate facility sites. This custom function in the spreadsheet model uses the Google Maps Application Programming Interface (API - a set of routines, protocols, and tools for building software applications [Google, 2015]) to calculate the distance. To find the distances between the transfer stations and candidate facility sites, the address of each location is needed. Once the addresses are entered, the model shows the candidate site with shortest total travel distance as the chosen facility site.

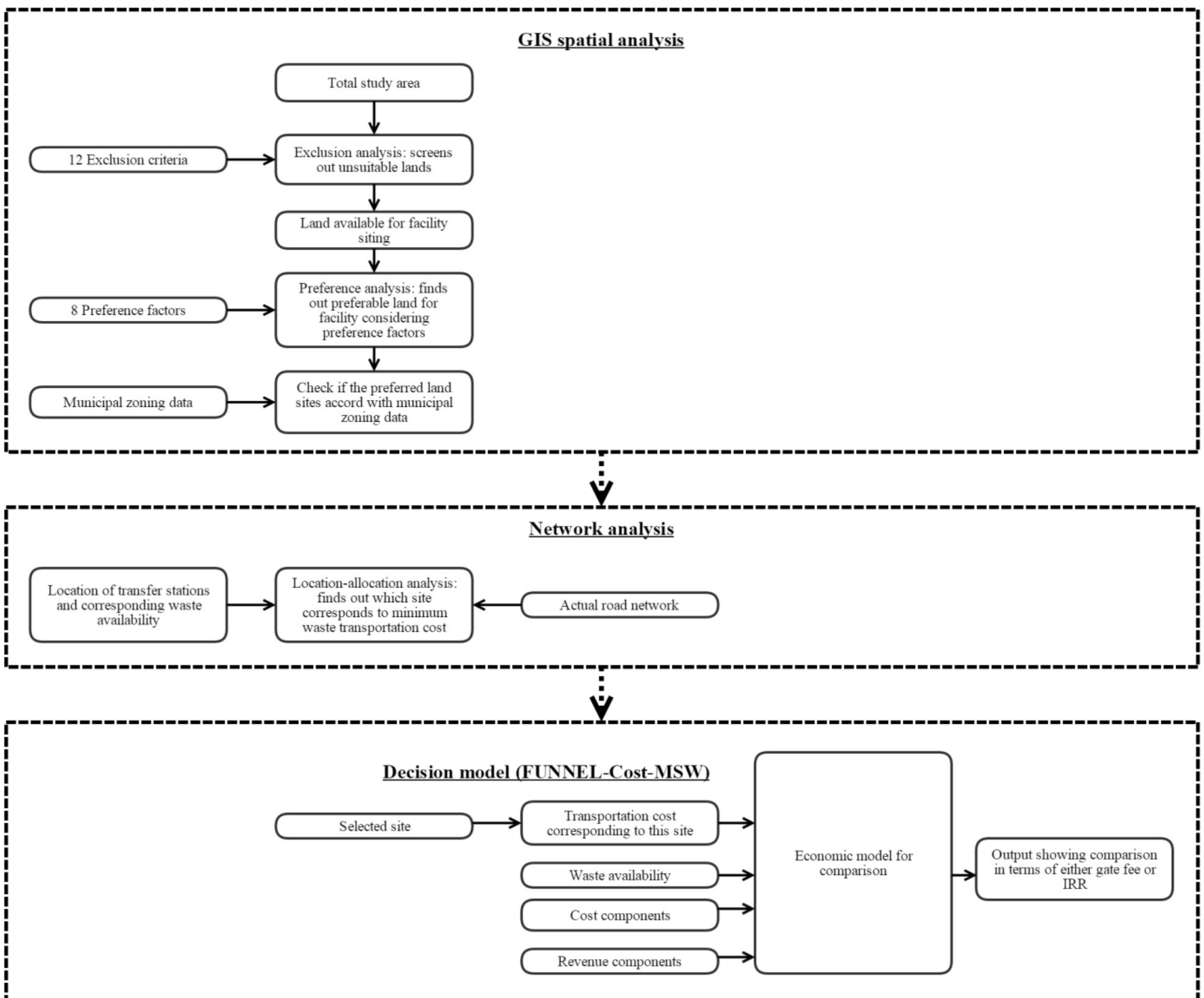


Figure 27: Methodology for waste management facility site selection and development of FUNNEL-Cost-MSW

4.2.2. Transportation Cost Calculation

Waste collection and transportation cost can be divided into three segments:

i) Collection cost from residences, industries, and institutions

ii) Waste transportation cost from transfer stations to waste conversion facilities

iii) Ash transportation cost from a waste conversion facility to a landfill

In FUNNEL-Cost-MSW, collection cost can be input either in $/tonne or total collection cost (cumulative $) as chosen by the user. Waste transportation cost from transfer stations to waste conversion facilities and ash transportation cost from waste conversion facility to landfill were calculated using the actual road network using ArcGIS and Google maps. The truck transportation cost consists of two components. The first is the fixed cost of loading/unloading ($/tonne) and does not change with the travel distance. The second component is the distance variable cost ($/tonne/km) consisting driver cost, fuel cost, etc., and depends on the transport distance. The total transportation cost was calculated by adding the fixed cost and the distance variable cost.

4.2.3. MSW conversion technology-based scenarios

The model, FUNNEL-Cost-MSW, compares ten MSW conversion technology-scenarios, as shown in Table 17.

Table 17: MSW conversion technology-based scenarios

Scenario label	Scenario name	Description of scenarios
Scenario 1	Gasification (producing biofuel)	Production of biofuel (methanol) through MSW gasification
Scenario 2	Gasification (generating electricity)	Generation of electricity from syngas by MSW gasification
Scenario 3	Anaerobic digestion	Anaerobic digestion of MSW to produce electricity from biogas
Scenario 4	Composting	Production of compost from MSW

Scenario label	Scenario name	Description of scenarios
Scenario 5	Incineration	Combined heat and power generation
Scenario 6	Landfilling	Disposal of MSW to a landfill
Scenario 7	Gasification (producing biofuel) integrated with anaerobic digestion	Production of biofuel and electricity through MSW gasification and anaerobic digestion, respectively
Scenario 8	Gasification (producing electricity) integrated with anaerobic digestion	Production of electricity through MSW gasification and anaerobic digestion
Scenario 9	Gasification (producing biofuel) integrated with composting	Production of biofuel and compost through MSW gasification and composting, respectively
Scenario 10	Gasification (producing electricity) integrated with composting	Production of electricity and compost through MSW gasification and composting, respectively

It was assumed that an existing landfill was used for both the disposal of the remaining waste (waste left after being treated at the facilities) and the ash left following thermal or biological treatment. These scenarios are discussed further in subsequent sections.

4.2.3.1. Scenario 1: Gasification (producing biofuel)

Gasification is a thermo-chemical partial oxidation process that converts organic or fossil fuel based carbonaceous materials into carbon monoxide, hydrogen, and methane by reacting the material at high temperatures (>700 ^{o}C) with a controlled amount of oxygen and/or steam (Luque and Speight, 2015; Yang and Chen, 2015). Biofuel (e.g., methanol, ethanol) can be produced from such synthetic gas through reactions such as methyl carbonylation and hydrogenolysis (Jacobs Consultancy, 2013).

The use of gasification to produce syngas and biofuel has been investigated by several researchers. For instance, Yang and Chen (2015) studied the gasification of biomass to produce synthetic liquid fuel production and focussed on the development of biomass gasification techniques to reduce tar and produce high purity hydrogen, and Luque and Speight (2015) described the application of biomass gasification for power generation and synthetic fuel production. In this study, gasification of MSW followed by the catalytic transformation of syngas to biofuel has been considered. Similar technology is currently being used by Enerkem Co. (Enerkem, 2015; Jacobs Consultancy, 2013).

Here it was assumed that solid waste is transported from transfer stations to a waste sorting facility. The waste is sorted and the waste suitable for thermal treatment goes to a gasification facility and the rest goes to a landfill. The ash collected after gasification is also transported to landfill. The waste suitable for thermal treatment goes through gasification and is converted to methanol and ethanol. The biofuel production rate and the GHG reduction rate (CO_2-eq saved by not landfilling waste) was assumed to be 380 litres/BDT (Arena et al., 2015; Jacobs Consultancy, 2013) and 2 tonnes of CO_2-eq/tonnes of MSW (Chornet, E., 2012; Nguyen et al., 2007; Sultana and Li, 2014; Zaman, 2010).

4.2.3.2.**Scenario 2: Gasification (producing electricity)**

Gasification technology can be used to produce electricity as well. Many studies have been conducted on generating electrical energy from gasified biomass. For instance, Pereira et al. (2012) presented a number of latest gasification technologies available for biomass gasification for producing electricity and Yassin et al. (2009) studied the technical and economic performance of fluidized bed gasification processes to produce energy from waste. Yassin et al. (2009) reported on the implication of fluidized bed gasifier combined with either of gas engine, combined cycle gas turbine or steam turbine in terms of costs and efficiencies and found fluidized bed gasifier combined with combined cycle gas turbine as the most attractive option.

In this study, a fluidized bed gasifier coupled with a combined cycle gas turbine was considered to produce electric energy. The electricity production rate and the GHG reduction rate (CO_2-eq saved by not landfilling waste) was assumed to be 1800 kWh/BDT (Arena et al., 2015; Jacobs

Consultancy, 2013) and 2 tonnes of CO_2-eq/tonnes of MSW (Fruergaard et al., 2009; Sultana and Li, 2014; Zaman, 2010).

4.2.3.3.Scenario 3: Anaerobic digestion

The biodegradable fraction of solid waste is a sizable portion of Alberta's total waste composition and therefore treatment of this waste has a significant part in an integrated solid waste management system. Anaerobic digestion is an attractive solution for biodegradable waste treatment. This technology is a collection of processes in which micro-organisms break down organic material in an enclosed vessel in the absence of oxygen (DeBruyn and Hilborn, 2007). Three principle products of anaerobic digestion are biogas, digestate, and water. Biogas consists primarily of methane and carbon dioxide, and can be combusted to produce heat and to run a generator producing electricity. Among several investigators, Mao et al.(2015) and Mata-Alvarez et al. (2000) have reviewed the research and industrial achievements of anaerobic digestion of organic solid wastes.

In this study, the Dranco process was considered for biodegradable waste treatment (OWS, 2015). The Dranco process is a high-solids, single-stage anaerobic digestion system. The biogas yield, electricity production rate, and GHG reduction rate (CO_2-eq saved by not landfilling waste) were assumed to be 181.4 m^3/tonne (Akbulut, 2012; Sultana and Li, 2014; Verma, 2002), 2.14 kWh/ m^3 (Akbulut, 2012; Sultana and Li, 2014), and 2 tonnes of CO_2-eq/tonnes of MSW (DiStefano and Belenky, 2009; Sultana and Li, 2014), respectively.

4.2.3.4.Scenario 4: Composting

The biological decomposition of biodegradable materials under controlled and mainly aerobic conditions is known as composting. The sole product of the composting process is compost. Windrow composting is the most used composting method in Alberta (Government of Alberta, 2012b) and is considered in this study. Ruggieri et al. (2009) and Emery et al. (2007) studied the environmental and economic modelling of composting process.

Capital cost and OPEX for composting were calculated here using Eqs. 6 and 7. These two equations were developed from the data available from the Government of Alberta (2010b) and Ruggieri et al.(2009). Compost production rate and the GHG reduction rate were assumed to be 0.3 tonne/tonne of waste (Verma, 2002) and 0.63 tonnes of CO_2/ tonnes of MSW (Keystone Environmental, 2014).

$$\text{Capital cost (\$)} = (457.55 \times \ln(\text{Capacity}) - 2742) \times 1000 \tag{6}$$

$$\text{OPEX (\$/year)} = (41.831 \times \ln(\text{Capacity}) - 234.72) \times 1000 \tag{7}$$

According to Sustainable Resources Development's (AESRD) regulations and composting facility standards in Alberta, facilities that compost more than 20,000 tonnes/year are regulated differently than those that compost less than 20,000 tonnes/year (Environmental Assurance, 2007) and there are different costs associated with each facility (Environmental Assurance, 2007). In this study, the maximum unit size of the composting facility was assumed to be 20,000 tonnes/year. For the capacities more than 20,000 tonnes/year, it was assumed that a new composting facility was built.

4.2.3.5.Scenario 5: Incineration

Waste incineration incorporates waste combustion. Incineration of waste can be broadly divided into two categories: mass burning of nonhomogeneous (i.e., as received) waste and burning of homogeneous waste (i.e., pre-treated) (Rand et al., 2000). Moveable grate incineration for mass burning is a thoroughly tested and worldwide used technology (Astrup et al., 2009; Rand et al., 2000). On the other hand, fluidized bed incinerators are generally used for pre-sorted or homogeneous waste burning (Astrup et al., 2009; Rand et al., 2000).

In this study, moveable grate incineration was considered to produce combined heat and power. The rates of heat and power generation (exported to grid) were assumed to be 2083 kWh/tonne (Fruergaard et al., 2010) and 575 kWh/tonne (Fruergaard et al., 2010). Capital cost and OPEX for incineration were calculated here using Eqs. 8 and 9. These two equations were developed from the data available from Murphy and McKeogh (2004) and Tsilemou and Panagiotakopoulos (2006).

$$\text{Capital cost (\$)} = 1445.6 \times 10^{0.9547} \tag{8}$$

$$\text{OPEX (\$/tonne)} = -1 \times 10^{-9} \times (capacity)^2 + 0.0002 \times capacity + 60.453 \tag{9}$$

4.2.3.6.**Scenario 6: New landfill**

Landfills have been an integral part of waste management systems and the final destination of waste till now, since it is the simplest and cheapest option for many scenarios (Allen, 2001). Obersteiner et al.(2007) studied on life cycle assessment of landfilling based on empirical data. Sumathi et al. (2008) studied the siting of a new landfills through a multi-criteria decision-making analysis and a GIS. In this study, capital cost, OPEX, and post-closure cost for landfilling were calculated using Eqs. 10 to 12. These equations were developed using cost data available for landfills with different capacities from Sultana and Li (2014) and Zhang et al.(2011).

$$\text{Capital cost (\$)} = 875.51 \times \text{capacity} + 6{,}000{,}000 \tag{10}$$

$$\text{OPEX}\left(\frac{\$}{\text{tonne} - \text{yr}}\right) = 3 \times 10^{-9}(\text{capacity})^2 - 0.0003 \times \text{capacity} + 31.989 \tag{11}$$

$$\text{Post closure cost}\left(\frac{\$}{\text{tonne} - \text{yr}}\right) = 7 \times 10^{-10}(\text{capacity})^2 - 5 \times 10^{-5} \times \text{capacity} + 2.2039 \tag{12}$$

These cost data include site development, pre-development, operating, gas capturing cost, and post-closure cost. Here capital cost includes pre-development (site selection allowance, land acquisition allowance and approval allowance) and site development costs (site clearing and preparation, utilities allowances, site infrastructure allowances, cell excavation and base preparation, engineered leachate containment and collection system, leachate recirculate system, landfill gas collection and flaring system, cap system construction, environmental monitoring infrastructure allowances). OPEX includes administration and support staff, waste disposal operations, daily cover placement, leachate treatment, reporting. Post-closure cost includes post-closure staffing and administration cost, leachate treatment and maintenance allowance of the landfill.

4.2.3.7. **Scenario 7-10: Integrated facilities**

At integrated facilities, waste from transfer stations is sorted and distributed within the facility. Waste suitable for thermal treatment goes to a gasification facility; waste applicable to biological treatment goes to either an anaerobic digestion or a composting facility. Waste unsuitable for both thermal and biological treatment goes to the landfill. Figures 28(a) and 28(b) show the flow charts showing the waste flow at an integrated facility.

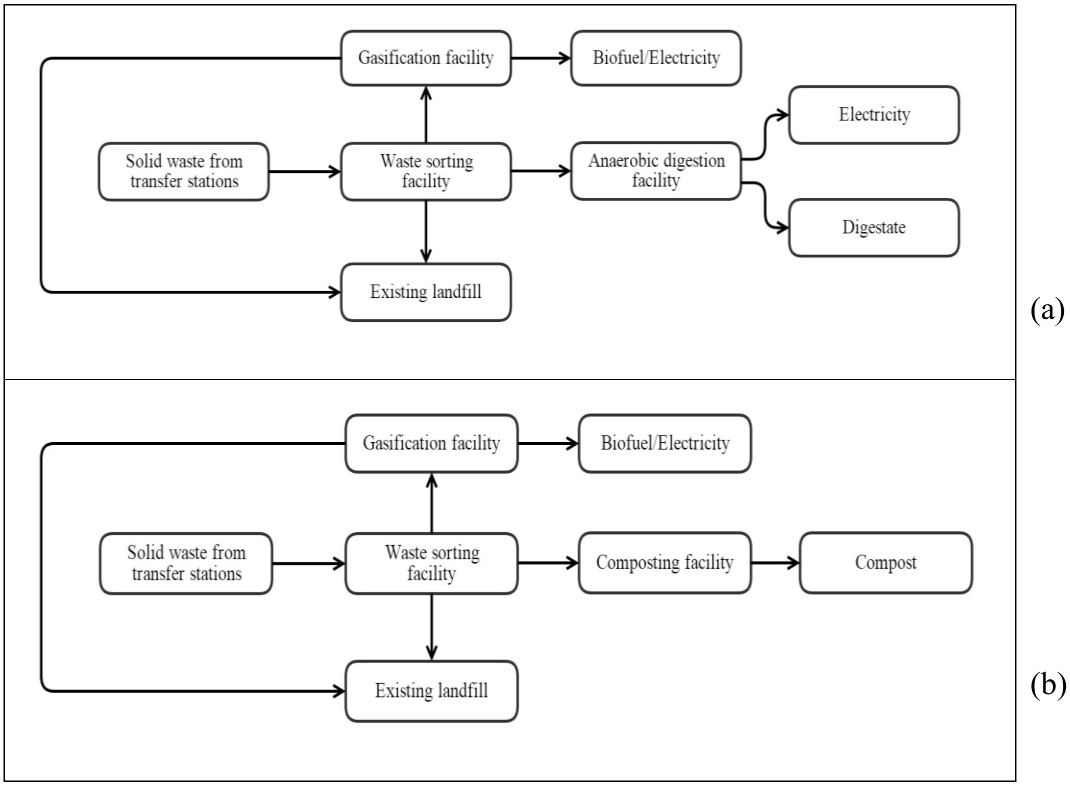


Figure 28: (a) Flow of waste from transfer stations to an integrated gasification and anaerobic digestion facility, (b) Flow of waste from transfer stations to an integrated gasification and composting facility

4.2.4. Decision-Making Model (FUNNEL-Cost-MSW)

A user-friendly model was developed to help make MSW management decisions. Initially, the user inputs waste availability and associated variables into the model. Since there are some counties/municipalities that do not have detailed data on how much waste will be useful for either thermal or biological treatment, this model offers three options at the waste availability input stage. The three options are:

i) Input only total waste: This option is suitable if the user does not know how much waste is suitable for thermal and biological treatment but knows the total available waste amount. For this option, the model assumes that 40% of the waste is suitable for thermal treatment, 40% for biological treatment, and 20% will be landfilled (TRI Environmental Consulting Inc., 2014).

ii) Input total waste with classification: This option is suitable if the user knows the total waste along with how much waste is suitable for thermal and biological treatment. The user does not need to know the detailed breakdown of available waste composition.

iii) Input total waste with detailed breakdown of waste composition: This option is suitable if the user knows the detailed breakdown of the total available waste composition.

Waste suitable for thermal and biological treatment is considered to have, on average, 15% and 50% moisture content, respectively. In addition, an average ash content of 15% has been assumed for all the gasification scenarios (Wilson et al., 2013). In addition to waste availability information, the model asks the user the following information:

a) Selling price of biofuel ($/liter)
b) Selling price of electricity cost ($/kWh)
c) Selling price of heat ($/kWh)
d) Compost price ($/tonne)
e) Carbon credit/offset rate ($/tonne)
f) Existing landfill's tipping fee ($/tonne)
g) Incentives available (if any) for each scenario

Once this information is entered, the user can indicate whether or not the facility owner pays the transportation cost from the transfer station to the waste conversion facility to be included in the total cost.

For the first two scenarios (gasification to produce biofuel and gasification to produce electricity), only waste suitable for thermal treatment goes to the gasification facility. Waste with very high moisture content cannot be directly treated in a gasification facility and requires either pre-drying or diversion to some other waste management facility (e.g., biological treatment, landfill). Hence, the model provides the option of selecting the thermal or biological treatment of waste in standalone gasification facilities. Depending on the moisture content of the waste, biological treatment (which can handle high moisture content) or gasification (which requires low moisture content) can be selected. Default values of required moisture contents are available in the model for making the decision.

The amount of capital cost of the waste use facility is critical for its economic viability. The model input includes a database with the capital costs of the various waste conversion facilities. However, these can also be input by the user. The model also has the option of considering capital cost alternatives, if available. For each scenario, separate modules were developed that include a flow chart, assumptions, cost components, and revenue components. This model provides the option of choosing the revenue components (for example, consideration of the carbon credit). Revenue components available for each scenario are shown in Table 18. A default value for the CO_2 saved by diverting waste from landfills to other options has been assumed for each scenario. These default values can be changed by the user.

Table 18: Revenue components available for the ten scenarios

Scenario	Biofuel sale	Electricity sale	Sale of heat	Compost	Gate fee/ Tipping fee	Carbon credit	Incentives
Gasification (producing biofuel)	√				√	√	√
Gasification (producing electricity)		√			√	√	√

Scenario	**Biofuel sale**	**Electricity sale**	**Sale of heat**	**Compost**	**Gate fee/ Tipping fee**	**Carbon credit**	**Incentives**
Composting				√	√	√	√
Incineration		√	√		√	√	√
Landfilling					√		√
Gasification (producing biofuel) integrated with anaerobic digestion	√	√		√	√	√	√
Gasification (producing electricity) integrated with anaerobic digestion		√		√	√	√	√
Gasification (producing biofuel) integrated with composting	√			√	√	√	√
Gasification (producing electricity) integrated with composting		√		√	√	√	√

For each scenario except landfilling, it was assumed that a waste sorting facility was built close to the waste conversion facility. Economic factors of the sorting facility, together with the factors for the first three standalone scenarios, are shown in Table 19. For the other two scenarios, capital cost and operating expenditure (OPEX) were calculated using equations developed from empirical data. A 30-year project life was assumed for all the scenarios except for landfilling, which was assumed to have a 25-year lifetime. The model provides two types of comparison: comparison of calculated gate fees with a specified IRR and comparison of IRRs with a specified gate fee. Both outputs can be obtained for all the ten scenarios.

All currency figures in this chapter are expressed in USD and the base year is 2014 unless otherwise noted. Conversion between the Euro and USD was done at the rate of 1 Euro= USD 1.38 and conversion between Canadian and US$ was done at the rate of USD 1= CAD 1.09. Costs have been adjusted to the year 2014 using historical inflation rates (Bank of Canada, 2014). An inflation rate of 2% was assumed for 2015 and onward. In this chapter, OPEX (operating expenditure) includes variable, fixed, and sustaining capital.

Table 19: Economic parameters of various facilities

	Capacity (base case)	Capital Cost	Operating Expenditure	Scale Factor	Reference
Sorting facility	53,571 (MSW/year)	$8 million	25 ($/tonne)	0.6	(Kumar et al., 2003; Sultana and Li, 2014; Yassin et al., 2009)
Gasification to produce biofuel	500,000 BDT/year	$263 million	0.35 ($/liter of biofuel produced)	0.6	(Arena et al., 2015; Jacobs Consultancy, 2013; Sultana and Li, 2014)
Gasification to produce electricity	18,214 BDT/year	$25.5 million	1.525 million ($/year)	0.6	(Sultana and Li, 2014; Yassin et al., 2009)
Anaerobic digestion	15,000 BDT/year	$9.45 million	810,000 ($/year)	0.6	(Murphy and McKeogh, 2004; Sultana and Li, 2014)

4.3. Case Study: Parkland County

There is a considerable focus in various jurisdictions in Alberta and Canada on the use and disposal of MSW. Throughout Alberta (and other parts of Canada), municipalities focus variously on waste reduction at source, collection services, waste diversion from landfill, reuse, recycling and composting of diverted waste, and recovery and generation of energy from residual waste. Alberta has 17 cities, 108 towns, 74 rural municipalities, and 64 municipal and other districts. Alberta's municipalities dispose their MSW at around 166 landfills (Page and Pate, 2013). Though the City of Edmonton's public landfill began with a capacity for 13.2 million tonnes of waste in 1975, the city's landfill had been rapidly filling; so the city decided to divert as much waste as possible (Edmonton Sun, 2013).

In 2011, Parkland County had a population of 30,568 (Statistics Canada*,* 2011). Currently the county generates approximately 15,098 tonnes of waste per year (Sultana and Li, 2014) and does not have any landfill sites; former sites were closed and converted into transfer stations. Currently, the county transports its waste to the Beaver Regional Landfill and has a contract rate of 62.50 $/tonne with the Beaver Regional Waste Management Commission (Stantec, 2010). This rate provides for disposal at 26 $/tonne and hauling at 36.50 $/tonne (Stantec, 2010). Figure 29(a) shows Parkland County's current waste transportation system. As shown in Fig. 29(a), Parkland County has six existing transfer stations and waste is currently transported from these stations to the Beaver Regional Landfill. Building a waste conversion facility to treat both the county's and part of the neighboring county's waste could help Parkland County move toward a sustainable waste management system. Waste availability in Parkland County and its neighboring counties is shown on Table 20.

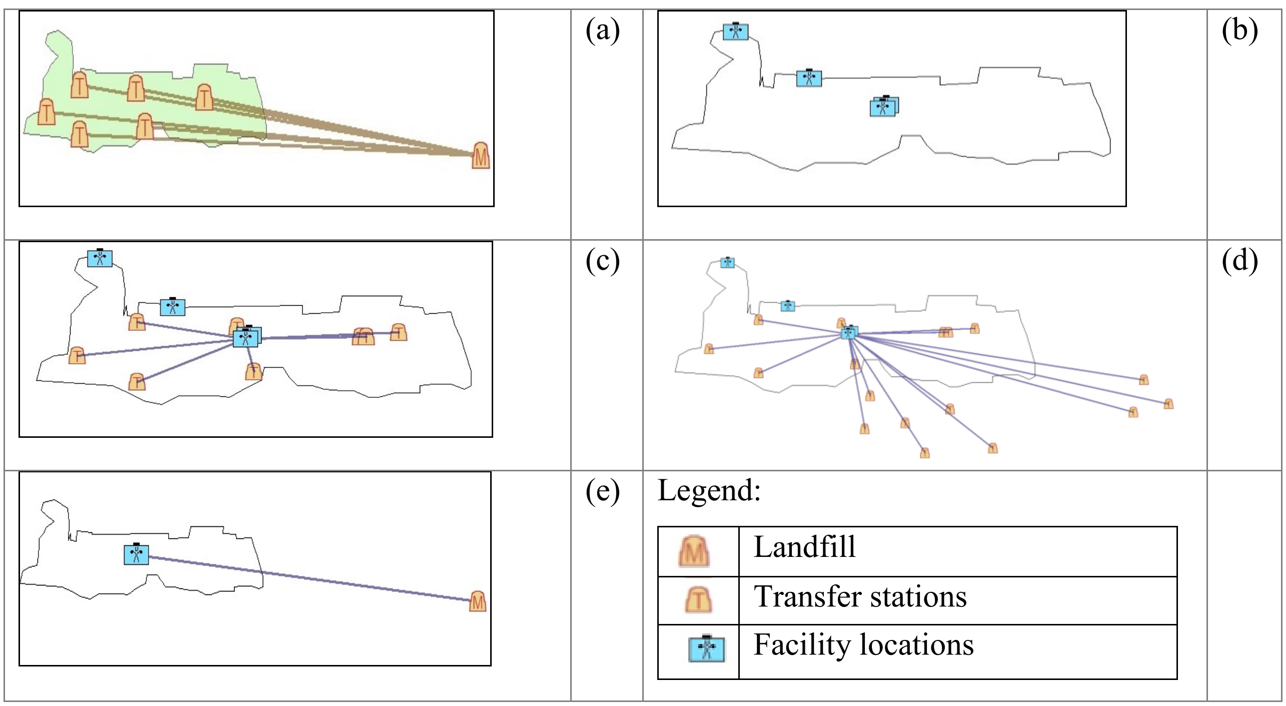


Figure 29: (a) Parkland County's current waste transportation scenario, (b) Identified facility locations within Parkland County, (c) Chosen facility location and waste transportation scenario for up to 39,598 tonne/year waste availability, (d) Chosen facility

location and waste transportation scenario for waste availability of more than 39,598 tonne/year, (e) Transportation of ash and unsuitable waste from facility to landfill

Table 20: Waste availability in Parkland and surrounding counties (Capital Region Waste Minimization Advisory Committee, 2013; Sultana and Li, 2014)

County name	Waste availability (tonne/year)
Parkland	15,098
Spruce Grove	14,750
Stony Plain	9,750
Leduc and Beaumont	21,172
St. Albert	27,524
Strathcona	45,694

4.3.1. Site Selection and Transportation Cost Calculation

Exclusion and preference analyses were conducted and municipal zoning data from Parkland County were used to determine candidate sites. For exclusion and preference analyses, 12 exclusion criteria and 8 preference factors were selected based on environmental and social considerations for Alberta. These analyses are described in detail in the methodology section. In the preference analysis, the AHP was used to assign weights to the preference factors. Table 12 in chapter 3 shows the values assigned to each factor after pairwise comparison and weights of these factors.

Figure 29(b) shows the four candidate facility locations within Parkland County as identified by this study.

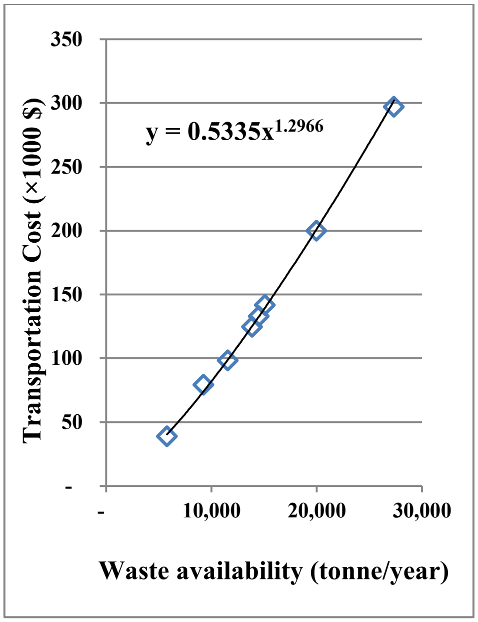
After exclusion and preference analyses were done and municipal zoning was considered, a facility location was chosen based on a location-allocation analysis. Figure 29(c) shows the chosen facility location and selected transportation system for up to 39,598 tonne/year waste. This capacity is the sum of the waste available at Parkland County, Spruce Grove, and Stony Plain.

Typical truck loading and unloading cost was considered to be 5.45 \$/tonne (Kumar et al., 2003; Chornet, 2012) and the variable cost (related to distance traveled) was considered to be 0.2 \$/tonne-km (Chornet, 2012). The average truck size considered in this study is a 6.5 tonne/load (Sultana and Li, 2014).

Travel distance was taken as the distance from the existing six transfer stations in Parkland County, Spruce Grove, and Stony Plain to the chosen waste conversion facility location. The distance travelled was calculated using the actual road network provided through ArcGIS. As shown in Fig. 30(a), transportation costs increase as available waste increases. Equation (13) was developed using the correlation shown in Fig. 30(a) and was used to calculate the transportation cost corresponding to the input waste availability for this case study.

$$\text{Transportation cost} = 0.5335 \times \text{waste availability}^{1.2966} \qquad (13)$$

Since only 39,598 tonnes of waste are available per annum within Parkland County, Spruce Grove, and Stony Plain, additional adjoining counties are taken into consideration to increase waste. Among the surrounding counties, Leduc's landfill has the lowest remaining life (around 6-14 years) (Chomlak, 2013). Therefore, for waste availability greater than 39,598 tonne/year, another correlation of transportation cost with plant capacity was developed, one that includes the waste available from Leduc. Figure 29(d) shows the transfer stations and facility location when Leduc's transfer stations are taken into account.



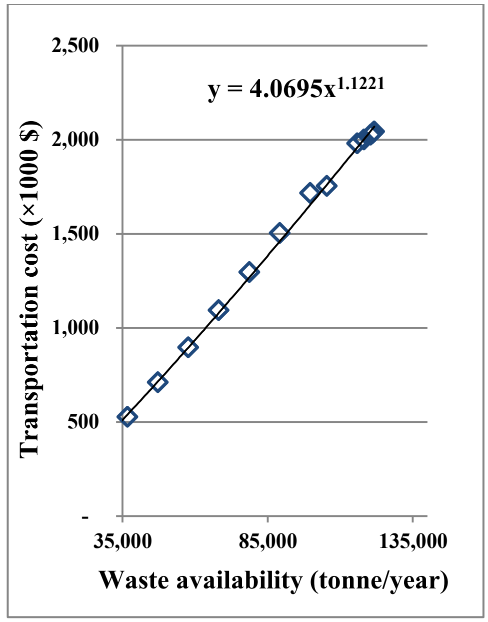


Figure 30: (a) Correlation between transportation cost and waste availability of less than 39,598 tonne/year (b) Correlation between transportation cost and waste availability for capacities more than 39,598 tonne/year

Figure 30(b) shows the correlation of transportation cost and plant capacity. Equation (14) was developed using the correlation shown in Fig. 30(b) and was used for this case study when the waste availability was more than 39,598 tonne/year.

$$\text{Transportation cost (\$)} = 4.0695 \times \text{waste availability}^{1.1221} \tag{14}$$

After treating the waste, ash and the remaining unsuitable waste are landfilled (see Fig. 29(e)). For this case study, ash and unsuitable waste were considered to be landfilled at the Beaver Regional Landfill (currently used by Parkland County [Stantec, 2010]).

Since for this case study the chosen facility location does not change when the waste availability goes above 39,598 tonne/year, the correlation between ash and unsuitable waste transportation cost and waste availability remains the same. Figure 31 shows the correlation between ash and unsuitable waste transportation cost and waste availability. Eqn. 15 was developed using the correlation (showed in Fig. 31) and was used for this case study to calculate ash and unsuitable waste transportation cost.

$$\text{Ash and unsuitable waste transportation cost} = 35.565 \times \text{waste availability} \tag{15}$$

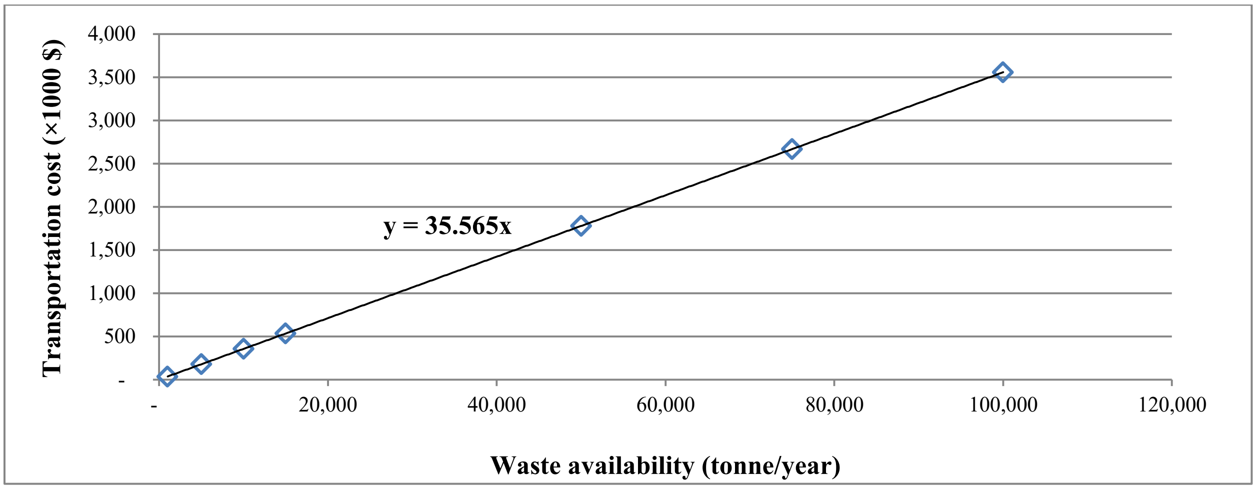


Figure 31: Correlation between ash and unsuitable waste transportation cost and waste availability

4.3.2. Economic Comparison of Scenarios[12]

The key input variables considered in the model are the amount of waste available, selling rate of biofuel, selling rate of electricity, compost rate, and carbon credit value. Based on these variables, the model estimates the gate fee and IRR. In this section, comparison of gate fees and comparison of IRRs are discussed in 4.3.2.1 and 4.3.2.2, respectively. These comparisons are based on the values listed in Table 21.

[12] Incineration faces a lot of public perception challenges in its adoption in the province of Alberta. Hence, for the case study of Parkland County, Scenario 5 (incineration) was not considered for economic comparison.

Table 21: Input data considered for economic comparison of various scenarios for the case study

Input variables	Values	References
Selling rate of biofuel ($/liter)	0.8	(Methanex Corporation, 2015a)
Selling rate of electricity ($/kWh)	0.08	(Alberta Government, 2015)
Compost rate ($/tonne)	30	(Amyot, 2005; Antler, 2012; Government of Alberta, 2012b)
Carbon credit/offset rate ($/tonne of CO_2)	13	(Partington, 2013; Preferred Carbon Group, 2011)
Existing landfill's tipping fee ($/tonne)	25	(Stantec, 2010; Sultana and Li, 2014)
Subsidies available for scenarios ($)	-	User-defined

As mentioned earlier, there is an option in this model to input a portion of available waste for thermal or biological treatment or for landfilling; but to simplify scenario comparison in this section, it was assumed that 40%, 40%, and 20% of the available waste were directed to thermal treatment, biological treatment, and landfilling, respectively. This assumption has been made on waste charaterization studies carried out for some regions of Alberta (TRI Environmental Consulting Inc., 2014).

4.3.2.1. Comparison in Terms of Calculated Gate Fee

An IRR of 10% was assumed for comparative assessment of the scenarios. Figures 32(a) and 32(b) shows the gate fees for different scenarios as the waste availability changes.

Generally, the term "gate fee" is used for the charge levied on the waste material coming into a waste management facility. In this chapter, however, the term "gate fee" has been used as the charge levied by a waste conversion facility and the term "tipping fee" has been used as the charge levied by the landfills. Gate fee/tipping fee calculation formula used in this model:

$$\text{Gate fee}\left({}^{\$}/_{\text{tonne}}\right)$$

$$= \frac{\text{Total cost (\$)} + \text{profit(\$)} - \text{revenue components (except gate fee or tipping fee)(\$)}}{\text{amount of available waste (tonne)}} \quad (16)$$

For landfilling, the tipping fee is the only revenue component considered (unless power from landfill gas is considered), whereas for waste conversion facilities, there are other revenue components (i.e., biofuel sale, electricity sale, etc.). With an increase in waste availability, total cost and all revenue components accordingly increase. As a result, the landfilling tipping fee increases with an increase in waste availability and the gate fee (associated with other waste conversion scenarios) decreases with an increase in waste availability (for waste conversion scenarios, the total revenue increase rate is higher than the total cost increase because there are more revenue components, e.g. biofuel sale, electricity sale, available for waste conversion scenarios). As Figs. 32(a) and 32(b) show, landfilling tipping fees decrease with an increase in waste availability up to a certain capacity (around 50,000 tonne/year), due to the decrease in operating and post-closure costs (e.g., leachate treatment cost); beyond this capacity, tipping fees increase with an increase in waste availability due to increased operating and post-closure costs.

For a waste availability of 25,000-50,000 tonne/year, composting is the cheapest solution (77 to 86 $/tonne gate fee). This is mainly due to the higher capital cost of the other waste conversion and landfilling scenarios. When waste availability is low, scenarios with higher capital costs would come with higher gate fees. As waste availability increases, gate fees associated with waste conversion scenarios decrease. For a waste availability of 50,000-150,000 tonne/year, a gasification (producing electricity) facility integrated with composting becomes the cheapest solution with a gate fee of 42 to 77 $/tonne.

Moreover, calculated gate fees change with changes in capital investment. If there is an incentive available for the development of a waste conversion facility (such as a grant or other investment), then the total capital investment is low. The impact on gate fees with changes in capital investment for a waste availability of 100,000 tonne/year and a 10% IRR is shown in Figs. 32(c) and 32(d).

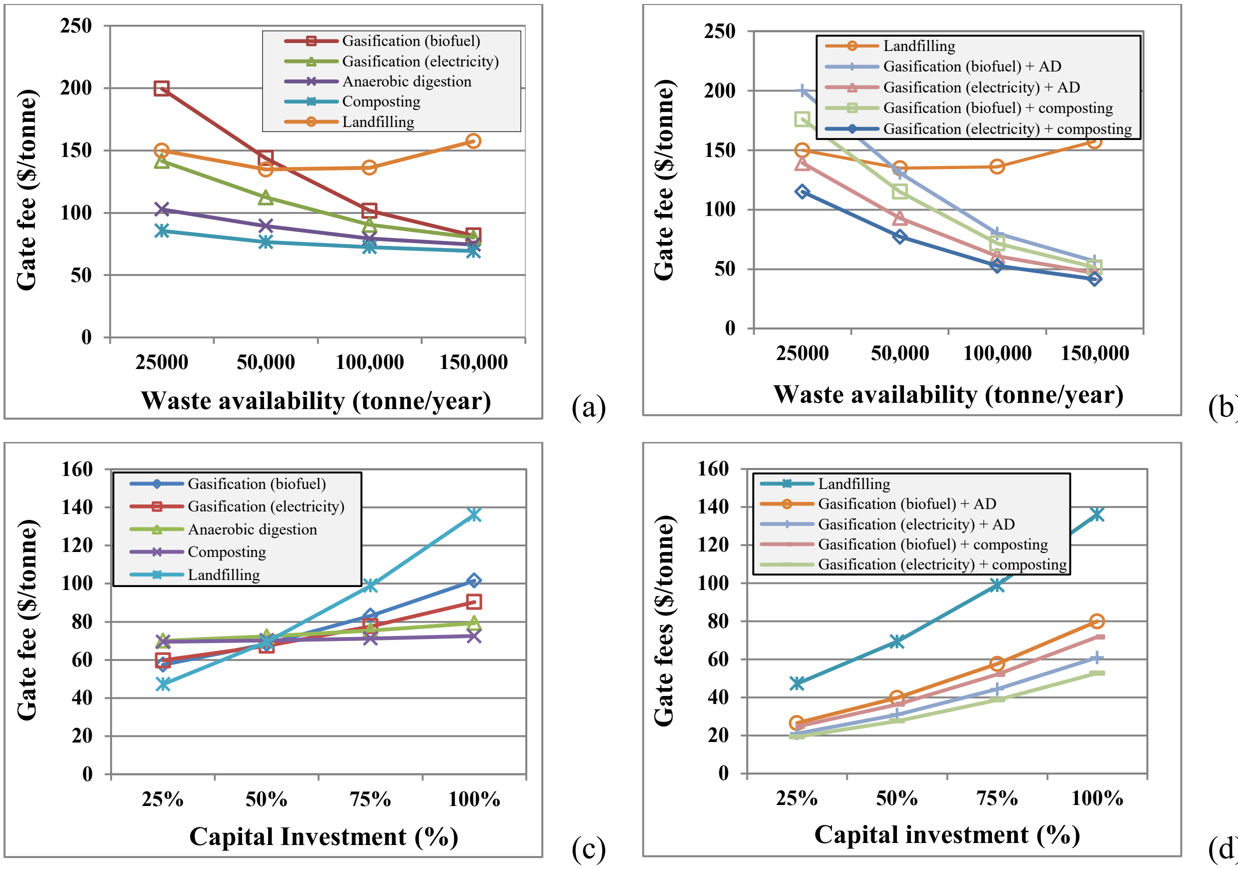


Figure 32: Comparison of gate fees for (a) standalone waste conversion scenarios with landfilling for different waste availability, (b) integrated waste conversion scenarios with landfilling for different waste availability, (c) standalone waste conversion scenarios with landfilling for different capital investment, and (d) integrated waste conversion scenarios with landfilling for different capital investment

Landfilling and integrated waste conversion facility's gate fees decrease by 65% when capital investment decreases from 100% to 25%. On the other hand, gasification (producing biofuel) gate fees decrease from 102 to 57 $/tonne (43.4% decrease) when capital investment decreases from 100% to 25%. Similarly, gasification (producing electricity) gate fees decrease from 90 to 60 $/tonne (33.8% decrease) with a decrease in capital investment from 100% to 25%. The anaerobic digestion and composting gate fees decrease from 79 to 70 $/tonne (11.7% decrease) and from 72 to 69 \$/tonne (4.16% decrease), respectively, with a decrease in capital investment from 100% to 25%. The relationship between gate fee and capital investment (%) can be shown as follows:

$$\text{Gate fee or tipping fee} \\ = \frac{\text{Cap. invest. (\%)} \times \text{cap. cost} + \text{var. cost} + \text{profit} - \text{revenue components (except gate fee)}}{\text{waste availability}} \quad (17)$$

Hence, for a specific waste availability, the rate of change in gate fee due to changes in capital investment depends on the capital cost of the corresponding scenario. The higher the capital cost, the higher the rate of the change of the gate fee for a change in capital investment. Since integrated waste conversion scenarios have a higher capital cost than standalone waste conversion scenarios, integrated waste conversion scenarios have higher rate of change of gate fee for a capital investment change. With regard to landfilling, since the capital cost of a landfill with 100,000 tonne/year capacity is very high, it shows a higher rate of change of gate fee for capital investment change.

Hence, it can be concluded that, in general, for waste conversion scenarios gate fees decrease with an increase in the capacity. Landfilling tipping fee, on the other hand, decreases up to a certain capacity (around 50,000 tonne/year) and then increases with an increase in the capacity, due to change in operating and post-closure cost. Landfilling and integrated waste conversion scenarios show higher rate of change in gate fees compared to standalone scenarios.

4.3.2.2. Comparison in Terms of Calculated IRR

For comparative analysis based on IRR, a gate fee of 70 \$/tonne has been assumed. Figure 33(a) and 33(b) show the IRRs for different scenarios as waste availability changes.

As Figs. 33(a) and 33(b) show, for a gate fee of 70 \$/tonne, integrated gasification (electricity) with composting has the highest IRRs (an IRR range from 8.87% to 13.17% for waste availability of 50,000-100,000 tonne/year). After this scenario, integrated gasification (producing electricity) with anaerobic digestion has the next highest IRR (an IRR range of 6.79% to 11.49% for waste availability of 50,000-150,000 tonne/year). Landfill has the lowest IRR for waste availabilities greater than 70,000 tonne/year for a 70 $/tonne tipping fee. Within a range of 50,000 to 70,000 tonne/year waste availability, gasification (producing biofuel) shows the lowest IRR.

Here, a higher IRR is an indication of higher earnings with a gate fee of 70 $/tonne against a comparatively lower total cost. Since the integrated waste conversion scenarios have higher earnings than the corresponding total cost, integrated waste conversion scenarios show higher IRRs. Moreover, since composting has a lower capital cost than the earning with 70 $/tonne gate fee, composting shows a higher IRR (comparatively higher than other standalone waste conversion scenarios) as well.

A high rate of change of IRR indicates higher earnings because of the higher selling rate of any revenue component (e.g., 0.8 $/liter for biofuel compared to 0.08 $/kWh for electricity) associated with that scenario. In this study, no revenue components (except tipping fee) were considered for landfilling, which resulted in a decreasing IRR trend with increases in the total cost due to increases in waste availability.

Moreover, calculated IRRs change with changes in capital investment. Changes in calculated IRRs with changes in capital investment are shown in Figures 33(c) and 33(d) for a waste availability of 100,000 tonne/year and gate fee of 70 $/tonne.

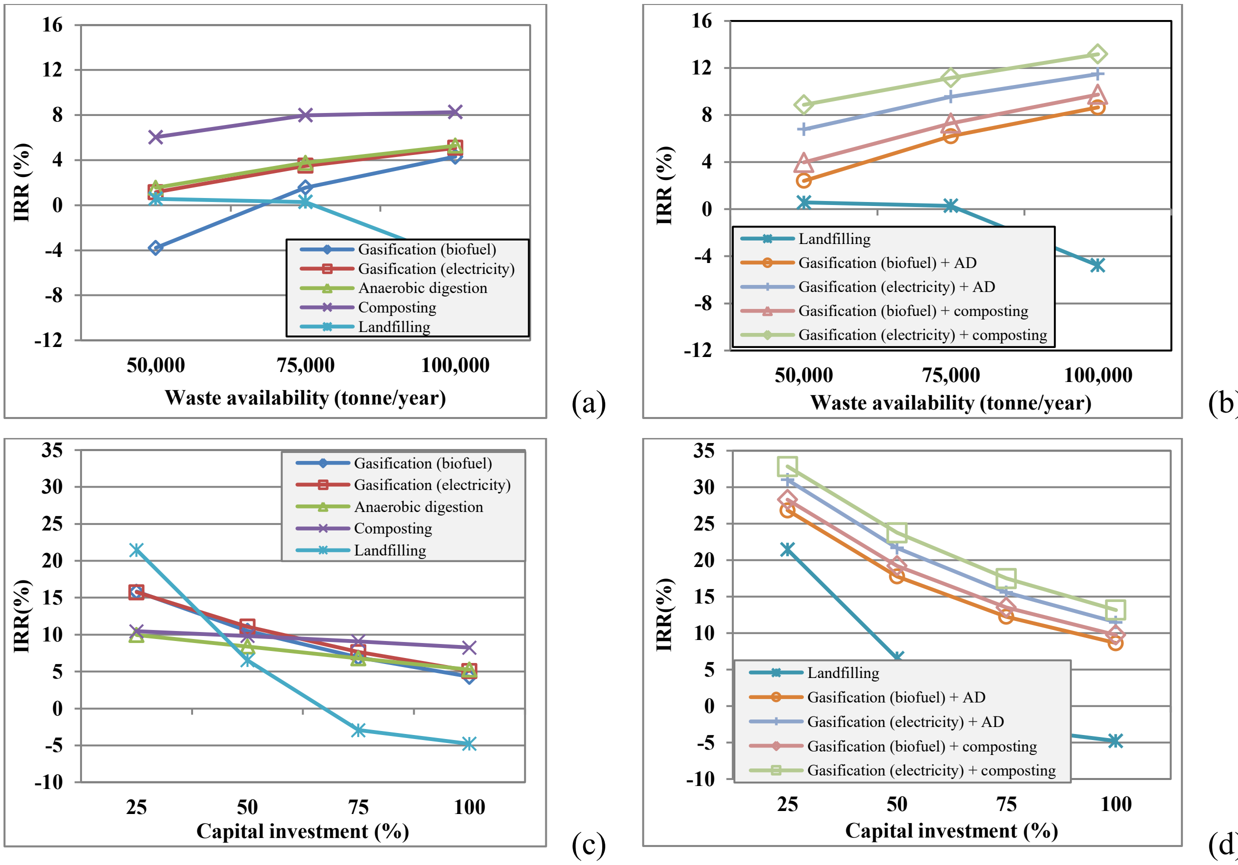


Figure 33: Comparison in terms of IRRs for (a) standalone waste conversion scenarios with landfilling, (b) integrated waste conversion scenarios with landfilling for different waste availability scenarios, (c) standalone waste conversion scenarios with landfilling and (d) integrated waste conversion scenarios with landfilling for different capital investment scenarios

As the capital investment decreases, the IRR increases. Landfilling shows the highest IRR increase (from -4.76% to 21.46%) for a decrease in capital investment from 100% to 25%, whereas anaerobic digestion and composting show the lowest IRR increases (from 5.28% to 9.97% and from 8.26% to 10.46%, respectively) for a decrease in capital investment from 100% to 25%.

As mentioned above, a higher IRR is an indication of higher earnings compared to corresponding lower total cost. Since integrated waste conversion scenarios have higher earnings (because they have more revenue components) compared to their corresponding total cost, integrated waste conversion scenarios show higher IRRs than standalone waste conversion scenarios.

In addition, a higher IRR change indicates higher earnings because of the higher selling rate of any revenue component. Moreover, it has been mentioned earlier that scenarios with a higher capital cost show a higher rate of change in the total cost and hence a higher rate of change of IRR as the capital investment changes.

Therefore, it can be summarized that, in general, for waste conversion scenarios, IRRs increase with an increase in the capacity. For landfilling, on the other hand, IRRs decrease with an increase in the capacity. Landfilling and integrated waste conversion scenarios show higher rate of change in IRRs compared to that of standalone scenarios.

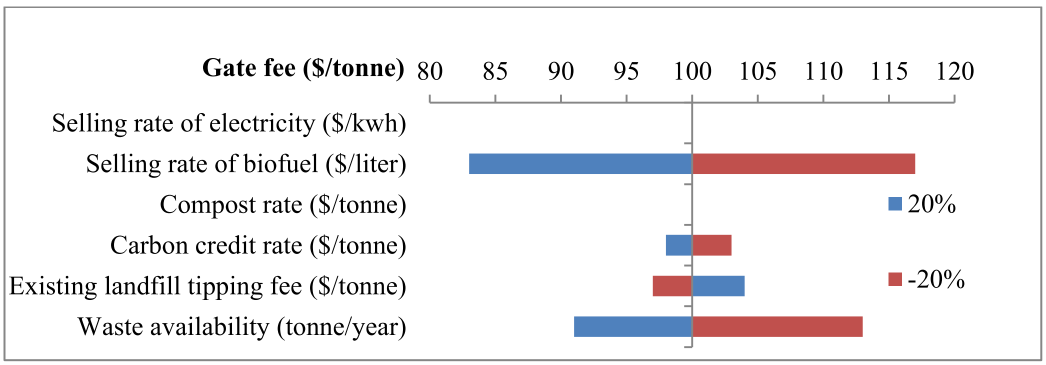
4.3.3. Sensitivity Analysis

The sensitivity analysis presented in this section provides a better understanding of the key parameters' impacts on the overall cost. Here, impacts of the key parameters are shown on the calculated gate fees and IRRs for each scenario. The values of all the key parameters were changed by ±20%. Figures 34 and 35 show the impact of this change for all of the scenarios. The main reason behind performing the sensitivity analysis with ±20% is the historical range of change of the parameters. The rate of electricity fluctuated over the last two years (from October 2012 to February 2015) between 0.6 $/kWh and 0.95 $/kWh (Alberta Government, 2015). And the rate of methanol fluctuated over the last 10 years (January 2005 to April 2015) between 0.6 $/gal and 2.5 $/gal. Changing the parameters' value by ±20% of the base value helps us to do the sensitivity analysis with credible values of the parameters. These diagrams show us which parameter has greater impact.

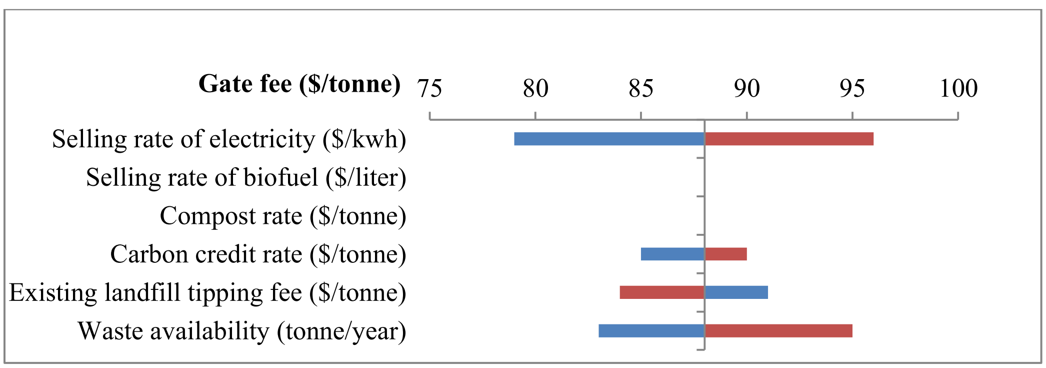
Two sensitivity analyses have been conducted in this study, one for the gate fee and one for the IRR.

4.3.3.1. Sensitivity Analysis for Gate Fee

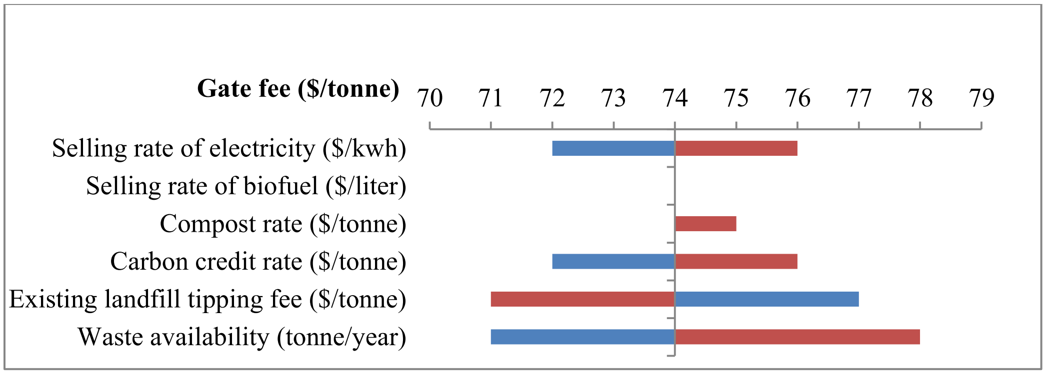
A sensitivity analysis for the gate fee was done for a constant IRR of 10% and for the base values of the key parameters shown in Table 21. The values of all the key parameters were changed by ±20% and the impact this change had on the gate fees is shown in Fig. 34 in tornado diagrams. These diagrams show us which parameter has greater impact.



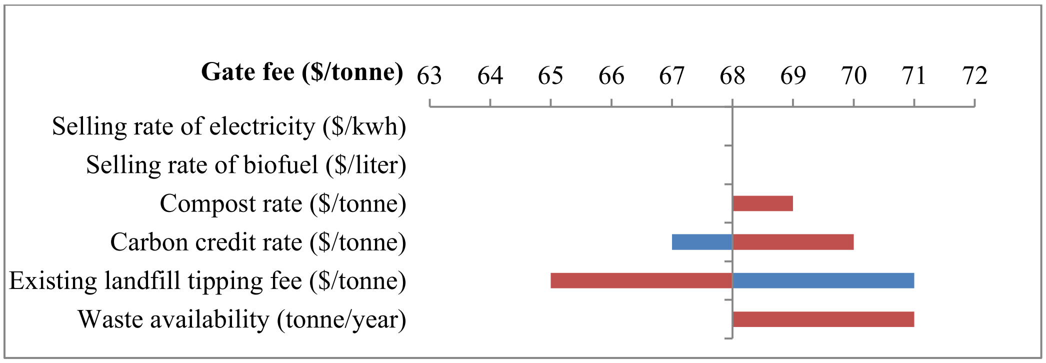
(a)



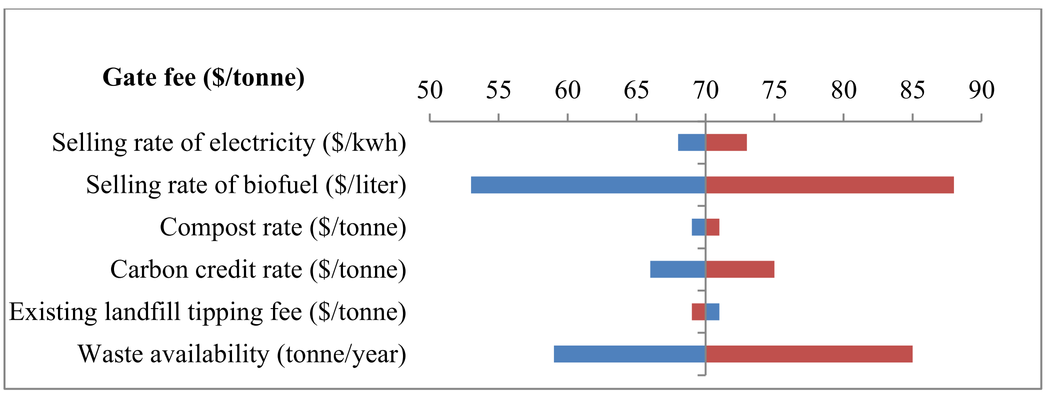
(b)


Gate fee ($/tonne)
70 71 72 73 74 75 76 77 78 79
Selling rate of electricity ($/kwh)
Selling rate of biofuel ($/liter)
Compost rate ($/tonne)
Carbon credit rate ($/tonne)
Existing landfill tipping fee ($/tonne)
Waste availability (tonne/year)

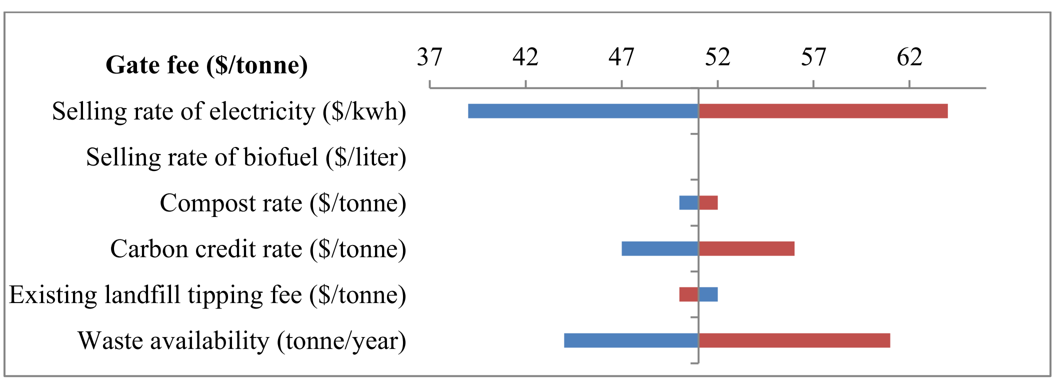
(c)


Gate fee ($/tonne)
63 64 65 66 67 68 69 70 71 72
Selling rate of electricity ($/kwh)
Selling rate of biofuel ($/liter)
Compost rate ($/tonne)
Carbon credit rate ($/tonne)
Existing landfill tipping fee ($/tonne)
Waste availability (tonne/year)

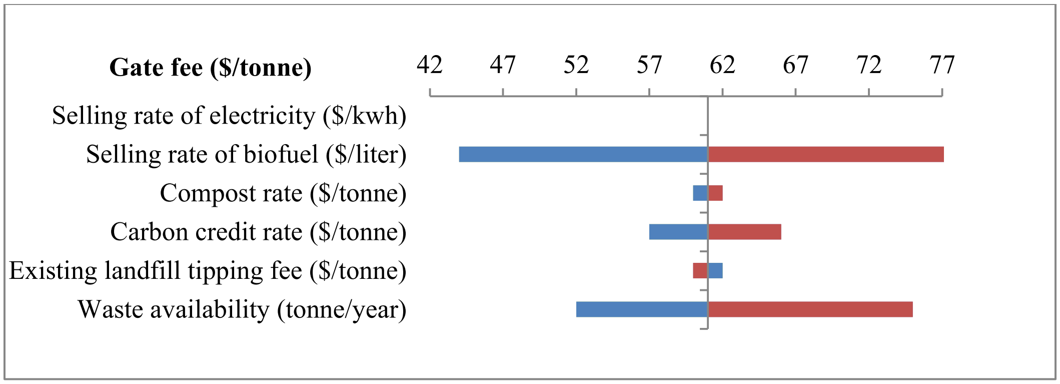
(d)


Gate fee ($/tonne)
50 55 60 65 70 75 80 85 90
Selling rate of electricity ($/kwh)
Selling rate of biofuel ($/liter)
Compost rate ($/tonne)
Carbon credit rate ($/tonne)
Existing landfill tipping fee ($/tonne)
Waste availability (tonne/year)

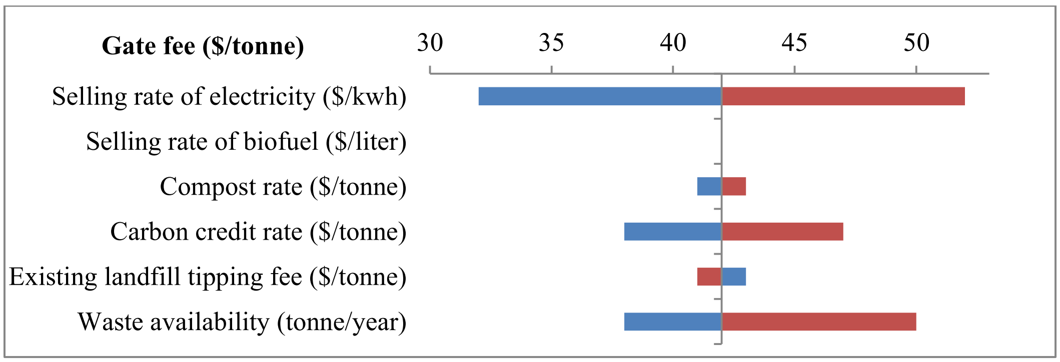
(e)


Gate fee ($/tonne)
37 42 47 52 57 62
Selling rate of electricity ($/kwh)
Selling rate of biofuel ($/liter)
Compost rate ($/tonne)
Carbon credit rate ($/tonne)
Existing landfill tipping fee ($/tonne)
Waste availability (tonne/year)

(f)



(g)



(h)

Figure 34: Sensitivity analysis of (a) gasification (producing biofuel), (b) gasification (producing electricity), (c) anaerobic digestion, (d) composting, (e) gasification (producing biofuel) integrated with anaerobic digestion, (f) gasification (producing electricity) integrated with anaerobic digestion, (g) gasification (producing biofuel) integrated with composting, and (h) gasification (producing electricity) integrated with composting

For the gasification (producing biofuel) scenario, the selling rate of the biofuel is the dominating factor. This is mainly due to the high conversion rate of biofuel (380 liters/BDT - Jacobs Consultancy, 2013). A 20% change in biofuel cost results in a gate fee change of around 17 $/tonne, and a 20% change in waste availability changes the gate fee by around 10 $/tonne.

For the gasification (producing electricity) scenario, the selling rate of electricity is the most influential variable because of the high conversion rate (1800 kWh/BDT). A 20% change in the selling rate of electricity change the gate fee by around 7 $/tonne.

For the anaerobic digestion scenario, an existing landfill's tipping fee and waste availability have more influence than other parameters. A 20% change in an existing landfill's tipping fee changes the gate fee by 3 $/tonne, whereas a 20% increase in waste availability increases the gate fee by 4 $/tonne and a 20% decrease in waste availability decreases the gate fee by 3 $/tonne.

For the composting scenario, a 20% change in an existing landfill's tipping fee changes the gate fee by 3 $/tonne.

For gasification (biofuel) integrated with anaerobic digestion, the selling rate of biofuel is the most influential parameter; a 20% change in the selling rate of biofuel changes the by 17 $/tonne. A 20% increase in waste availability decreases the gate fee by 11 $/tonne and a 20% decrease in waste availability increases the gate fee by 15 $/tonne.

For the gasification (electricity) integrated with anaerobic digestion scenario, the selling rate of electricity is the most influential variable. A 20% change in the selling rate of electricity changes the gate fee by 17 $/tonne. Waste availability is the second most influential parameter for this scenario. A 20% increase in waste availability decreases the gate fee by 7 $/tonne gate fee and a 20% decrease in waste availability increases the gate fee by 9 $/tonne.

For the gasification (biofuel) integrated with composting scenario, the selling rate of biofuel is the most influential parameter; a 20% change in the selling rate of biofuel changes the gate fee by 17 $/tonne. A 20% increase in waste availability decreases the gate fee by 9 $/tonne, and a 20% decrease in waste availability increases the gate fee by 13 $/tonne.

For the gasification (electricity) integrated with composting scenario, a 20% change in electricity cost changes the gate fee by 10 $/tonne. Waste availability is the second most influencing parameter for this scenario. A 20% increase in waste availability decreases the gate fee by 5 $/tonne, and a 20% decrease in waste availability increases the gate fee by 8 $/tonne.

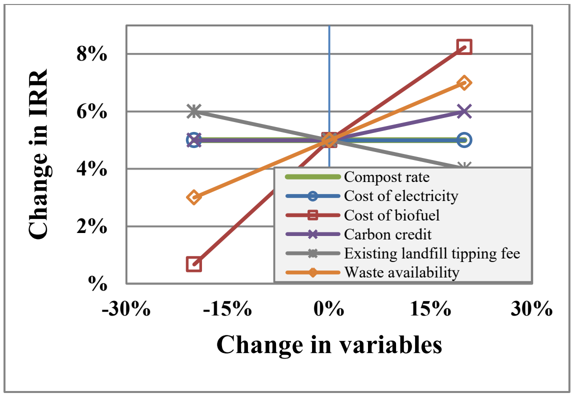
Hence, to summarize, selling rates of biofuel and electricity are the dominating factors for gasification (producing biofuel) and gasification (producing electricity) scenarios, respectively. Waste availability and existing landfill's tipping fee are the most influencing factors for anaerobic digestion and composting scenarios, respectively.

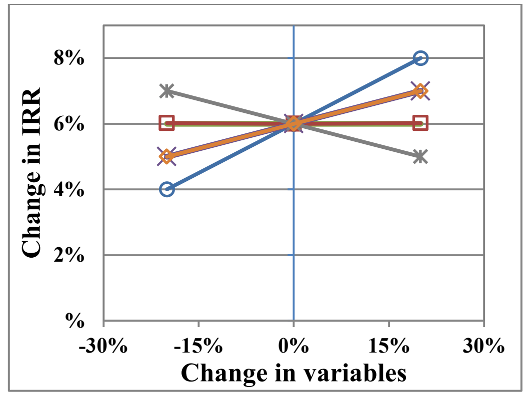
4.3.3.2. Sensitivity Analysis for the IRR

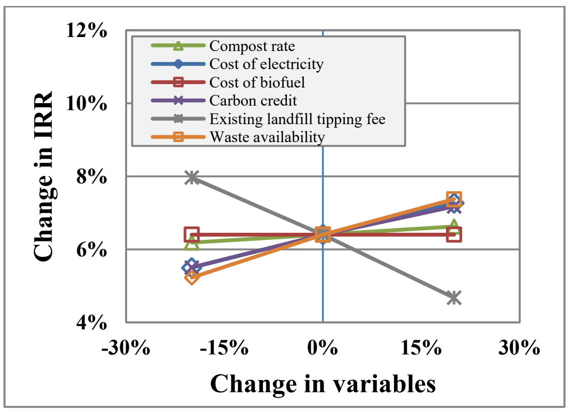
A sensitivity analysis for the IRR was done for a constant gate fee of 70 $/tonne of wet MSW and for the base values of the key parameters shown in Table 21. The values of all the key parameters were changed by ±20% and the impact this change had on the gate fees is shown in Fig. 35. These diagrams show us which parameter has greater impact.

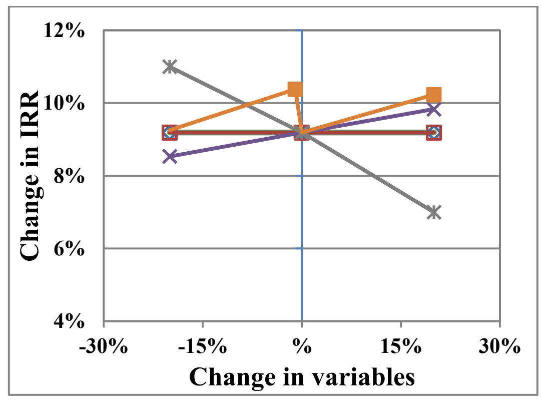
For the gasification (producing biofuel) scenario, biofuel cost is the dominating factor. A 20% increase in biofuel cost results in an increase of around 3.2% of IRR and a 20% decrease in biofuel cost causes a decrease of around 4% of IRR. Moreover, a 20% change in waste availability causes a change of around 2% in the IRR.

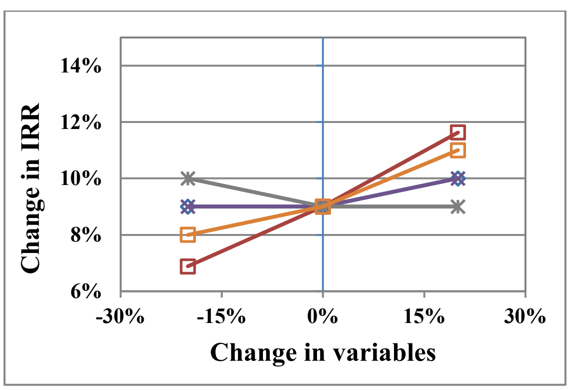
For the gasification (producing electricity) scenario, electricity cost is the most influential variable. A 2% change in IRR results in a 20% change in electricity cost.

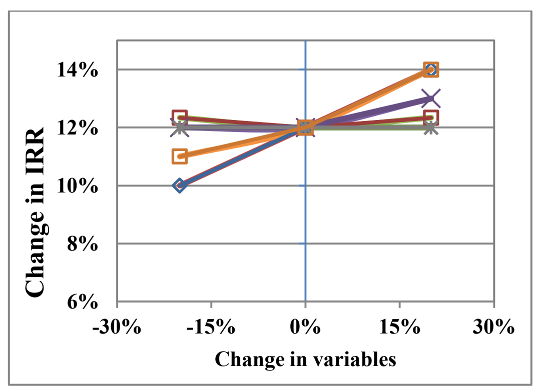

Change in IRR
8%
6%
4%
2%
%
-30%
-15%
0%
15%
30%
Change in variables
Compost rate
Cost of electricity
Cost of biofuel
Carbon credit
Existing landfill tipping fee
Waste availability
(a)

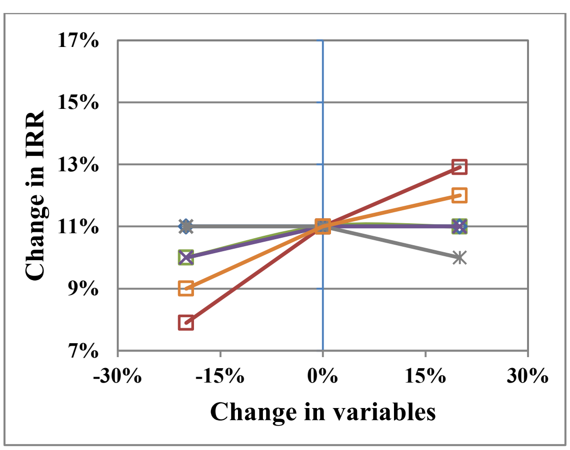

Change in IRR
8%
6%
4%
2%
%
-30%
-15%
0%
15%
30%
Change in variables
(b)


Change in IRR
12%
10%
8%
6%
4%
-30%
-15%
0%
15%
30%
Change in variables
Compost rate
Cost of electricity
Cost of biofuel
Carbon credit
Existing landfill tipping fee
Waste availability
(c)


Change in IRR
12%
10%
8%
6%
4%
-30%
-15%
%
15%
30%
Change in variables
(d)


Change in IRR
14%
12%
10%
8%
6%
-30%
-15%
0%
15%
30%
Change in variables
(e)


Change in IRR
14%
12%
10%
8%
6%
-30%
-15%
0%
15%
30%
Change in variables
(f)


Change in IRR
17%
15%
13%
11%
9%
7%
-30%
-15%
0%
15%
30%
Change in variables
(g)

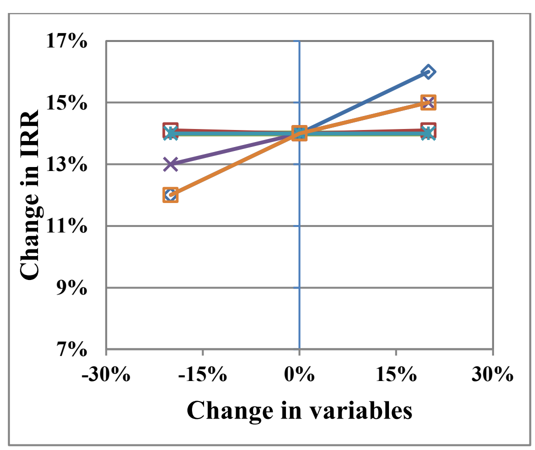

Change in IRR
17%
15%
13%
11%
9%
7%
-30%
-15%
0%
15%
30%
Change in variables
(h)

Figure 35: Sensitivity analysis of (a) gasification (producing biofuel) (b) gasification (producing electricity) (c) anaerobic digestion (d) composting (e) gasification (producing biofuel) integrated with anaerobic digestion (f) gasification (producing electricity) integrated with anaerobic digestion (g) gasification (producing biofuel) integrated with composting (h) gasification (producing electricity) integrated with composting

For the anaerobic digestion scenario, an existing landfill's tipping fee is the most influential parameter. A 20% increase in an existing landfill's tipping fee results in a decrease of around 1.73% in the IRR and a 20% decrease in an existing landfill's tipping fee results in an increase of around 1.56% in the IRR.

For the composting scenario, an existing landfill's tipping fee is the most influential factor. A 20% increase in an existing landfill's tipping fee brings about a decrease in the IRR of 2% and a 20% decrease in an existing landfill's tipping fee brings about an increase of around 2% in the IRR.

For the gasification (biofuel) integrated with anaerobic digestion scenario, the cost of biofuel is the most significant parameter; a 20% change of the cost of biofuel causes a change of 2% in the IRR. A 20% increase in waste availability results in an increase of 2% in the IRR and a 20% decrease in waste availability results in a decrease of around 1% in the IRR.

For the gasification (electricity) integrated with anaerobic digestion scenario, electricity cost is the most influential variable. A 20% change in the cost of electricity results in a change of 2% in the IRR. Moreover, waste availability is the second most influential parameter for this scenario. A 20% increase in waste availability results in an increase of 2% in the IRR and 20% decrease in waste availability causes a decrease of 1% in the IRR.

For the gasification (biofuel) integrated with composting scenario, the cost of biofuel is the most influential parameter; a 20% increase in biofuel cost causes an increase of around 2% in the IRR and a 20% decrease in biofuel cost causes an decrease of around 3% in the IRR. A 20% increase in waste availability causes an increase of around 1% in the IRR and a 20% decrease in waste availability causes a decrease of around 2% in the IRR.

For the gasification (electricity) integrated with composting scenario, a 20% change in the cost of electricity causes a change of around 2% in the IRR. Moreover, a 20% increase in waste availability causes an increase of 1% in the IRR and a 20% decrease in waste availability causes a decrease of around 2% in the IRR.

4.4. Conclusion

The objective of this research was to develop a model that compares different waste management scenarios. This model is a generic framework that can be used in any county or city. For this research, a case study of waste management for Parkland County was conducted. First, a suitable location for a facility was found through a suitability analysis and a location-allocation analysis using ArcGIS. The model compared ten scenarios, including landfilling, with respect to calculated gate fees and calculated IRRs. The key parameters involved in this model are biofuel cost, electricity cost, compost cost, existing landfill's tipping fee, and carbon credit rate (i.e., offset).

For a 10% IRR and a waste availability of 25,000-50,000 tonne/year, composting is the cheapest solution (77-86 $/tonne gate fee), and for a waste availability of 50,000-150,000 tonne/year, a gasification (producing electricity) facility integrated with composting is the cheapest solution with a gate fee of 42-77 $/tonne. Moreover, for a gate fee of 70 $/tonne, integrated gasification (electricity) with composting shows the highest IRRs (an IRR range from 8.87%-13.17% for a waste availability range of 50,000-100,000 tonne/year). Integrated gasification (producing electricity) with anaerobic digestion shows the next highest IRR (IRR range of 6.79%-11.49% for a waste availability range of 50,000-150,000 tonne/year).

A sensitivity analysis was also performed to better understand the impact of key parameters on gate fees, where it was found that, waste availability is an influential factor for each scenario. Selling rates of biofuel and electricity are dominating factors for gasification (producing biofuel) and gasification (producing electricity) scenarios, respectively.

Chapter 5: Conclusion and Recommendations for Future Work

5.1. Conclusion

The motivation of this research was the concept of utilizing MSW to produce value-added products (e.g., biofuel, electricity, compost) resulting in both cleaner energy production and better solid waste management. This study incorporated site selection for MSW utilization facility and economic comparison of MSW utilization pathways. A new site selection methodology was developed and analyzed to select a suitable site for MSW utilization facility using Geographic Information System (GIS). After that, a comprehensive decision making model, called **FUN**damental E**N**gineering Principl**E**s-based Mode**L** for Estimation of **Cost** of Energy and Fuels from **MSW** (FUNNEL-Cost-MSW), was developed to help waste management decision making by comparing ten waste management scenarios.

In the first step of the study, a detailed assessment of MSW availability was performed by collecting data from the landfills. GIS software ArcGIS was used for the spatial analysis and suitable site selection for waste utilization facility. Site selection was performed in two stages through exclusion and preference analysis. Twelve constraints and eight preference factors were considered (based on environmental and social concern) for the exclusion and preference analysis, respectively. In the exclusion analysis, unsuitable lands were screened out from the study area based on the twelve constraints. After that, preference analysis was performed to find out the relative preference of different regions considering the 8 preference factors. Analytic Hierarchy Process (AHP) was used to assign weights to the preference factors considering their social and environmental importance. Three different weights were assigned to each of the preference factors by changing their relative importance. Weights assigned to the factor waste availability were 0.44, 0.36, and 0.28. Six scenarios (tabulated in Table 22) were analyzed to observe how the location and amount of suitable sites vary for three different weights. For scenarios 1, 2, and 3, all waste locations (e.g., landfills, transfer stations) were assigned the same weight invariably how much waste is available at those waste locations; for scenarios 4, 5, and 6, waste locations with different amounts of waste were assigned different weights according to waste availability at the corresponding locations.

Table 22: MSW site selection scenarios based on preference analysis and AHP

Scenario label	Description
Scenario 1	Selected facility site depends on waste locations; waste-availability-weightage (WA weightage)=0.44 (calculated using AHP)
Scenario 2	Selected facility site depends on waste locations; WA weightage=0.36
Scenario 3	Selected facility site depends on waste locations; WA weightage=0.28
Scenario 4	Selected facility site depends on waste locations and on the amount of waste availability; WA weightage=0.44
Scenario 5	Selected facility site depends on waste locations and on the amount of waste availability; WA weightage=0.36
Scenario 6	Selected facility site depends on waste locations and on the amount of waste availability; WA weightage=0.28

It was found that as the weight of waste availability increases, regions with higher suitability index[13] increase. It was also found that, if the suitability analysis is dependent on the amount of waste availability, then the regions with higher suitability index are less in amount.

In the next step of the study, a comprehensive decision making model, called FUNNEL-Cost-MSW, was developed and its application was demonstrated through a case study. The case study was conducted on Parkland County and its surrounding counties in the province of Alberta, Canada. For this case study, a site selection was conducted through a suitability analysis and location-allocation analysis. The economic model framework was developed in such a way that the user can either use the default conditions or different cost parameters.

Comparison of the ten different waste conversion scenarios (as mentioned before) has been done for different investment percentages and different incentives available for these scenarios. The model can be used to investigate the sensitivity of different parameters on either gate fees or IRRs.

A case study was conducted for Parkland County to choose a waste conversion technology for present conditions. For 10% IRR and a waste availability of 25,000-50,000 tonne/year, composting is the cheapest solution (77-86 $/tonne gate fee[14]), and for a waste availability of 50,000-150,000 tonne/year, a gasification (producing electricity) facility integrated with composting becomes the cheapest solution with a gate fee of 42-77 $/tonne.

Out of the economical comparison of the ten waste management scenarios it was found that, waste conversion scenarios become more economical with an increase in the capacity; landfilling

[13] Suitability index is the number that is used in a land suitability map (LSM) to indicate how suitable the location is. The higher the suitability index, the more suitable the location is.
[14] Gate fee is the charge levied on the waste material coming into a waste management facility.

becomes expensive as the capacity increases due to the higher post-closure and operating cost; and landfilling, and the integrated waste conversion scenarios are more sensitive to capital investment than the standalone scenarios.

The site selection methodology developed within GIS environment and results of scenario analysis are applicable to any region. In addition, the model, FUNNEL-Cost-MSW, is generic and can be used by any city/county/municipality. This model can be used for assessing the waste management options for different jurisdictions taking into account economic, social and environmental factors.

5.2. Recommendations for Future Work

This study developed a GIS-based methodology for waste conversion facility site selection and created a decision-making model by economically comparing ten waste management scenarios. The followings are some key recommendations for future work:

1. In this study, the GHG reduction values associated with carbon credit calculation were collected from peer-reviewed literatures. Here, GHG reduction values are the sum of CO_2-eq saved by avoiding landfilling and replacing burning gasoline. GHG emission associated with MSW treatment by a specific technology depends on the composition of MSW and on the energy consumption by the technology. Life cycle GHG emission from each of the ten waste management scenarios could be performed.
2. This model provides an economic comparison of ten different waste management scenarios. But, when making waste management decisions, there are other factors that need to be considered besides economic comparison. These factors are the landfill's remaining life, available spaces for new landfills, difficulty in getting a new landfill

permit, etc. Moreover, diverting waste from the landfill to waste-to-energy saves landfill space and increases the remaining life of the landfill.

3. This model uses Microsoft Excel's IRR formula to calculate IRR for a specific gate fee. Microsoft Excel uses a numerical root finding technique and it tries to use the closest rate (in an algorithmic sense, since it does not depend on the slope in addition to actual numerical closeness) to the guess rate it uses. Hence, below some threshold value of gate fees (i.e. 70 $/tonne gate fee), MS Excel does not return any value for IRR (since it does not find any close rate within a certain number of iterations). Further work is recommended to overcome this shortcoming of FUNNEL-Cost-MSW.
4. Future work is recommended to find 10 optimum locations in Alberta for waste conversion facility siting in order to develop a sustainable waste management infrastructure for the province of Alberta.

This comprehensive GIS and decision making FUNNEL-Cost-MSW model can be used for assessing the waste management options for different jurisdictions taking into account economic, social and environmental factors.

Appendices

Appendix A: Sample Calculation of Suitability Index Values

Table A1 shows a sample calculation of suitability index value for any specific cell of the study area map.

Table A1: Sample calculation of suitability index values

Preference factors	**Grading values (C)**	**Weight of preference factors (w)**	**Cell value for each factor, C_p=C×w**	**Preference cell value ($\sum C_p$)**	**Constraint map value for corresponding cell, C_{E}= 0 or 1**	**Suitability index, SI=$C_E \times C_p$**
Waste availability	9	0.36	3.24			
Water availability	8	0.22	1.76			
Urban and rural areas	7	0.15	1.05			
Roads	6	0.09	0.54	7.25	1	7.25≈7
Transmission lines	5	0.06	0.3			
Substations	4	0.06	0.24			
Land cover	3	0.03	0.09			
Slope	1	0.03	0.03			

Appendix B

a) Python code for creating a shapefile containing transfer sites' locations

```
import arcpy, os

from arcpy import env

env.overwriteOutput = True

## Set the Spatial Reference.

prjFile = os.path.join(arcpy.GetInstallInfo()["InstallDir"],

                    "Coordinate Systems/Geographic Coordinate Systems/North America/NAD 1983
(CSRS).prj")

spatialRef = arcpy.SpatialReference(prjFile)

#arcpy.env.extent = arcpy.Extent("R:/AmitResearch/Biomass
Group/Mohib/biomass/Arifa/Plastic_Alberta/ABnew/AlbertaGIS/ABdata.gdb/CensusDivisions")

ptList =[[-110.579,49.964],[-110.300, 49.669],[-110.030, 50.500]]

pt = arcpy.Point()

ptGeoms = []

for p in ptList:

   pt.x = p[0]

   pt.Y = p[1]
```

```
    ptGeoms.append(arcpy.PointGeometry(pt, spatialRef))

arcpy.CopyFeatures_management(ptGeoms, r"D:\AfterRasterAgain\pointnew1.shp")
```

b) Python code for developing a location-allocation layer

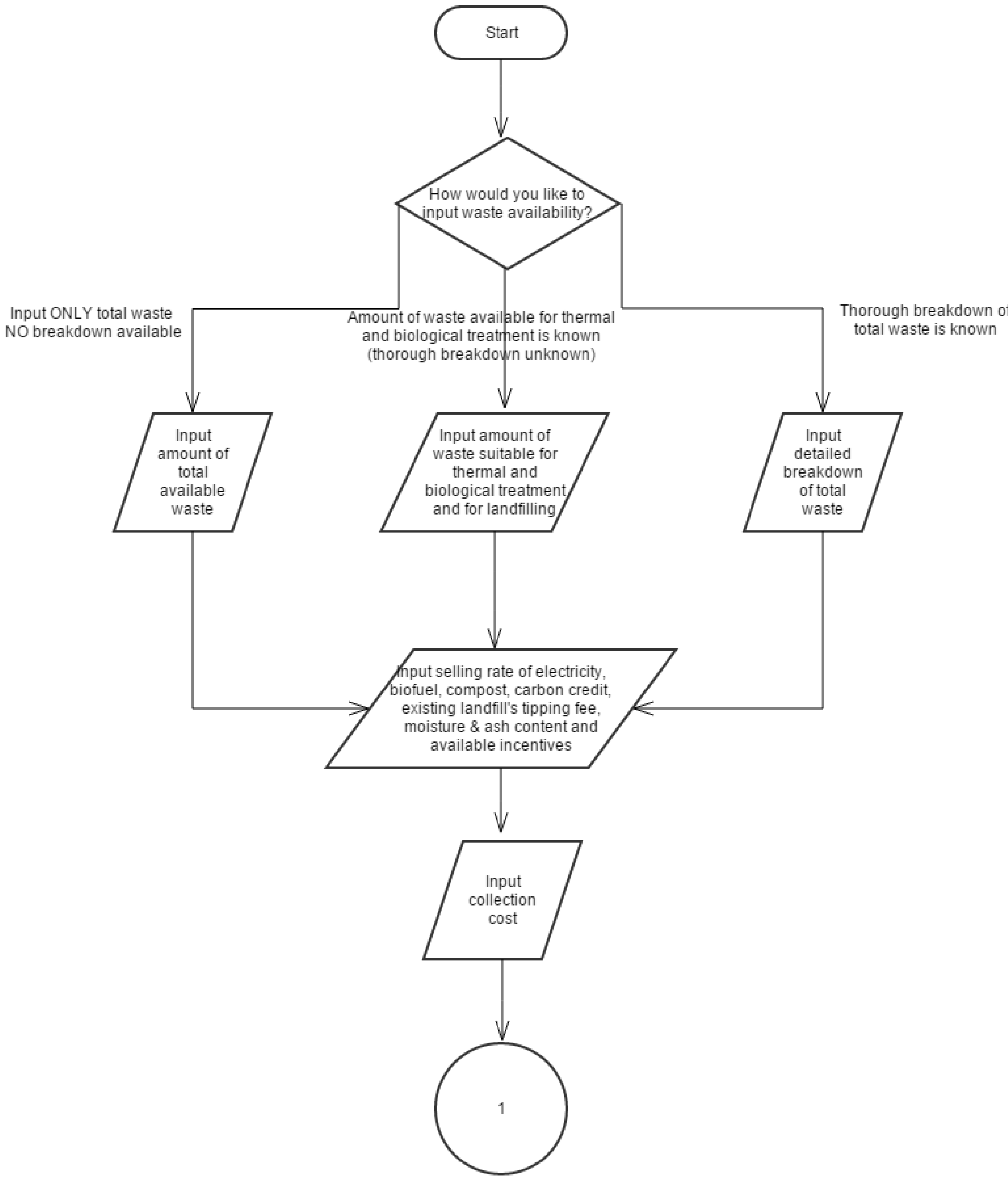
```
#Import system modules

import arcpy, os

from arcpy import env

try:

    #Check out the Network Analyst extension license

    arcpy.CheckOutExtension("Network")

    #Set environment settings

    env.workspace = "D:/AfterRaster/PreferenceTest.gdb"

    env.overwriteOutput = True



    #Set local variables

    inNetworkDataset = "R:/AmitResearch/Biomass
Group/Mohib/biomass/Arifa/Plastic_Alberta/ABnew/ABnew/ABnet1_home/ABnet1.gdb/ABnet
work1/ABnetwork2_ND"

    outNALayerName = "FacilityLocation1"
```

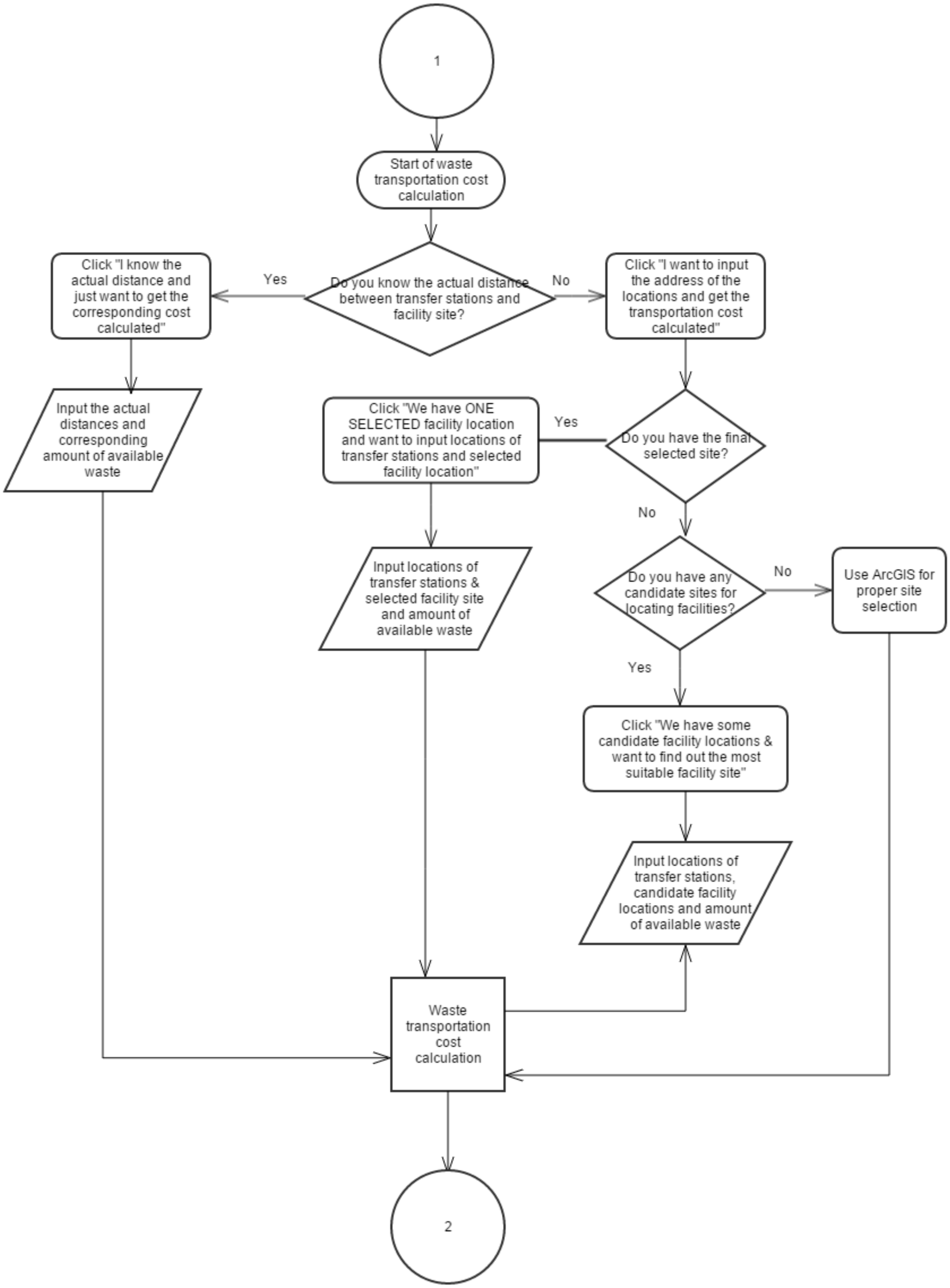
```
impedanceAttribute = "Meters"

inFacilities = "D:/AfterRaster/SI_8_9NewRoads.shp"

requiredFacility = "Analysis/ExistingStore"

inDemandPoints = "D:/AfterRasterAgain/pointnew4.shp"

outLayerFile = "D:/AfterRasterAgain" + "/" + outNALayerName + ".lyr"



#Create a new location-allocation layer. In this case the demand travels to

#the facility. We wish to find 3 potential store locations out of all the

#candidate store locations using the maximize attendance model.

outNALayer = arcpy.na.MakeLocationAllocationLayer(inNetworkDataset,

                                        outNALayerName,

                                        impedanceAttribute,

                                        "DEMAND_TO_FACILITY",

                                        "MINIMIZE_FACILITIES",1,

                                        "500000",

                                        "LINEAR")
```

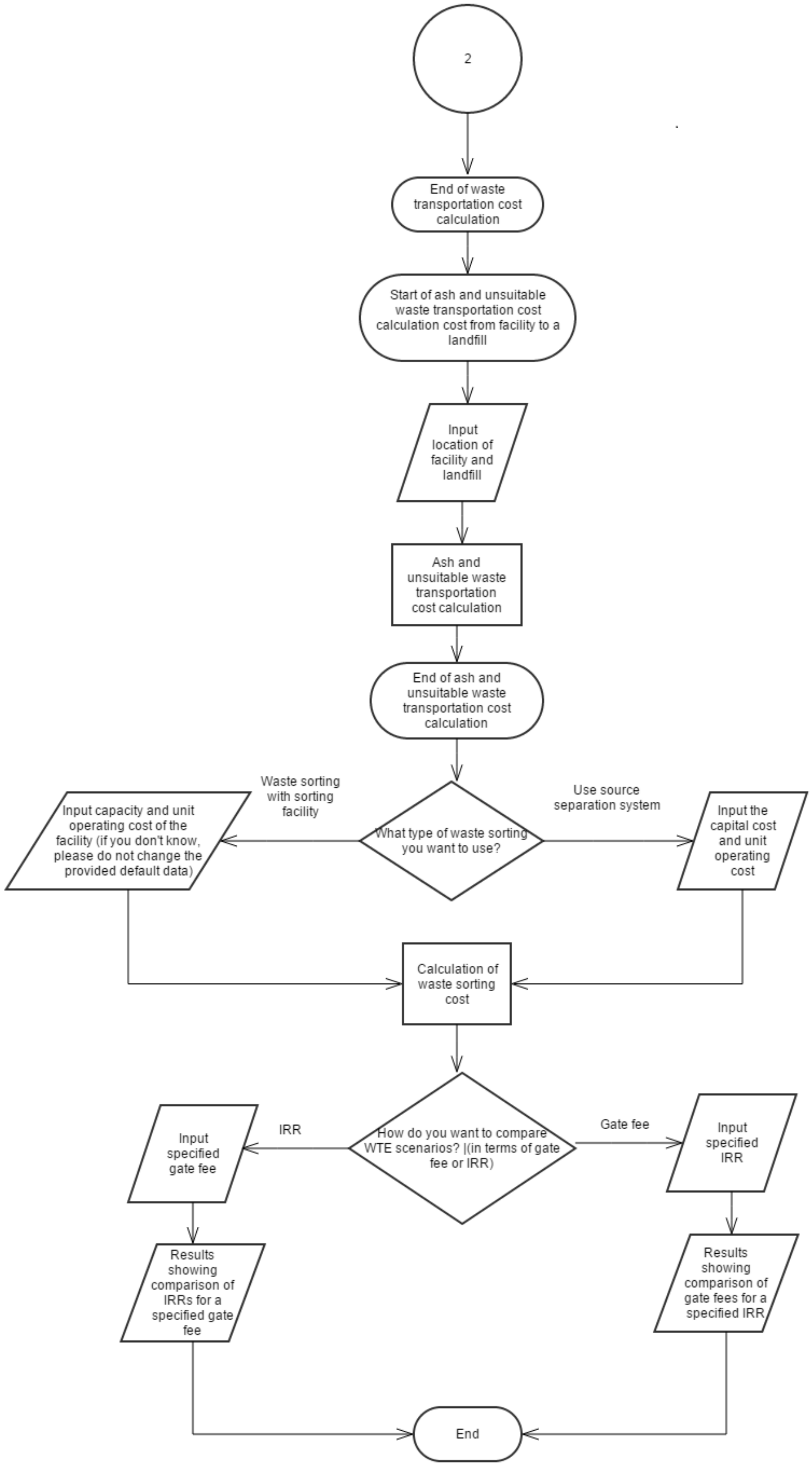
```
    #Load the candidate store locations as facilities
    arcpy.AddLocations_na(outNALayer,"Facilities",inFacilities,"","")


    #Load the tract centroids as demand points
    arcpy.AddLocations_na(outNALayer,"Demand Points",inDemandPoints,"","")


    #Solve the location-allocation layer
    arcpy.Solve_na(outNALayer)


    #Save the solved location-allocation layer as a layer file on disk with
    #relative paths
    arcpy.SaveToLayerFile_management(outNALayer,outLayerFile,"RELATIVE")


    print "Script completed successfully"


except Exception as e:
    # If an error occurred, print line number and error message
```

```
import traceback, sys

tb = sys.exc_info()[2]

print "An error occured on line %i" % tb.tb_lineno

print str(e)
```

Appendix C: Brief overview of FUNNEL-Cost-MSW




1
Start of waste transportation cost calculation
Do you know the actual distance between transfer stations and facility site?
Yes
No
Click "I know the actual distance and just want to get the corresponding cost calculated"
Click "I want to input the address of the locations and get the transportation cost calculated"
Input the actual distances and corresponding amount of available waste
Click "We have ONE SELECTED facility location and want to input locations of transfer stations and selected facility location"
Yes
Do you have the final selected site?
No
Input locations of transfer stations & selected facility site and amount of available waste
Do you have any candidate sites for locating facilities?
No
Use ArcGIS for proper site selection
Yes
Click "We have some candidate facility locations & want to find out the most suitable facility site"
Input locations of transfer stations, candidate facility locations and amount of available waste
Waste transportation cost calculation
2


2
End of waste transportation cost calculation
Start of ash and unsuitable waste transportation cost calculation cost from facility to a landfill
Input location of facility and landfill
Ash and unsuitable waste transportation cost calculation
End of ash and unsuitable waste transportation cost calculation
What type of waste sorting you want to use?
Waste sorting with sorting facility
Use source separation system
Input capacity and unit operating cost of the facility (if you don't know, please do not change the provided default data)
Input the capital cost and unit operating cost
Calculation of waste sorting cost
How do you want to compare WTE scenarios? |(in terms of gate fee or IRR)
IRR
Gate fee
Input specified gate fee
Input specified IRR
Results showing comparison of IRRs for a specified gate fee
Results showing comparison of gate fees for a specified IRR
End

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