Integrated Solid Waste Management Alternatives in Consideration of Economic and Environmental Factors: A Mathematical Model Development and Evaluation

by

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Dedication

To the memory of my little sister María Angélica (1985-1998):

Estarás presente en mi corazón, por siempre.

To my dad and mom; para Don Memo y Doña Miriam.

To my sister Lilliana, my brother in law Mario and their two children.

Los quiero mucho!

Biography

He was born in the rural town of San Isidro del General, Costa Rica, Central America, in February 17, 1969. His mother is Doña Miriam Mora and his father is Don Guillermo Solano. Later he moved to the capital city San José with his family. He completed his elementary school in 1980 and his high school in 1985. In 1986, he started university level studies at the University of Costa Rica. He obtained his 5-year degree (Licenciatura) in Civil Engineering in 1991. After graduating, he worked as a junior instructor at the University of Costa Rica for two years, teaching basic engineering courses and doing research in the Environmental Engineering field. During this period, Solano gained experience and interest in the environmental situation of his country, particularly in the area of solid waste management. He decided to continue his studies to strengthen his skills and knowledge and came to the United States to start graduate work in August 1994. He obtained a Master of Science degree in August 1996 and a Doctor in Philosophy degree in August 1999, both at North Carolina State University. In August 2, 1999 he started working as a Research Environmental Engineer at the Research Triangle Institute in North Carolina.

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North Carolina State University

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Chapter 1: Introduction

Municipal solid waste (MSW) is defined as the combination of all solid, non-hazardous wastes generated in residential, multifamily and commercial areas. Municipal solid waste management (MSWM) is an integral part of the civil infrastructure and is an inevitable activity necessary to handle and dispose MSW in a proper manner. MSWM is becoming an exceedingly complex activity due to increasing environmental regulations that continue to impose stricter MSWM requirements. There are strict regulations and controls on pollutants resulting from MSW management. For example, newer landfills are required to have liner systems for leachate collection and are also required to collect and treat landfill gases. Additionally, public opposition to opening new landfills is growing, resulting in measures targeted at reducing MSW disposal at landfills.

Municipalities may respond to these growing issues and problems by considering different management programs. Diversion from landfills will save landfill space and will prolong the life of landfills. Decreasing the amount of MSW disposed in landfills will likely reduce emissions such as methane and leachate that are generated at landfills. Recycling of materials will likely save energy and environmental emissions by avoiding the extraction and use of virgin materials. Combustion and composting will divert MSW from going to landfills. Lately environmental issues are becoming more important in defining new policies. Therefore, environmental management authorities may need to examine the effect of environmental implications of MSWM. For example, to support a national goal of reducing emissions of gases with high global warming potential, a municipality may be required to identify cost-effective solid waste management (SWM) strategies that have lower levels of green house gas emissions.

The challenge facing the municipalities is in identifying cost-effective MSWM strategies to meet local goals and needs. Many communities and local regulatory agencies are responding to these MSWM issues by considering a variety of proactive plans and MSWM strategies, including voluntary and mandatory recycling programs, source reduction programs and alternative waste processing options. The specific goals and objectives of each community for implementing these plans depend on the local, site-specific conditions and issues. For instance, a community facing an existing or imminent landfill space crisis may set a goal to reduce the amount of waste sent to landfill disposal, and in response may consider the following options: source reduction; waste diversion through recycling; and an alternative waste disposal option such as waste combustion. The most appropriate choice, however, is not very clear. For instance, if the recycling markets are low in that community, then a recycling program may not be as economical as one of the other options. Alternatively, if the community is currently recovering most of the combustible waste items as recyclable material, then adding a waste-to-energy facility may not be the most efficient choice. Further, the overall environmental benefit of an SWM strategy is not explicitly understood. For example, recycling effort, in general, is known to reduce consumption of natural resources and save some processing activities at manufacturing facilities. It is not clear however, whether these savings truly offset the environmental harm that may be caused by the additional waste handling activities (such as collection truck operation and energy consumption at waste recovery facilities) associated with an SWM strategy. Therefore, the net benefit, if any, of alternative SWM strategies on the environment is not well characterized. In the absence of this knowledge, making economically and environmentally beneficial choices from among a large number of SWM strategies becomes difficult.

Municipalities are currently lacking appropriate tools and procedures to examine systematically a large number of SWM strategies and identify efficient alternatives to meet their goals and site-specific conditions. The primary objective of this research is to develop and demonstrate a quantitative procedure and a modeling framework for integrated solid waste management (ISWM). This model is a linear programming (LP) model that incorporates cost and environmental information associated with MSWM activities. The mathematical development of this model is described in Chapter 2, which is an extension of earlier efforts by Solano (1996) and Kaneko (1994). Several mathematical models have been defined in the past in an attempt to study an integrated

MSW management system, but none have incorporated as many MSWM components and a comprehensive environmental characterization in a integrated manner as the present model.

The environmental burdens are characterized using a life cycle methodology. This is founded on the Life Cycle Assessment (LCA) framework. LCA can be used to estimate the overall environmental impact of a product during its entire life. It is a concept established by the Society of Environmental Toxicology and Chemistry (SETAC) in 1990 and its structure contains three separate but interrelated components: life cycle inventory (LCI), life cycle impact analysis and life cycle improvement analysis. LCI studies consist of the quantification of the energy and raw material inputs and environmental releases associated with each stage of production. Most of the published LCA studies (Shapiro, 1993; and Unweltbundesamt, 1996) are focussed on packaging materials. Sauer *et al.* (1994) performed a life cycle inventory for children's diaper systems. Kirkpatrick (1993), Boguski *et al.* (1993), Baumann and Rydberg (1994), and Barton *et al*. (1996) discuss the use of an LCA framework in analyzing solid waste management.

It is possible to treat each waste component of the MSW stream as a separate material undergoing a series of processes, such as collection, separation, treatment, disposal and remanufacturing, that constitute a MSW management alternative. Within each process, an LCI of a pollutant associated with the quantity of waste processed can be established. For instance, at a combustion facility, the net energy and raw material consumption and the associated emissions resulting from combusting a ton of waste (with known composition) can be estimated. Further, the contribution by individual waste items to the LCI can be estimated based on appropriate allocation schemes. It is possible then to quantify the energy and raw material consumption and the environmental releases associated with a given MSW management strategy.

This approach facilitates the evaluation and comparison of alternative MSW management strategies where each strategy is defined by a set of active process options, flow of waste items through these options, and the set of waste items recovered for recycling. The evaluation of a strategy can be carried out based on cost, energy consumption, and emissions of CO, CO_2 (fossil), CO_2 (biomass), NO_x, SO_x, particulate matter, particulate matter (PM_{10}), and greenhouse gases. The mathematical model represents all feasible MSW management strategies for a given MSW system. Solution of this model using an LP solver provides a mechanism for a systematic search through these feasible alternatives.

The applicability of the ISWM model is demonstrated through a series of MSWM scenarios that are typically faced by most municipalities in the US. The ISWM model was used to represent these scenarios in the context of hypothetical, but realistic case studies. The first illustrative case study presented in Chapter 3 is used to analyze several diversion scenarios and to examine the tradeoff between cost and an environmental criterion. Further, the ISWM model was used to generate different alternative strategies using the modeling to generate (MGA) (Brill *et al.*, 1990) approach. In Chapter 4, the ISWM model was applied to examine SWM strategies for different MSW management programs that are typically considered by municipalities in the US. Their effectiveness in achieving different SWM policy goals, namely, maximizing resource recovery, minimizing landfill utilization and minimizing environmental emissions, were also evaluated. Using the ISWM model, a number of alternative strategies were generated and the range of effectiveness of an SWM program on these policy goals was also computed. Through these illustrative applications, the power and flexibility of the ISWM model in studying site-specific MSW management issues is demonstrated.

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Chapter 2: Integrated Solid Waste Management Using a Life-Cycle Methodology for Considering Cost, Energy, and Environmental Emissions – 1. A Mathematical Model

2.1 Introduction

Management of municipal solid waste (MSW), an integral and inevitable consequence of most human activities, is getting increased attention at national and local levels. Many communities and local regulatory agencies are responding by considering a variety of proactive solid waste management (SWM) strategies, including voluntary and mandatory recycling programs, source reduction programs and alternative waste processing options. The specific goals and objectives of each community for implementing SWM plans depend on site-specific conditions and issues. For instance, a community facing a landfill space crisis may set a goal to reduce the amount of waste sent to landfill disposal and may consider source reduction, waste diversion through recycling, and volume reduction alternatives such as converting waste to energy. The most appropriate choice, however, is often not clear. For instance, if the market prices of recyclable materials are low, then a recycling program may not be as economical as one of the other options. Alternatively, if the community is currently recovering most of the combustible waste items as recyclable material, then adding a waste-to-energy facility may not be the most efficient choice. Further, the overall environmental benefit of an SWM strategy is not explicitly understood. For example, a recycling effort, in general, is known to reduce consumption of natural resources and save some processing activities at manufacturing facilities. It is not clear, however, whether these savings truly offset the environmental burdens associated with the additional collection activities as well as energy consumption at waste recovery facilities associated with recycling. Typically, the net benefit, if any, of each SWM alternative to the environment is not well characterized, making it difficult to select an environmentally beneficial choice.

Several modeling studies addressing individual unit processes for MSW management have been reported. They include modeling studies for: collection processes by Chang *et al.* (1997b), Esmaili (1972), and Liebman *et al.* (1975); recyclable material recovery facilities by Lund *et al.* (1994); and landfill operations by Lund (1990), Jacobs and Everett (1992), and Kaneko (1995). Studies by Milke and Aceves (1989) and Diamadopoulos *et al.* (1995) focused only on recycling programs. Each study primarily examined a unit process with limited or no interactions with others. Some studies have also considered some interactions among a limited set of unit processes (Hasit and Warner (1981), Gottinger (1988), Movassaghi (1993), Hsieh and Ho (1993), Chang *et al.* (1993), Chang and Wang (1996, 1997a and 1997b), Chang *et al.* (1996, 1997a), Chang and Lu (1997), Ferrel and Hizlan (1997), Karagiannidis and Mousiopoulos (1997), Huang *et al.* (1997), Huang and Baetz (1997) and Hokkanen and Salminen (1997)).

More recently, studies to examine integrated MSW management options that do consider interactions among unit processes have been reported. In these studies, the waste flows are either allocated a priori among the unit operations or chosen based on cost considerations. Examples of such studies include those by Kaneko (1995), Barlaz *et al.* (1995), Ranjithan *et al.* (1995), Solano (1996), Barlishen and Baetz (1996), Ferrel and Hizlan (1997), and Kosmicki (1997a). Several researchers have reported studies considering environmental implications of MSW management. In general, the environmental factors were characterized, at different degrees of detail, by the emissions associated with the waste handling activities. For example, the work reported by Chang et al. (1993; 1996) and Chang and Wang (1996; 1997a) considered the emissions of certain air pollutants from collection vehicles, but did not consider the emissions of the same pollutants from other activities, such as fuel combustion in rolling-stock, generation of electricity used in waste processing facilities, or emissions off-sets associated with the amount of electricity replaced by that generated at a waste-to-energy facility. Similarly, Chang and Lu (1997), Karagiannidis and Mousiopoulos (1997), and Hokkanen and Salminen (1997) presented studies that included limited environmental considerations.

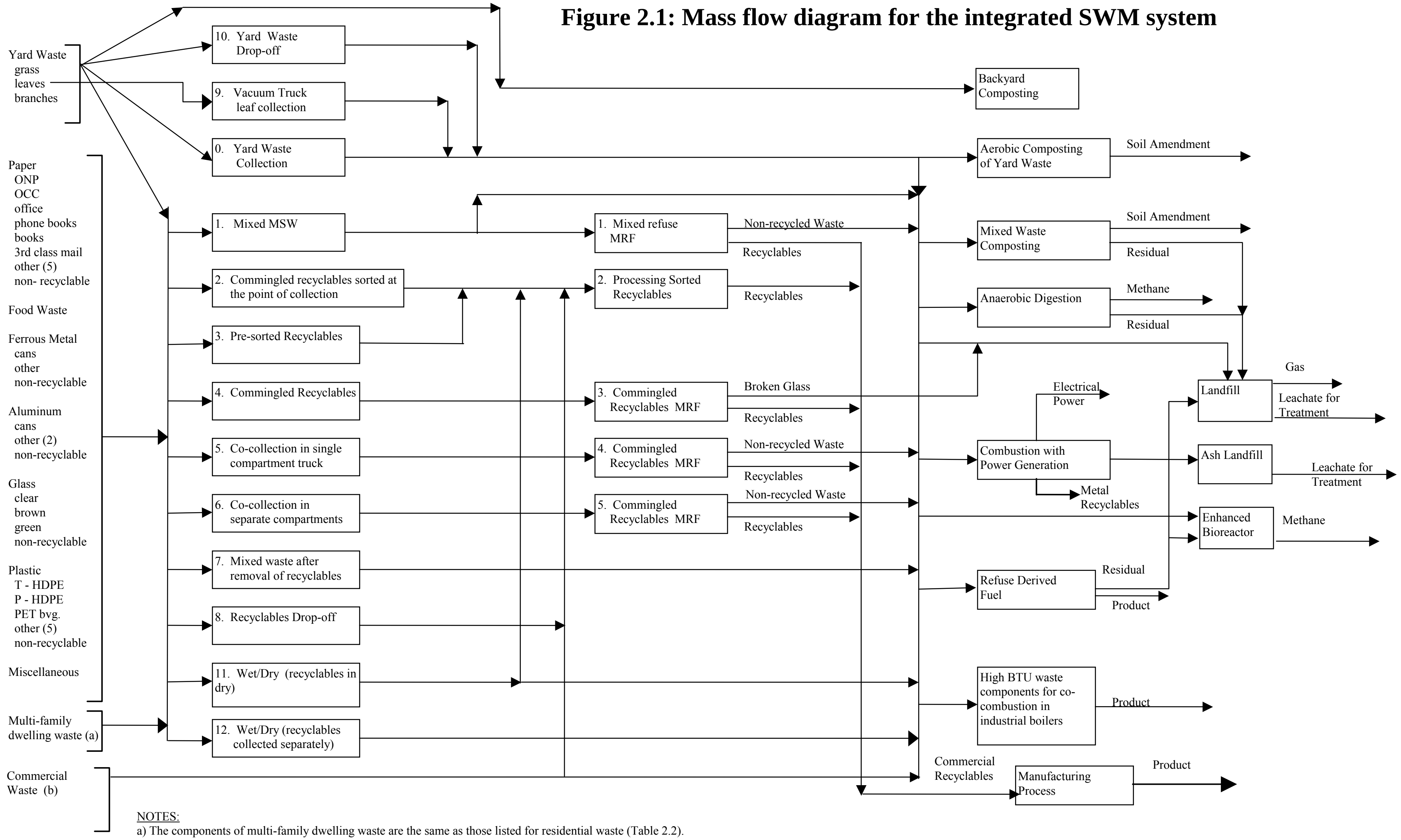
Lately, several researchers have adopted a life-cycle methodology to characterize environmental considerations with respect to an array of pollutants. Powell et al. (1996) and Powell (1997) described a procedure to evaluate the environmental implications for an MSW management strategy. The unit processes and mass flows in the SWM strategy are specified a priori by the user and are not selected by the procedure. Alternatively, Ljunggren and Sundberg (1996; 1997) reported a mathematical programming-based approach to determine the optimal MSW management strategy with respect to cost and environmental objectives. The environmental objective was characterized using an empirical, life-cycle methodology. The solution of the underlying model, however, requires the use of a nonlinear programming procedure, which is highly sensitive to the starting solution and the size of the model.

Linear programming (LP) models have been shown to be applicable for cases where not many combinations of waste flow paths are present (Solano, 1996). However, when considering a larger number of unit operations with numerous combinations of waste flow paths, the mathematical equations to maintain a mass balance become nonlinear. Since waste can flow from a facility to multiple downstream facilities, the waste items may be sent selectively to each facility. For example, after recovering recyclables from mixed waste at a material recovery facility (MRF), it is desirable to send only the high heat content items in the residual waste stream to a combustion facility so that the most amount of energy could be generated, and to send the remaining items to a landfill. However, such separation will not take place at typical processing facilities. Mass balance equations can be introduced to avoid this artificial waste flow splitting. As simple implementations of these equations result in a set of nonlinear equations, a special and unique modeling approach to maintain linearity is used in the model presented in this paper.

This paper presents an LP-based decision model designed to aid in identifying environmentally and economically efficient strategies for integrated MSW management. The economic and environmental burdens associated with SWM are estimated using a life cycle methodology implemented using a set of unit process models (Weitz et al., 1999; http://www.rti.org/units/ese/p2/lca.cfm#life). This mathematical modeling framework can be used to represent a wide range of MSW unit processes and their interrelationships (Figure 2.1), to characterize the major activities that take place within each unit process, to estimate the economic and environmental factors associated with each unit process, and to identify efficient SWM strategies. The life-cycle inventory (LCI) of a total of 32 environmental parameters is tracked at all MSW unit processes defined below. Cost and nine environmental parameters (CO, CO_2 (biomass derived), CO_2 (fossil fuel derived), NO_x, SO_x, total particulate matter (PM), particulate matter of size less than 10 microns (PM_{10}), greenhouse gas equivalents, and energy consumption) can be either optimized individually or constrained to meet specified targets. The integrated solid waste management (ISWM) model is designed such that it will represent a site-specific system, incorporating local issues and restrictions based on information provided by individual users. The size of this model, which varies depending on the MSW system, is on the order of 10,000 decision variables and as many constraints.

An illustrative example is used to describe the features and capabilities of the model. The second part of this two-part paper (Solano et al., 1999) discusses applications of the ISWM model and presents more extensive case studies.

Figure 2.1: Mass flow diagram for the integrated SWM system



NOTES:
a) The components of multi-family dwelling waste are the same as those listed for residential waste (Table 2.2).
b) The components of commercial waste are given in Table 2.2. Collection options for commercial waste are not shown but are analogous to options 1 and 3.
*Transfer stations (truck and rail) are not shown due to space limitations. They are included in Table 2.1b.

2.2 Problem Description and Terminology

The functional elements of a waste management system include collection and transport, recyclable material recovery, treatment of waste prior to final disposal, and disposal in a landfill. For each of these activities, there are a number of alternative unit processes. For example, there are a number of options that can be used to collect MSW including the collection of mixed waste or the separate collection of yardwaste, commingled recyclables and the residual MSW. Of course, different types of separation or material recovery facilities will be required based on the manner in which waste is collected. A complete list of the unit processes considered in the model is presented in Table 2.1.

Table 2.1a: Unit processes for waste management activities: Collection

Unit Process	**Code**
1. Residential sector	
Collection of yard trimmings for aerobic composting	C0
Collection of mixed waste	C1
Collection of commingled recyclables sorted at the point of collection by the collection crew	C2
Collection of pre-sorted recyclables	C3
Collection of commingled recyclables sorted at a MRF with old newsprint (ONP) in a separate compartment	C4
Collection of commingled recyclables and mixed waste (bagged separately) in a single compartment truck	C5
Collection of commingled recyclables and mixed waste (bagged separately) in a two compartment truck	C6
Collection of mixed waste after removal of recyclables or yardwaste	C7
Recyclables drop-off by the generator	C8r
Collection of leaves using a vacuum truck	C9
Yard trimming drop-off by the generator	C10
Collection of wet/dry components and commingled recyclables in separate compartments	C11
Collection of wet/dry components in separate compartments after collection of recyclables by C2, C3 or C4	C12
2. Multi-family sector	
Recyclables drop-off by the generator	C8m
Collection of mixed waste in one truck	C13
Collection of pre-sorted recyclables in multiple bins	C14
Collection of ONP and other commingled recyclables in two bins	C15
Collection of mixed waste after removing recyclables through C14 or C15	C16
Collection of wet/dry components and commingled recyclables in separate compartments	C17
Collection of wet/dry components in separate compartments after collection of commingled recyclables by C14 or C15	C18
3. Commercial sector	
Collection of pre-sorted recyclables	C19
Collection of mixed waste before or after recyclables removal	C20

Table 2.1b: Unit processes for waste management activities: Transfer

Unit Process	Code
Transfer of mixed waste	TR1
Transfer of commingled recyclables	TR2
Transfer of both mixed waste and sorted recyclables coming in separate bags and collected in a single-compartment truck	TR3
Transfer of both mixed waste and sorted recyclables coming in separate bags and collected in a two-compartment truck	TR4
Transfer of pre-sorted recyclables	TR5
Transfer of MSW onto trains at transfer station	RT1
Transfer of mixed waste from trains to vehicles that transport MSW to a traditional landfill	RT2
Transfer of mixed waste from trains to vehicles that transport MSW to an enhanced decomposition landfill	RT3

Table 2.1c: Unit processes for waste management activities: Separation

Unit Process	Code
MRF to process mixed refuse coming from mixed waste collection options (C1, C13), residual collection options (C7, C16) and wet/dry collection options (C11, C12, C17, C18)	S1
MRF to process pre-sorted recyclables collected through C2, C3, C14 or dropped off by the generator (C8)	S2
MRF to process commingled recyclables collected through commingled recyclables collection options C4, C15 or wet/dry options C11, C17	S3
MRF to process commingled recyclables collected by C5	S4
MRF to process commingled recyclables collected by C6	S5

Table 2.1d: Unit processes for waste management activities: Treatment

Unit Process	Code
Aerobic composting of yardwaste in a centralized facility	T1
Combustion	T3
Refuse derived fuel for combustion	T5
Mixed waste composting	T7

Table 2.1e: Unit processes for waste management activities: Disposal

Unit Process	Code
Traditional landfill	D1
Ash monofill	D2
Enhanced decomposition landfill	D3

The MSW system includes three types of sectors: residential, multifamily and commercial, and the collection unit processes are categorized by these generation sectors (Table 2.1a). Transfer stations, a central facility at which collected refuse is consolidated for more efficient transportation are also included. Transfer station alternatives were designed to receive waste from separate collection alternatives (Table 2.1b). Similarly, each MRF design is dependent upon the manner in which refuse is collected and delivered to that MRF (Table 2.1c). For instance, a MRF for processing presorted recyclables (S2) will require less sorting than a MRF for processing mixed waste (S1).

The waste treatment facilities considered each have the potential to generate a product, such as energy or compost, and will reduce the mass of the waste to be buried in a landfill (Table 2.1d). Finally, three landfills were considered including a traditional landfill operated to minimize water infiltration, an ash landfill to receive combustion ash only, and a landfill operated to enhance decomposition (Table 2.1e).

The generation of MSW is categorized by sector. This categorization is necessary to represent the different waste generation rates and waste compositions for each sector. Further, each community may have a unique mix of these sectors, and the waste from each sector may be handled differently. The waste compositions and generation rates are annual average values. MSW is divided into 48 components (USEPA, 1997) as shown in Table 2.2. This table indicates which items are applicable in each sector. For example, residential sectors include 42 items and the commercial sectors include 24 items. Sixteen of the items in Table 2.2 may be defined by the user for additional flexibility.

The ISWM model described here considers MSW from curbside through final disposal or conversion to a set of useful products. For instance, depending on the SWM strategy, old newsprint set out at the curbside can be: 1) buried in a landfill; 2) recovered as a recyclable and sent to a remanufacturing facility; 3) burned in a waste-to-energy facility where its BTU content can be recovered as electricity and the ash generated will be buried in a monofill; 4) decomposed in a mixed waste composting facility where it will become part of the compost produced; or 5) converted to refuse derived fuel (RDF) and used for energy. Similarly, each waste item can be processed by a large number of combinations of unit processes. Figure 2.1 shows a diagram of all possible flow paths of the different waste items through the SWM system, which includes all the waste processing options described above. The interrelationships among the different options are implicitly represented in this figure.

The primary use of the ISWM model is to explore and evaluate the numerous SWM strategies that are feasible for the integrated SWM system represented in Figure 2.1 and to identify alternatives that are economically and environmentally efficient. Each SWM strategy is defined by a set of appropriate unit processes and the amounts of each waste item processed in each unit process. The components and terminology used to describe the ISWM model are discussed in the following subsections.

Table 2.2: Waste composition by sectors

Item	Abbreviation	Residential		Commercial
		Single Family	Multi-Family	
Yard Trimmings, Leaves	YTL	√ (1)	√ (1)	N/A
Yard Trimmings, Grass	YTG	√	√	N/A
Yard Trimmings, Branches	YTB	√	√	N/A
Old Newsprint	ONP	√	√	√
Old Corrugated Cardboard	OCC	√	√	√
Office Paper	OFF	√	√	√
Phone Books	PBK	√	√	√
Books	BOOK	√	√	N/A
Old Magazines	OMG	√	√	N/A
3rd Class Mail	MAIL	√	√	√
Paper Other #1	PAOT1	√	√	√
Paper Other #2	PAOT2	√	√	√
Paper Other #3	PAOT3	√	√	√
Paper Other #4	PAOT4	√	√	N/A
Paper Other #5	PAOT5	√	√	N/A
CCCR Other (2)	CCR_O	N/A	N/A	√
Mixed Paper	PMIX	√	√	√
HDPE - Translucent	HDT	√	√	N/A
HDPE - Pigmented	HDP	√	√	N/A
PET Beverage Containers	PPET	√	√	√
Plastic - Other #1	PLOT1	√	√	N/A
Plastic - Other #2	PLOT2	√	√	N/A
Plastic - Other #3	PLOT3	√	√	N/A
Plastic - Other #4	PLOT4	√	√	N/A
Plastic - Other #5	PLOT5	√	√	N/A
Mixed Plastic	PLMIX	√	√	√
CCNR Other (3)	CNR_O	N/A	N/A	√
Ferrous Cans	FCAN	√	√	√
Ferrous Metal - Other	FMOT	√	√	√
Aluminum Cans	ACAN	√	√	√
Aluminum - Other #1	ALOT1	√	√	N/A
Aluminum - Other #2	ALOT2	√	√	N/A
Glass - Clear	GCLR	√	√	√
Glass - Brown	GBRN	√	√	√
Glass - Green	GGRN	√	√	√
Mixed Glass	GMIX	√	√	√
CNNR Other (4)	NNR_O	N/A	N/A	√
Paper - Non-recyclable	PANR	√	√	N/A
Food Waste	FW	√	√	N/A
CCCN Other (5)	CCN_O	N/A	N/A	√
Plastic - Non-Recyclable	PLNR	√	√	N/A
Miscellaneous (combustible) (6)	MIS_CNN	√	√	N/A
CCNN Other (7)	CNN_O	N/A	N/A	√
Ferrous - Non-recyclable	FNR	√	√	N/A
Al - Non-recyclable	ANR	√	√	N/A
Glass - Non-recyclable	GNR	√	√	N/A
Miscellaneous (8)	MIS_NNN	√	√	N/A
CNNN Other (9)	NNN_O	N/A	N/A	√

* denotes an item considered for recycling

Notes:

1. An item considered in a sector is indicated by a "√."
2. CCCR-Other represents commercial wastes that are combustible, compostable and recyclable.
3. CCNR-Other represents commercial wastes that are combustible, non-compostable and recyclable.
4. CNNR-Other represents commercial wastes that are non-combustible, non-compostable and recyclable.
5. CCCN-Other represents commercial wastes that are combustible, compostable and non- recyclable.
6. Miscellaneous-combustible represents wastes from the residential and multifamily sectors that are combustible but non-recyclable.
7. CCNN-Other represents commercial wastes that are combustible, non-compostable and non- recyclable.
8. Miscellaneous represents wastes from the residential and multifamily sectors that are non-combustible and non-recyclable.
9. CNNN-Other represents commercial wastes that are non-combustible, non-compostable and non- recyclable.

2.2.1 Collection Combinations

Combinations of collection unit processes are grouped to form "Collection Combinations" such that each combination can collect all of the waste generated by any portion of the population or generation sector. For example, a combination of yardwaste collection and residuals mixed waste collection can collect all waste generated. Another example is the combination of yardwaste collection, commingled recyclables collection and residuals mixed waste collection. In the first instance, all waste items not collected as yardwaste will be collected by the residuals mixed waste collection. In the second instance, the residuals mixed waste collection will collect all waste items not collected as yardwaste and recyclables. A collection combination including only commingled recyclables collection and yardwaste collection, however, could not collect all generated waste since there is no option available to collect non-recyclable and non-yardwaste items such as food waste. All alternative collection combinations composed of available collection unit processes are defined a priori. Examples of feasible collection combinations and the corresponding waste flow alternatives are shown in Table 2.3. The list of all collection combinations is shown in Table 2.4.

Table 2.3: Examples of collection combinations and waste flow alternatives

Collection Combination	Waste Flow Alternatives
Residential: Mixed waste collection (C1)	• Mixed waste collection to landfill (C1 → D1) • Mixed waste collection to combustion (C1 → T3 ➔ D2)
Residential: Commingled recyclables collection (C2), Residual mixed waste collection (C7)	• Commingled recyclables collection to pre-sorted recyclables MRF (C2 → S2) and residual mixed waste collection to landfill (C7 → D1) • Commingled recyclables collection to pre-sorted recyclables MRF (C2 → S2) and residual mixed waste collection to combustion (C7 → T3 ➔ D2)
Residential: Yardwaste collection (C0), Commingled recyclables collection (C2), Residual mixed waste collection (C7)	• Yardwaste collection to yardwaste composting (C0 → T1); commingled recyclables collection to pre-sorted recyclables MRF (C2 → S2) and residual mixed waste to landfill (C7 → D1) • Yardwaste collection to yardwaste composting (C0 → T1); commingled recyclables collection to pre-sorted recyclables MRF (C2 → S2) and residual mixed waste collection to combustion (C7 → T3 ➔ D2)
Residential: Yardwaste collection (C0), Pre-sorted recyclables collection (C3), Residual mixed waste collection (C7)	• Yardwaste collection to combustion (C0 → T3); pre-sorted recyclables collection to pre-sorted recyclables MRF (C3 → S2) and residual mixed waste collection to mixed waste MRF and then MRF residuals to landfill (C7 → S1 → D1) • Yardwaste collection to combustion (C0 → T3 ➔ D2); pre-sorted recyclables collection to pre-sorted recyclables MRF (C3 → S2) and residual mixed waste collection to mixed waste transfer station and then to landfill (C7 → TR1 → D1)
Multifamily: Recyclables drop-off collection (C8m), Residual mixed waste collection (C16)	• Recyclables drop-off collection to pre-sorted recyclables MRF (C8m → S2) and residual mixed waste collection (C16) to landfill (D1) • Recyclables drop-off collection to pre-sorted recyclables MRF (C8m → S2) and residual mixed waste collection (C16) to combustion (T3 ➔ D2)
Multifamily: Pre-sorted recyclables collection (C14), Residual mixed waste collection (C16)	• Pre-sorted recyclables collection to pre-sorted recyclables MRF (C14 → S2) and residual mixed waste collection (C16) to mixed waste transfer station and then to landfill (C16 → TR1 → D1) • Pre-sorted recyclables collection to pre-sorted recyclables MRF (C14 → S2) and residual mixed waste collection (C16) to mixed waste transfer station and then to combustion (C16 → TR1 → T3 ➔ D2)
Commercial: Commingled recyclables collection (C19), Residual mixed waste collection (C20)	• Commingled recyclables collection to pre-sorted recyclables MRF (C19 → S2) and residual mixed waste collection to landfill (C20 → D1) • Commingled recyclables collection to pre-sorted recyclables MRF (C19 → S2) and residual mixed waste collection to combustion (C20 → T3 ➔ D2)

Table 2.4: List of all collection combinations (a)

Sector Type	Collection Combination Option		
Residential	C1 C5 C6 C11 C12	C0 / C7 C2 / C7 C3 / C7 C4 / C7 C8r / C7 C10 / C7	C0 / C2 / C7 C0 / C3 / C7 C0 / C4 / C7 C0 / C8r / C7 C10 / C2 / C7 C10 / C3 / C7 C10 / C4 / C7 C10 / C8r / C7
Multifamily	C13 C17 C18	C8m / C16 C14 / C16 C15 / C16	
Commercial	C20	C19 / C20	

(a) The codes for the collection unit processes are defined in Table 2.1a.

2.2.2 Waste Flow Alternatives

Waste collected by each collection combination can flow through alternative transfer, separation, treatment and disposal options. Each waste flow alternative includes a set of unit processes to handle all waste collected by a specific collection combination. For example, a collection combination consisting of yardwaste and residuals mixed waste collection must be followed by waste flow alternatives to handle yardwaste (e.g., yardwaste composting) and mixed waste (e.g., combustion and ash landfill, dry landfill, RDF, mixed waste MRF, and mixed waste composting). For each available collection combination, a set of waste flow alternatives is defined. Examples of waste-flow alternatives for some collection combinations are shown in Table 2.3.

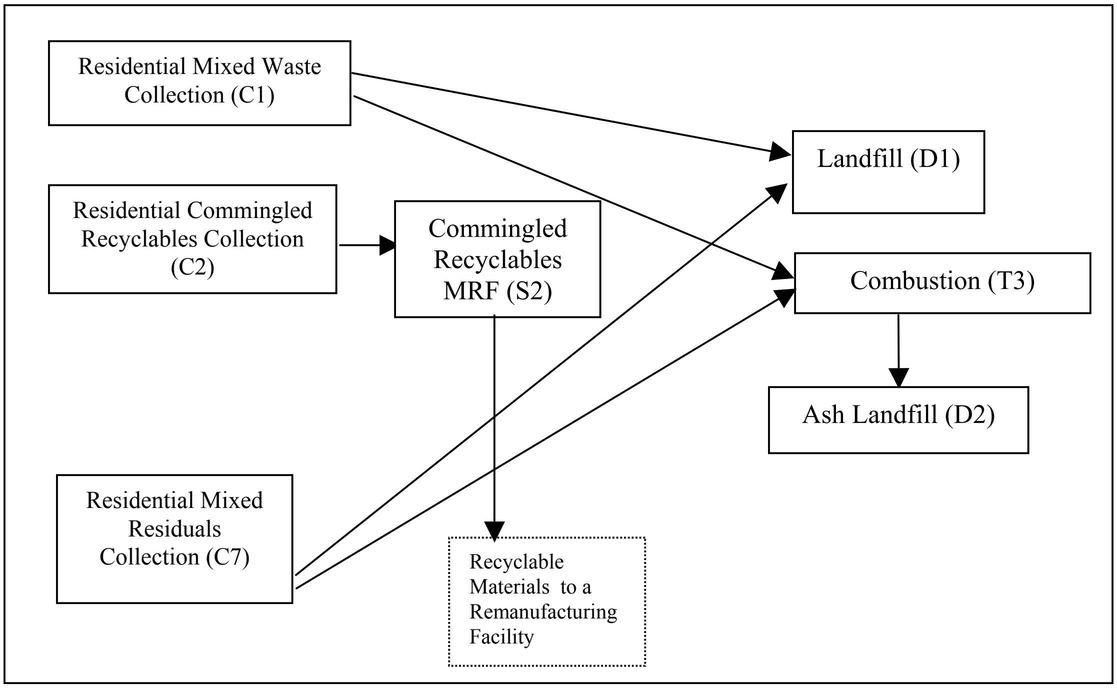
2.3 Conceptual Model Formulation

2.3.1 System Representation

The structure of the model and its formulation are described using a simple example consisting of the unit processes shown in Figure 2.2. The collection combinations (A1 and A2) and the waste flow alternatives (B11, B12, B21, and B22) for each collection combination used in this example are defined as follows:

A1 – mixed waste collection (C1);
A2 – commingled recyclables collection (C2) and residual mixed waste collection (C7);
B11 – mixed waste to landfill (C1 → D1);
B12 – mixed waste to combustion (C1 → T3 → D2);
B21 – commingled recyclables to pre-sorted recyclables MRF (C2 → S2) and residual mixed waste to landfill (C7 → D1);
B22 – commingled recyclables to pre-sorted recyclables MRF (C2 → S2) and residual mixed waste to combustion (C7 → T3 → D2).

Figure 2.2: Unit processes in the illustrative example



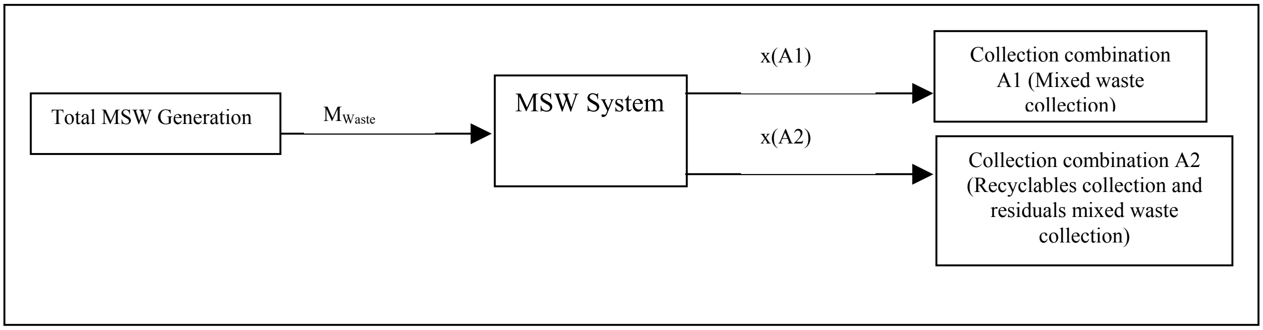
2.3.2 Mass Balance

Level 1

A variable is defined to represent the portion of the total mass of waste generated that is handled by each collection combination. In Figure 2.3, M_{Waste} represents the total mass of waste generated in tons/year, and x(A1) and x(A2) represent the portions (in tons/year) of M_{Waste} handled by collection combinations A1 and A2, respectively. The mass balance is then defined as:

$$x(A1) + x(A2) = M_{Waste} \quad \textbf{(Eq. 2.1)}$$

Figure 2.3: Mass balance for the MSW system



Level 2

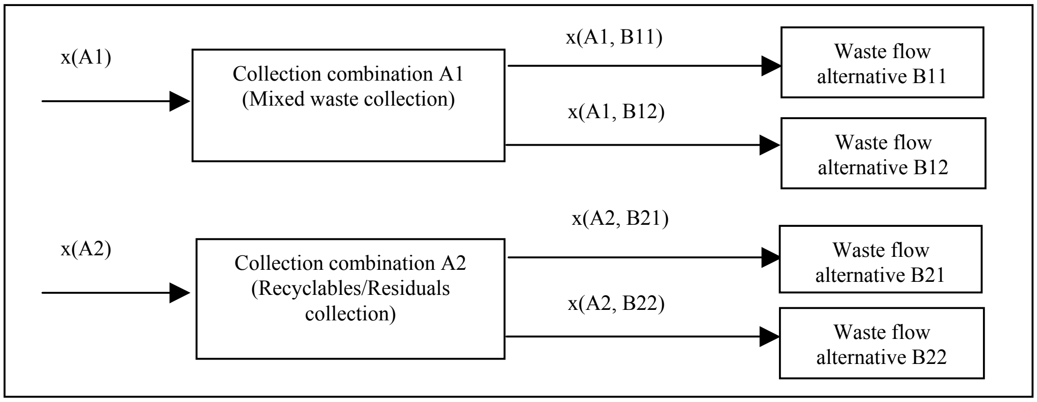
The mass entering a collection combination is then allocated to the different waste flow alternatives available for that collection combination. This mass allocation is shown in Figure 2.4 where x(A1) is allocated between waste flow alternatives B11 and B12 such that:

$$x(A1) = x(A1, B11) + x(A1, B12) \qquad \textbf{(Eq. 2.2)}$$

where x(A1, B11) is the mass portion of x(A1) handled by waste flow alternative B11 and x(A1, B12) is the mass portion of x(A1) handled by waste flow alternative B12. Similarly x(A2) is allocated between waste flow alternatives B21 and B22 such that:

$$x(A2) = x(A2, B21) + x(A1, B22) \qquad \textbf{(Eq. 2.3)}$$

Figure 2.4: Mass balances for collection combinations



Level 3

The mass allocated to a waste flow alternative is described in terms of mass portions associated with each waste item included in the waste stream. In this example, we assume that ONP and FW are the only two waste components in the waste stream. In Figure 2.5, the waste handled by the waste flow alternative B11, i.e., x(A1, B11), is shown as the sum of mass portions of waste items in the waste stream. The mass balance for this case is then written as:

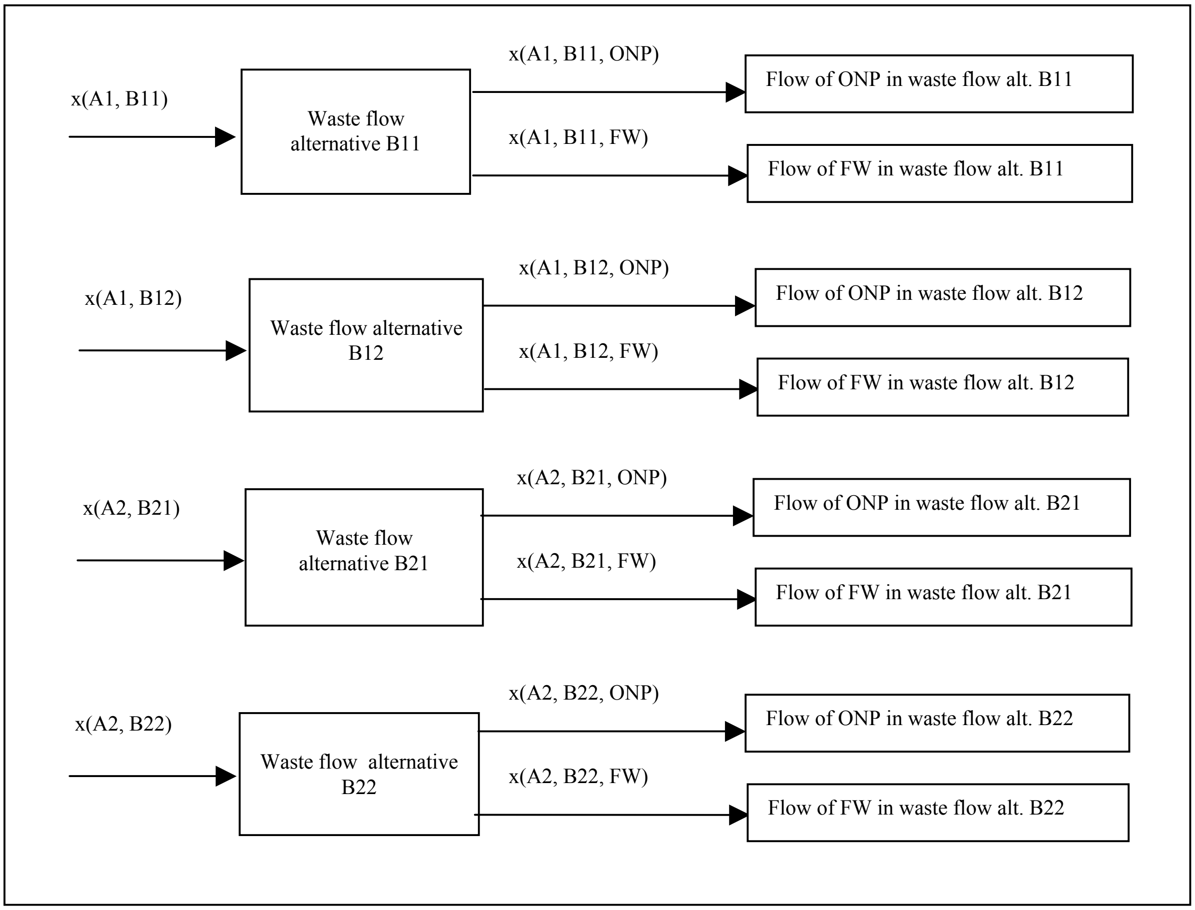
$$x(A1, B11) = x(A1, B11, ONP) + x(A1, B11, FW) \quad \textbf{(Eq. 2.4)}$$

where x(A1, B11, ONP) is the mass portion of waste item ONP handled by waste flow alternative B11 in collection combination A1, and x(A1, B11, FW) is the mass portion of waste item FW handled by waste flow alternative B11 in collection combination A1. Since each item is represented by a variable, different items may flow through different unit processes in the final solution.

Similarly, the mass balances for the other waste flow alternatives are represented as:

$$x(A1, B12) = x(A1, B12, ONP) + x(A1, B12, FW) \quad \textbf{(Eq. 2.5)}$$
$$x(A2, B21) = x(A2, B21, ONP) + x(A2, B21, FW) \quad \textbf{(Eq. 2.6)}$$
$$x(A2, B22) = x(A2, B22, ONP) + x(A2, B22, FW) \quad \textbf{(Eq. 2.7)}$$

Figure 2.5: Mass balances for waste flow alternatives



Level 4:

The mass of each waste item handled by a specific waste flow alternative is represented in terms of the mass portion of that item in each collection unit process used within that waste flow alternative. For instance, x(A1, B11, ONP), the mass of ONP handled by waste flow alternative B11, is allocated among all the collection unit processes used in that alternative. In B11, the only collection unit process used is the mixed waste collection (C1). Therefore, x(A1, B11, ONP) will be fully allocated to this collection unit process, resulting in the following equation:

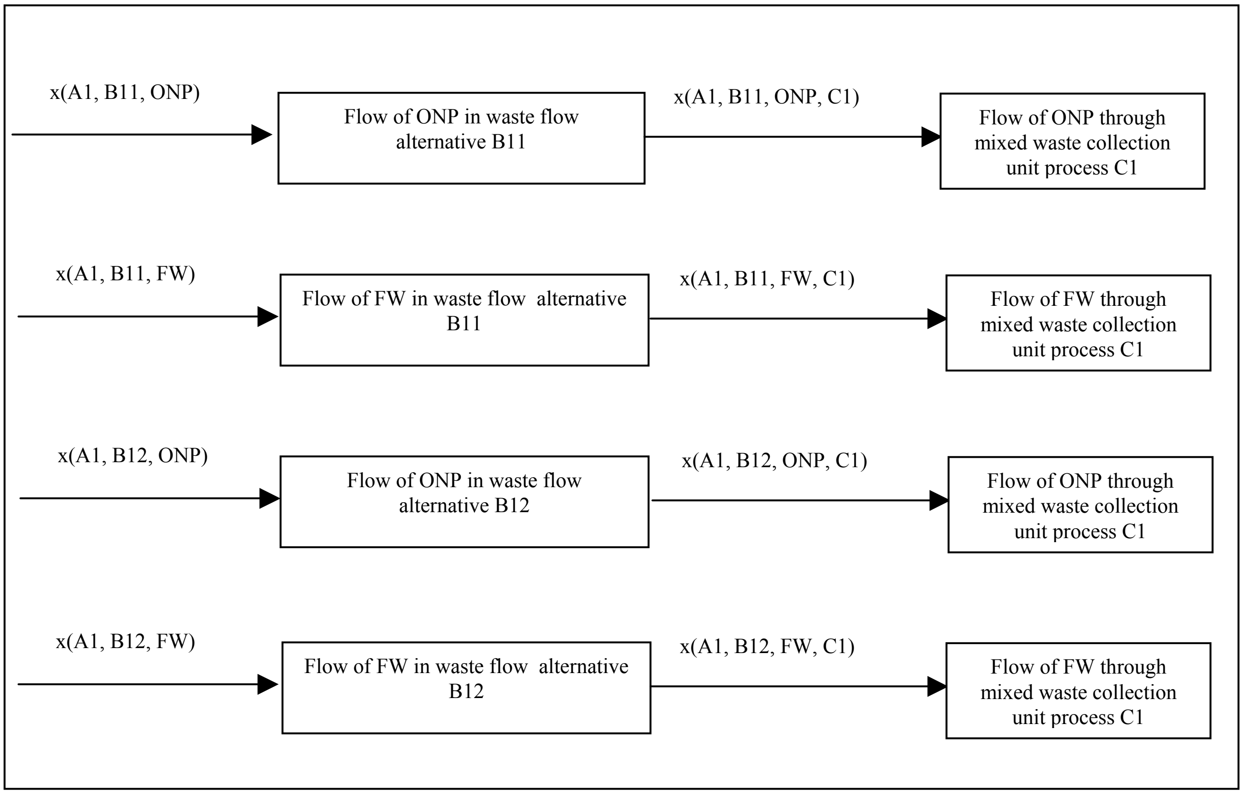
$$x(A1, B11, ONP) = x(A1, B11, ONP, C1) \qquad \textbf{(Eq. 2.8)}$$

where x(A1, B11, ONP, C1) is the mass portion of the waste item ONP handled by the collection unit process C1 within the waste flow alternative B11 in collection combination A1. Similarly, allocations of mass of all waste items in all other waste flow alternatives within collection combination A1 are represented by the following equations:

$$x(A1, B11, FW) = x(A1, B11, FW, C1) \qquad \textbf{(Eq. 2.9)}$$
$$x(A1, B12, ONP) = x(A1, B12, ONP, C1) \qquad \textbf{(Eq. 2.10)}$$
$$x(A1, B12, FW) = x(A1, B12, FW, C1) \qquad \textbf{(Eq. 2.11)}$$

The mass balances described by these equations for collection combination A1 are shown in Figure 2.6.

Figure 2.6: Mass balances for individual waste items handled in collection combination A1



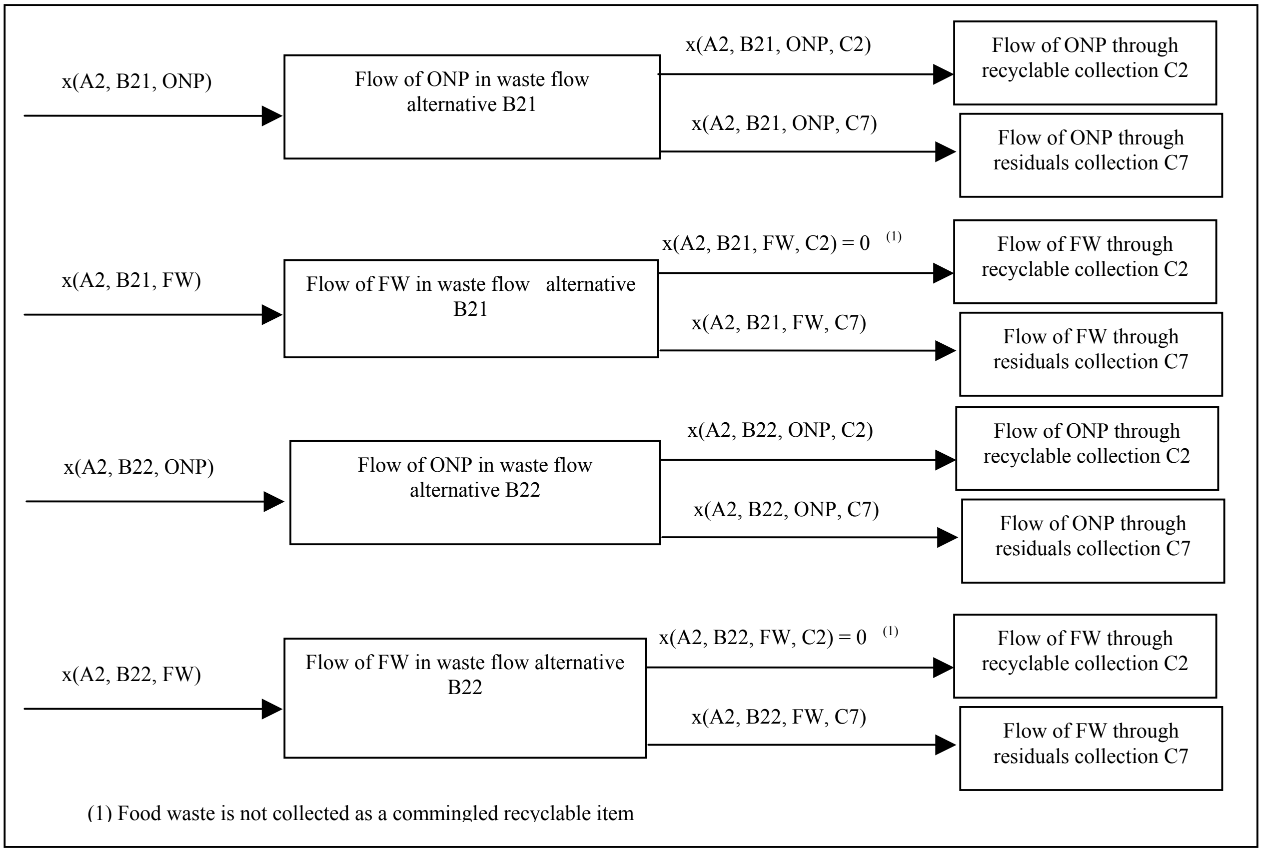
A similar set of equations exists for each collection combination. In the example, the mass portions of each waste item handled by collection combination A2 are allocated among all the collection unit processes (i.e., C2 and C7) in that collection combination. Consider the mass of ONP handled by the waste flow alternative B21 within collection combination A2. That mass of ONP can originate from both collection unit processes C2 and C7. In waste flow alternative B21, x(A2, B21, ONP, C2) represents the mass portion of ONP collected (as commingled recyclable) by collection unit operation C2 and x(A2, B21, ONP, C7) represents the mass portion of ONP collected (as residual mixed waste) by collection unit process C7. Then the mass balance for ONP handled by waste flow alternative B21 within collection combination A2 is represented by the following equation:

$$x(A2, B21, ONP) = x(A2, B21, ONP, C2) + x(A2, B21, ONP, C7) \quad \textbf{(Eq. 2.12)}$$

Similarly, mass balances for all waste items allocated among all available collection unit processes in each waste flow alternative within collection combination A2 are represented by the following equations and are shown in Figure 2.7.

$$x(A2, B21, FW) = x(A2, B21, FW, C2) + x(A2, B21, FW, C7) \quad \textbf{(Eq. 2.13)}$$
$$x(A2, B22, ONP) = x(A2, B22, ONP, C2) + x(A2, B22, ONP, C7) \quad \textbf{(Eq. 2.14)}$$
$$x(A2, B22, FW) = x(A2, B22, FW, C2) + x(A2, B22, FW, C7) \quad \textbf{(Eq. 2.15)}$$

Figure 2.7: Mass balances for individual waste items handled in collection combination A2



These mass balances are subject to other model constraints that ensure that waste flow is consistent with technically feasible alternatives. For example, since food waste is not recovered as a recyclable in a MRF, x(A2, B22, FW, C2) is zero. Similarly, the mass allocation of ONP between C2 and C7 is constrained by household capture rates and participation factors. The capture rate is the fraction of each recyclable component that a participating household actually separates for collection (or drop off) as a recyclable, while the participation factor is the fraction of households that set out recyclables for each collection cycle.

Level 5:

For each waste flow alternative, the mass portions entering the unit processes downstream of collection unit processes are described in terms of the mass collected by the corresponding collection unit process. For instance, the mass of ONP entering the combustion facility in waste flow alternative B12 within collection combination A1 (x(A1, B12, ONP, T3)) is equal to the mass of ONP collected by C1 corresponding to that waste flow alternative (x(A1, B12, ONP, C1)). Downstream of the combustion facility, the mass entering the ash landfill will be a function of mass of all waste items entering the combustion facility. The mass remaining after combustion is calculated as a function of the entering mass, the extent of combustion and a coefficient (Ψ) representing the item-specific ash content. These mass balances are illustrated in Figures 2.8 and 2.9.

Figure 2.8: Mass balances for waste handled by the collection unit processes in collection combination A1

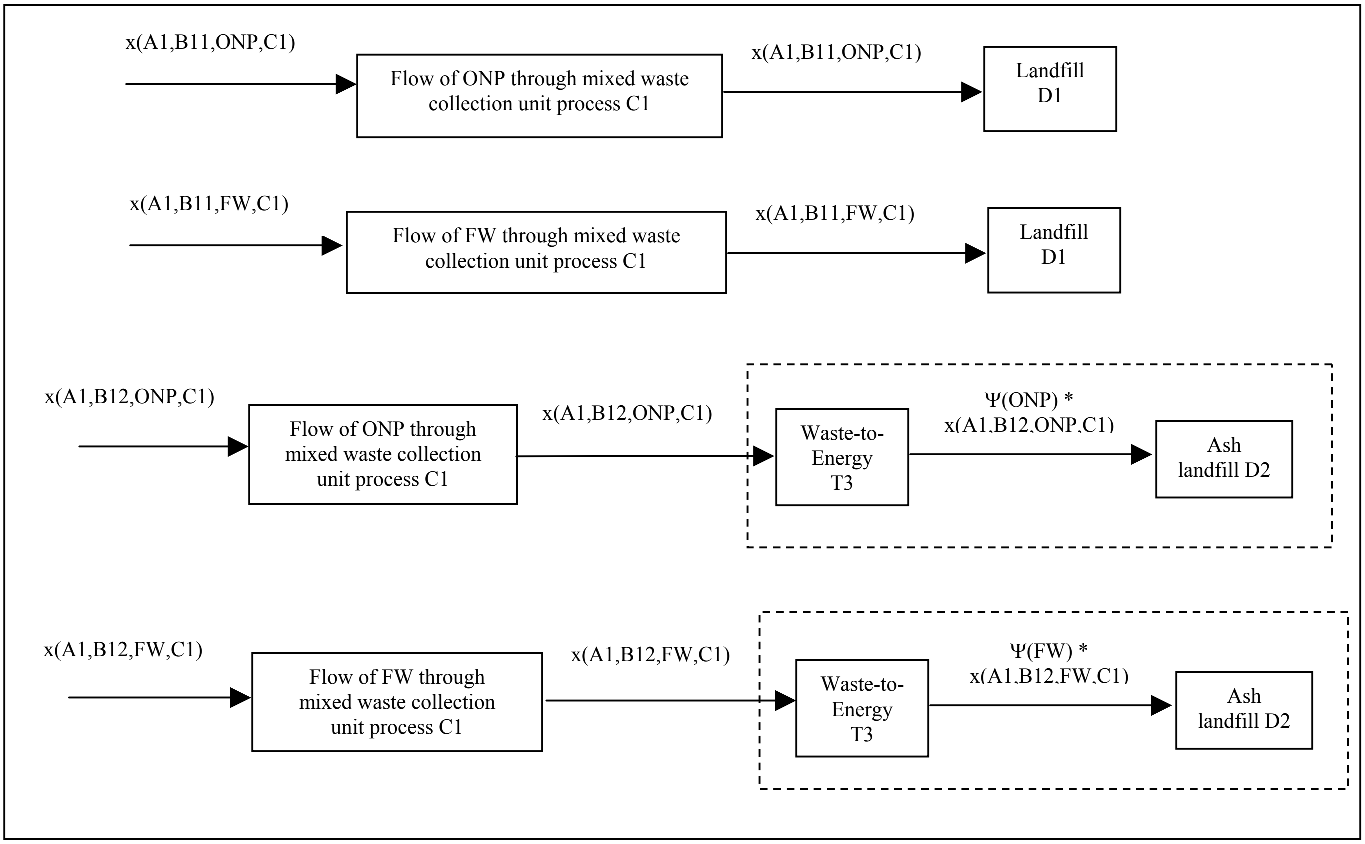
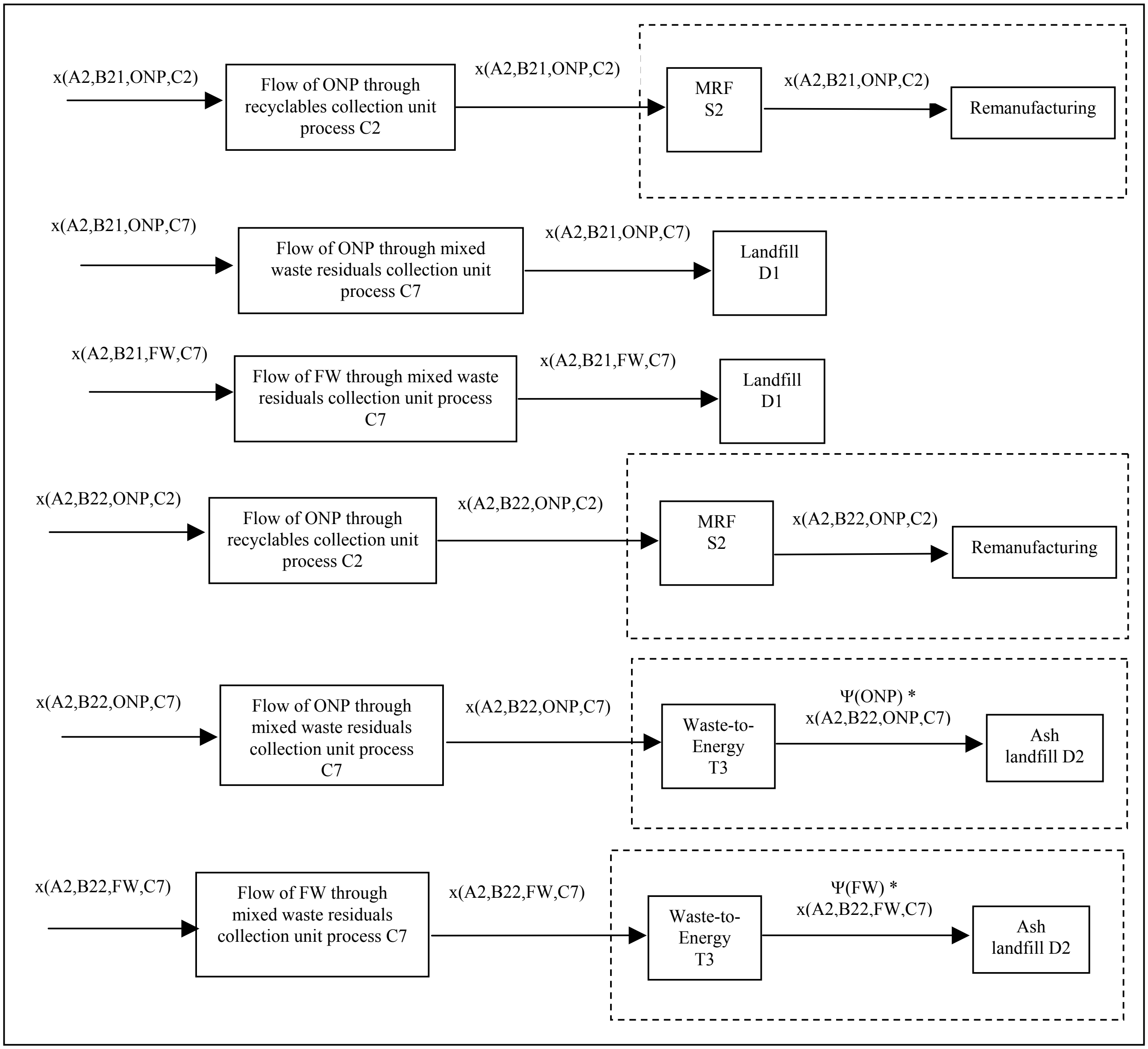


Figure 2.9: Mass balances for waste handled by the collection unit processes in collection combination A2



2.4 Mathematical Model Formulation

The conceptual model formulation described in the previous section is represented by a set of linear equations, which form the basis for a linear programming model. These linear equations enforce feasible mass flows of waste through the MSW system. Additional mathematical expressions are introduced to ensure that these feasible mass flows also meet other conditions, such as capacity restrictions at unit processes, minimum diversion requirements, and similar waste management goals. These feasible alternatives are then evaluated using an objective function, which represents either cost or the LCI for one of the nine environmental parameters. For example, an objective function could represent the net cost or SO_x emissions. Obtained through a search procedure, the solution to the LP model then identifies the alternative (i.e., the optimal solution) that gives the best value for the objective function. For example, SO_x emissions could be minimized.

The framework for formulating such an LP model is illustrated using the example described above. Although this example does not include all collection combinations and unit processes, the approach used to construct the equations for the example can be extended to construct the LP model for larger SWM systems. The LP model for the example includes 40 constraint equations and 40 variables, while the LP model for a system that would include every process option would have approximately 2.2 million constraints and 2.6 million decision variables. These numbers represent an upper bound on the size of the model. It is expected that a real system would not require that large a model since some options would not be considered.

Objective Functions

Two major types of objective functions are considered: minimization of cost and minimization of environmental emissions or energy consumption.

Cost Objective

The cost objective function is defined as follows.

$$\text{Net\_Cost} = \sum_{u \in U} \text{Cost}_u - \text{Revenue} \qquad \textbf{(Eq. 2.16)}$$

where:
Net_Cost is the net system cost (\$/year);
U is the set of unit processes: $U = C \cup S \cup T \cup D$;
C is the set of collection unit processes; in the example C = {C1, C2, C7};
S is the set of separation unit processes; in the example S = {S2};
T is the set of treatment unit processes; in the example T = {T3};
D is the set of disposal unit processes; in the example D = {D1, D2};
Cost_u is the total cost of unit process u (\$/year);
Revenue is from sales of recyclables (\$/year) as described in equation 2.18.

Unit process cost is defined as:

$$\text{Cost}_u = \sum_{k \in W} \alpha_{u,k} y_{u,k} \quad \forall\, u \in U \qquad \textbf{(Eq. 2.17)}$$

where:
$\alpha_{u,k}$ is the cost coefficient for processing waste item k at unit process u (\$/ton);
$y_{u,k}$ is the mass of waste item k processed by unit process u (tons/year);
W is the set of waste items: $W = WR \cup WN$, in which WR is the subset of recyclable waste items and WN in the subset of non-recyclable waste items. In the example: WR = {ONP} and WN = {FW}, representing old newsprint and food waste.

Revenue is defined as:

$$\text{Revenue} = \sum_{k \in WR} \lambda_k \sum_{s \in S} \delta_{s,k} y_{s,k} \qquad \textbf{(Eq. 2.18)}$$

where:
Revenue is the total revenue from the sale of recyclable materials (\$/year);
λ_k is the revenue coefficient for recyclable item k (\$/ton);
$\delta_{s,k}$ is the fraction of recyclable waste item k actually separated at the separation unit process s: $1 \geq \delta_{s,k} \geq 0$;

$y_{s,k}$ is the mass of recyclable item k processed at separation unit process s (tons/year);

$S = \{S2\}$, a MRF in the example.

The revenue associated with energy recovery at a combustion facility or landfill is accounted for within the cost coefficient $\alpha_{u,k}$ in equation 2.17.

Environmental Objective

The LCI values of the nine environmental parameters (CO, CO_2 (biomass derived), CO_2 (fossil fuel derived), NO_x, SO_x, PM, PM_{10}, greenhouse gas equivalents, and energy consumption) are calculated for each unit process by individual waste component. The emissions are expressed in terms of mass generated per year when processing a ton of a waste item per year in a unit process, and energy consumption is estimated in terms of BTU consumed per year when processing a ton of a waste item per year in a unit process. Using these parameters, an environmental emissions (or energy consumption) objective function is defined as follows.

$$\mathrm{LCI}(p) = \sum_{u \in U} \mathrm{LCI}(p)_u \qquad \textbf{(Eq. 2.19)}$$

where:

U is the set of unit processes;

$\mathrm{LCI}(p)_u$ is energy consumption or the net environmental emissions of pollutant p at unit process U.

$\mathrm{LCI}(p)_u$ is defined as

$$\mathrm{LCI}(p)_u = \sum_{k \in W} \xi(p)_{u,k}\, y_{u,k} \quad \forall\, u \in U \qquad \textbf{(Eq. 2.20)}$$

where:

$\xi(p)_{u,k}$ is the energy consumption or the emission of pollutant p per ton of waste item k processed in unit process u;

$y_{u,k}$ is the mass of waste item k processed by unit process u (tons/year).

While only one objective can be optimized at a time, the values of all environmental parameters and cost are obtained for each solution. Furthermore, constraints can be added on these functions to support a multi-objective analysis.

Constraints

Mass Flow Constraints

The mass flow constraints are defined by the following set of equations.

1) Mass flows in collection combinations

$$\sum_{i \in A} x_i = M_{Waste} \qquad \textbf{(Eq. 2.21)}$$

where:
M_{Waste} is the total mass of waste generated (tons/year);
x_i represents the mass handled by collection combination i (tons/year);
A is the set of collection combinations;
A= {A1, A2}; A1 = {C1} and A2 = {C2, C7} in the example.

2) Mass flows in waste flow alternatives within each collection combination

$$x_i = \sum_{j \in B_i} x_{i,j} \quad \forall\, i \in A \qquad \textbf{(Eq. 2.22)}$$

where:
B_i represents the set of waste flow alternatives that can be established within collection combination i;
In the example: $B_i = \{B_{A1}, B_{A2}\}$; $B_{A1} = \{B11, B12\}$ and $B_{A2} = \{B21, B22\}$;
$x_{i,j}$ represents the mass handled by waste flow alternative j within collection combination i (tons/year).

3) Mass flows for specific waste items

$$x_{i,j,k} = \beta_k\, x_{i,j} \quad \forall\, i \in A, \forall\, j \in B_i, \forall\, k \in W \qquad \textbf{(Eq. 2.23)}$$

where:

$$\sum_{k \in W} \beta_k = 1.0$$

$x_{i,j,k}$ represents the mass of waste item k flowing in waste flow alternative j within collection combination i (tons/year);

β_k is the percentage of waste stream composed of waste item k.

4) Mass flows for each waste item collected by a collection unit process in a collection combination

i) If the collection combination includes only a mixed waste collection unit process, then the total portion of mass of each waste item is allocated to that collection unit process.

$x_{i,j,k,m} = x_{i,j,k} \quad \forall\ i \in A, \forall\ j \in B_i, \forall\ k \in W$ **(Eq. 2.24)**

where:
m is the only mixed waste collection unit process within collection combination i;
$x_{i,j,k,m}$ is the mass of waste item k collected by collection unit process m and flowing through waste flow alternative j within collection combination i (tons/year).

ii) If the collection combination includes two complementary collection unit processes (e.g., a recyclables collection and residuals collections unit processes), then the portion of mass of each waste item collected through that collection combination is allocated between the two collection unit processes according to the following equations.

$x_{i,j,k,r} = \phi_{k,r}\ x_{i,j,k} \quad \forall\ i \in A, \forall\ j \in B_i, \forall\ k \in W$ **(Eq. 2.25)**

$x_{i,j,k,m} = x_{i,j,k} - x_{i,j,k,r} \quad \forall\ i \in A, \forall\ j \in B_i, \forall\ k \in W$ **(Eq. 2.26)**

where:
r is either a recyclables collection unit process or a yardwaste collection unit process within collection combination i;
m is the mixed waste collection unit process (for handling the residuals) within collection combination i;
$x_{i,j,k,r}$ is the mass of waste item k collected by collection unit process r and flowing through waste flow alternative j within collection combination i (tons/year)**;**
$x_{i,j,k,m}$ is the mass of waste item k collected by collection unit process m and flowing through waste flow alternative j within collection combination i (tons/year)**;**

$\phi_{k,r}$ the fraction of waste item k collected by collection unit process r, is defined as $\phi_{k,r} = 0$ if $k \in$ WN and $0 \leq \phi_{k,r} \leq 1$ if $k \in$ WR

5) Mass flows of waste items processed by each unit process

For each mixed waste collection unit process:

$$y_{u,\,k} = \sum_{i\in A} \sum_{j\in B_i} x_{i,\,j,\,k,\,m} \quad \forall\, m \in C, \forall\, k \in W \qquad \textbf{(Eq. 2.27)}$$

where:
$y_{u,k}$ is the mass of waste item k processed (tons/year) at unit process u = m;
C is the set of all available collection unit processes; for the example, C= {C1, C2, C7}.

For each recyclable or yardwaste collection unit process:

$$y_{u,\,k} = \sum_{i\in A} \sum_{j\in B_i} x_{i,\,j,\,k,\,r} \quad \forall\, r \in C, \forall\, k \in W \qquad \textbf{(Eq. 2.28)}$$

where:
$y_{u,k}$ is the mass of waste item k processed (tons/year) at unit process u = r;
C is the set of all available collection unit processes; for the example, C= {C1, C2, C7}.

For each separation, treatment or disposal unit process:

$$y_{u,\,k} = \sum_{i\in A} \sum_{j\in B_i} \sum_{m\in C} x_{i,\,j,\,k,\,m} + \sum_{i\in A} \sum_{j\in B_i} \sum_{r\in C} x_{i,\,j,\,k,\,r}$$

$$\forall\, u \in (S \cup T \cup D), \forall\, k \in W \qquad \textbf{(Eq. 2.29)}$$

where:
$y_{u,k}$ is the mass of waste item k processed at unit process u (tons/year);
u is a unit process in waste flow alternative B_i which contains collection unit process m and/or collection unit process r;
$S \cup T \cup D$ is the set of all unit processes except for collection unit processes; for the example, $S \cup T \cup D$ = {S2, T3, D1, D2};
C is the set of all available collection unit processes; for the example, C= {C1, C2, C7}.

Diversion constraint

Constraints to require diversion of a minimum amount of waste from the landfill can be included. Mass diverted may include waste recovered as recyclable materials, waste combusted for energy recovery, and waste diverted for composting. In the example, the diversion rate is determined by the sum of the mass of recycled material at S2 and the mass sent to combustion (T3).

$$\left(\sum_{k \in WR} \delta_{S2,k}\, y_{S2,k} + \sum_{k \in W} y_{T3,k} \right) \geq \theta_{diversion}\, M_{Waste} \qquad \textbf{(Eq. 2.30)}$$

where:
$\theta_{diversion}$ is the specified target diversion rate: $0 \leq \theta_{diversion} \leq 1$

2.5 Supporting Components for the ISWM Model

The large array of inputs to the ISWM model was obtained through a series of studies as part of a comprehensive program to develop the life-cycle methods for use in SWM. These studies included efforts to represent cost and environmental factors in terms of unit coefficients $\alpha_{u,k}$ and $\xi(p)_{u,k}$ that are used in equations 2.17 and 2.20. In addition, numerous other parameters, such as those describing the fractions ($\delta_{s,k}$) of items separated at a MRF, are needed. In total, several thousand coefficients are generated to form the ISWM model.

Process models were developed for each MSW unit process to relate the quantity and composition of waste entering a unit process to the cost, energy consumption and environmental emissions for that process. Each process model contains sufficient input parameters so that it can represent site-specific situations. For example, the process model for collection incorporates factors such as weekly collection frequency, collection vehicle capacity, number of crew members, and number of houses served at each stop. For each process model, methods were developed to allocate costs, energy, and environmental emissions to individual waste components. For example, since recovered glass is not baled, the cost and environmental emissions associated with the use of a baler at a MRF is not allocated to recovered glass. Process models for collection (Curtis and Dumas, 1998), waste transportation (Kosmicki, 1997b), transfer stations (Kosmicki, 1997c), combustion (Harrison *et al.*, 1999) and landfills (Sich and Barlaz, 1999) have been presented.

Economic factors are represented by the net cost of each strategy. Net cost includes the amortized capital cost of facilities and equipment; labor, operation and maintenance; and the revenues from sales of recyclable materials, products and energy associated with the facilities that are included in an SWM strategy. The LCI associated with an SWM strategy is estimated in terms of net environmental releases and energy consumption that result from activities associated with waste processing. For example, activities (such as collection vehicle operation) associated with a collection unit process result in the release of several exhaust pollutants as well as energy consumption. Similarly, operation of a waste-to-energy facility results in air emissions and net energy production. The calculation of the amounts of environmental releases of pollutants from the MSW unit processes is carried out using a life-cycle methodology (Weitz *et al.*, 1999; http://www.rti.org/units/ese/p2/lca.cfm#life).

The net savings in environmental releases and energy consumption realized at the manufacturing facilities that use recycled material instead of virgin materials are also required to evaluate an SWM strategy that recover recyclables. These savings are represented as the difference in the emission of an environmental parameter or energy consumption between the recycle-based manufacturing process and the production process utilizing virgin material. This value is negative when the process utilizing a recyclable material reduces the environmental emission or the energy consumption. This same concept is also applied to energy. Energy may be recovered during waste combustion or from the beneficial use of landfill gas. When energy is recovered, an equivalent amount of energy generated from fossil fuels and the corresponding emissions are avoided. A remanufacturing process model, developed for each recyclable material, and an electrical energy process model are used to compute environmental coefficients that are used to estimate net environmental releases and energy consumption (Dumas, 1998). The electrical process model also calculates emissions associated with electricity consumption in any part of the MSW management system based on the average regional fuel mix used for power generation.

2.6 Summary

This paper presents a comprehensive mathematical programming model for ISWM considering cost, energy, and environmental emissions. This model is formulated as a linear programming model that can be solved to identify an efficient SWM strategy, which is defined by a comprehensive set of unit processes and the amount of each waste item handled within those unit processes. The modeling approach is described using a small example problem. Illustrations of the use of this model for a more extensive case study are presented in the companion paper by Solano et al. (1999).

This model is intended for planning, or screening, purposes and there are limitations to the existing implementation. Once simplification, for instance, is that economies of scale cannot be represented. The model is implemented in an interactive decision support system (Harrison et al., 1999) to allow trial-and-error modifications, however, so that some experimentation with alternative solutions can be carried out. For instance, if a small and impractical size for a facility is selected in the model solution, then the model can be modified to eliminate that facility or to constrain it to be no smaller than a specified capacity. This trial-and-error capability allows a user to explore the effects of economies of scale. Similarly, other simplifications can be addressed to some degree by modifying constraints or parameters to examine an issue more closely. In addition, of course, more detailed procedures would be needed to produce the final design for actual implementation of an SWM system in any given case.

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Chapter 3: Integrated Solid Waste Management Using a Life-Cycle Methodology for Considering Cost, Energy, and Environmental Emissions – 2. Illustrative Applications

3.1 Introduction

Many municipalities around the country are faced with the responsibility of finding more efficient ways to manage municipal solid waste (MSW) while meeting both budget constraints and tighter environmental goals. There are multiple alternatives for the collection, treatment and disposal of MSW including collection of mixed waste together with or separate from recyclables and yard waste, materials recovery facilities (MRFs) for recyclables recovery, yard and mixed waste composting, combustion and landfills for MSW or the ash remaining after combustion. Given the large number of available options for MSW management, identifying solid waste management (SWM) strategies that meet economic and environmental goals is a complex task. The integrated solid waste management (ISWM) model described in the companion paper (Solano *et al.*, 1999) is designed to identify efficient SWM strategies that meet site-specific conditions and local planning goals. The ISWM model incorporates an array of planning objectives, including minimizing cost, energy consumption and emissions of an array of pollutants (e.g., CO, NO_x, particulate matter, and SO_x) and constraints for meeting targets for recycling and waste diversion from landfill disposal. Environmental emissions and energy consumption are evaluated using a life-cycle methodology to calculate the life cycle inventory (LCI) of complete SWM strategies.

The ISWM model incorporates over 40 unit processes that cover major activities associated with waste collection, transportation, separation, treatment and disposal. Wastes from three types of generation sectors are considered: single family residential (referred to as "residential"); multifamily residential (referred to as "multifamily"); and commercial. Waste composition is categorized using 48 separate waste items. The

ISWM model, which is structured as a linear programming (LP) model, varies in size depending on the MSW system. It has on the order of 10,000 decision variables and as many linear constraints. The constraints describe the mass flow of each waste item through each unit process, represent site-specific constraints, and evaluate the economic and environmental burdens of an SWM strategy. Solution of this model using the CPLEX® software package on an MS Windows-based PII-450 personal computer with 258 MB RAM takes 10 to 20 seconds. A strategy identified by the ISWM model specifies the set of waste processing options, the waste flow paths through them, the amount of each waste item processed at each processing facility, and the amount of each recyclable material recovered, if any, at the MRFs.

The purpose of this paper is to illustrate the use of the ISWM model for examining typical SWM scenarios for a realistic, but hypothetical case study. These scenarios examine SWM strategies that minimize both cost and greenhouse gas emissions, consider different diversion targets, and examine the tradeoff among these objectives. The use of the model to generate alternative strategies is also demonstrated.

3.2 Description of the Case Study

A hypothetical case representing an urban region of medium size was defined. Waste generation rates and compositions were categorized in three sectors: a residential sector, a multifamily sector and a commercial sector. The key parameters and waste composition that define this case are summarized in Tables 3.1 and 3.2. The MSW system definition also required specification of many other input parameters (e.g., distances between waste processing facilities, collection frequencies, level of participation of households in different collection programs) that are described elsewhere (Solano, 1999). The unit processes included in this case are listed in Table 3.3 and the combination of collection alternatives is specified in Table 3.4. These tables include only a partial list of all unit processes that can be considered in the ISWM model (Solano et al., 1999). Items that are considered for recycling are indicated in Table 3.1. Where an item is considered for recycling, an offset analysis was used. To quantify the LCI in the manufacturing step, the LCI was calculated as the difference in emissions between the manufacturing processes that rely on virgin and recycled material, and negative LCI values result when recycling is beneficial. A similar analysis is used to account for energy recovered from combustion or recovery of landfill gas for energy generation.

Table 3.1: Waste stream composition (by wet weight) (1)

Item	Abbreviation	Residential (%)	Multifamily (%)	Commercial (%)
Yard Trimmings, Leaves	YTL	5.6	5.6	N/A
Yard Trimmings, Grass	YTG	9.3	9.3	N/A
Yard Trimmings, Branches	YTB	3.7	3.7	N/A
Old Newsprint*	ONP	6.7	6.7	2.2
Old Corrugated Cardboard*	OCC	2.1	2.1	36.0
Office Paper*	OFF	1.3	1.3	7.2
Phone Books*	PBK	0.2	0.2	0.3
Books*	BOOK	0.9	0.9	N/A
Old Magazines*	OMG	1.7	1.7	N/A
3rd Class Mail*	MAIL	2.2	2.2	2.3
Paper - Non-recyclable	PNR	17.1	17.1	N/A
CCCR Other (2)	CCR_O	N/A	N/A	1.9
HDPE - Translucent*	HDT	0.4	0.4	N/A
HDPE - Pigmented*	HDP	0.5	0.5	N/A
PET Beverage Containers*	PPET	0.4	0.4	0.2
Plastic - Non-Recyclable	PLNR	9.9	9.9	N/A
CCNR Other (3)	CNR_O	N/A	N/A	4.1
Ferrous Cans*	FCAN	1.5	1.5	0.7
Ferrous - Non-recyclable	FNR	3.2	3.2	N/A
Aluminum Cans*	ACAN	0.9	0.9	0.4
Al - Non-recyclable	ANR	0.5	0.5	N/A
Glass - Clear*	GCLR	3.9	3.9	1.9
Glass - Brown*	GBRN	1.6	1.6	0.8
Glass - Green*	GGRN	1.0	1.0	0.5
Glass - Non-recyclable	GNR	0.7	0.7	N/A
CNNR Other (4)	NNR_O	N/A	N/A	2.4
Food Waste	FW	4.9	4.9	N/A
CCCN Other (5)	CCN_O	N/A	N/A	17.1
Miscellaneous combustible (6)	MIS_CNN	7.5	7.5	N/A
CCNN Other (7)	CNN_O	N/A	N/A	11.3
Miscellaneous (8)	MIS_NNN	12.3	12.3	N/A
CNNN Other (9)	NNN_O	N/A	N/A	10.7

* denotes an item considered for recycling in this case study

Notes:

(1) The waste composition was adopted from USEPA (1997).

(2) CCCR-Other represents commercial wastes that are combustible, compostable and recyclable.

(3) CCNR-Other represents commercial wastes that are combustible, non-compostable and recyclable.

(4) CNNR-Other represents commercial wastes that are non-combustible, non-compostable and recyclable.

(5) CCCN-Other represents commercial wastes that are combustible, compostable and non- recyclable.

(6) Miscellaneous-combustible represents wastes from the residential and multifamily sectors that are combustible but non-recyclable.

(7) CCNN-Other represents commercial wastes that are combustible, non-compostable and non- recyclable.

(8) Miscellaneous represents wastes from the residential and multifamily sectors that are non-combustible and non-recyclable.

(9) CNNN-Other represents commercial wastes that are non-combustible, non-compostable and non- recyclable.

Table 3.2: Solid waste generation data

Sector Name	Population	Residents per home	Units (1)	Waste generation (2)	Total generation (tons/year)
Residential	450,000	2.63	171,103	2.64	216,810
Multifamily	150,000	N/A	750	2.64	72,270
Commercial	N/A	N/A	2,000	3,700	192,400

(1) For the residential sectors: houses; for the multifamily sectors: storage points; for the commercial sector: commercial locations.

(2) Expressed in lbs/person/day for the Residential and Multifamily sectors and in lbs/location/week for the commercial sector.

Table 3.3: Unit processes included in the hypothetical case study

Process	Code	Description
Residential Collection	C0	Collection of yard trimmings for aerobic composting
	C1	Collection of mixed MSW in one truck prior to separation of any component
	C2	Collection of commingled recyclables (sorted at the point of collection by the collection crew)
	C3	Collection of pre-sorted recyclables
	C4	Collection of commingled recyclables (to be sorted at a MRF); ONP in separate compartment
	C7	Collection of mixed MSW after removal of recyclables or yard waste
	C8r	Recyclables drop-off by the generator
Multifamily Collection	C8m	Recyclables drop-off by the generator
	C13	Collection of mixed MSW
	C14	Collection of pre-sorted recyclables (multiple bins)
	C15	Collection of commingled recyclables (two bins, ONP separate)
	C16	Collection of MSW after removal of recyclables via C14 or C15
Commercial Collection	C19	Collection of pre-sorted recyclables
	C20	Collection of mixed MSW (before or after recyclables removal)
Transfer	TR1	Transfer of mixed MSW
	TR2	Transfer of commingled recyclables (not in bags)
	TR5	Transfer of pre-sorted recyclables
	RT1	Rail transfer of MSW from collection vehicles
	RT2	Rail transfer of MSW from trains to haul vehicles at landfill D1
Separation	S1	Sorting of mixed refuse
	S2	Processing of pre-sorted recyclables collected via C2 and C3
	S3	Sorting of commingled recyclables collected via C4
Treatment	T1	Aerobic composting of yard waste
	T3	Combustion with electric power generation
Disposal	D1	Landfill
	D2	Ash Landfill

Table 3.4: Collection combinations included in the study

Sector	Collection Combinations
Residential	C1 C0 / C7 C2 / C7 C3 / C7 C4 / C7 C8r / C7
Multifamily	C13 C8m / C16 C14 / C16 C15 / C16
Commercial	C20 C19 / C20

Note: The codes for the collection unit processes are defined in Table 3.3.

3.3 Minimum Cost and Minimum Greenhouse Gas Emissions Scenarios

The ISWM model was applied to this case study to analyze two base scenarios. One of these scenarios was used to identify the minimum cost SWM strategy, and the other was used to identify the strategy that minimizes greenhouse gas emissions expressed in greenhouse gas equivalents (GHE). GHE, an optimizable environmental parameter in the ISWM model, is defined as a weighted sum of NO_x, CO_2 and CH_4 emissions as follows:

$$GHE = E[CO_2\,(fossil)] + 63\,E[CH_4] + 270\,E[NO_x] \qquad \textbf{(Eq. 3.1)}$$

where $E[CO_2\ (fossil)]$, $E[CH_4]$, and $E[NO_x]$ are emissions (in lbs/year) of fossil derived CO_2, CH_4, and NO_x, respectively. In this study, biomass derived CO_2 was assigned a weighting factor of zero and is not shown in equation 3.1. The user may adjust these weighting factors. All other optimizable environmental parameters except particulate matter of size less than 10 microns (i.e., CO, CO_2 (fossil derived), CO_2 (biomass derived), NO_x, SO_x, particulate matter (PM), and energy) were also calculated for each scenario. These scenarios have no site-specific restrictions or requirements imposed. The LP models for these scenarios consist of approximately 8,500 decision variables and

6,400 constraints and were solved using the CPLEX® LP solver. The resulting optimal SWM strategies for the minimum cost and minimum GHE scenarios are summarized in Tables 3.5 and 3.6, respectively, and the corresponding waste flows are shown in Figures 3.1 and 3.2.

Table 3.5: Optimal SWM strategy for the minimum cost scenario

Unit Process	**Cost** **(10^6\$/yr)**	**Energy** **(10^9 BTU /yr)**	**PM** **(10^3 lbs/yr)**	**NOx** **(10^3 lbs/yr)**	**SOx** **(10^3 lbs/yr)**	**CO** **(10^3 lbs/yr)**	**CO_2** **Biomass** **(10^3 lbs/yr)**	**CO_2** **Fossil** **(10^6 lbs/yr)**	**GHE** **(10^6 lbs/yr)**
Residential Collection									
Residuals (C7)	11.4	63.3	1.6	120	3.5	19.4	0	1.4	34
Recyclables Drop-off (C8)	0.34	$0.2\text{x}10^3$	1.7	58.2	7.8	159	0	3.2	18.9
Multifamily Collection									
Recyclables Drop-off (C8)	0.11	1.9	0.04	2.5	0.09	1.1	0	0.04	0.7
Residuals (C16)	2.28	15.3	0.4	32.3	0.8	5.1	0	0.3	9.0
Commercial Collection									
Mixed waste (C20)	7.73	48.0	1.2	96.8	2.6	15.5	0	1.1	27.2
Separation									
Pre-sorted recyc. MRF (S2)	0.21	4.1	1.8	5.6	9.3	0.9	0.6	1.5	3.2
Treatment	-	-	-	-	-	-	-	-	-
Disposal									
Landfill (D1)	11.3	6.7	6.4	25.9	30.8	17.3	$86.3 \text{ x } 10^3$	12.3	$6.5 \text{ x } 10^3$
Transportation	-	2.2	$0.4\text{x}10^3$	3.0	0.6	2.9	0	0.4	1.2
Recyclable revenues	1.29	-	-	-	-	-	-	-	
Remanufact. emissions (1)	-	$-0.3\text{x}10^3$	$-0.1\text{x}10^3$	-131	-246	-335	$-15.8 \text{ x } 10^3$	-23.3	-64.5
Net	**32.0**	**41.4**	**-97**	**214**	**-191**	**-114**	**$70.5 \text{ x } 10^3$**	**-3.2**	**$6.5 \text{ x } 10^3$**

Note: (1) Values in this row represent the difference between emissions associated with production from virgin and recycled materials. Negative values indicate avoided emissions attributable to the use of recycled materials for remanufacturing.

Table 3.6: Optimal SWM strategy for the minimum GHE scenario

Unit Process	**Cost (10^6\$/yr)**	**Energy (10^9BTU/yr)**	**PM (10^3lbs/yr)**	**NOx (10^3 lbs/yr)**	**SOx (10^3 lbs/yr)**	**CO (10^3 lbs/yr)**	**CO_2 Biomass (10^3lbs/yr)**	**CO_2 Fossil (10^6 lbs/yr)**	**GHE (10^6 lbs/yr)**
Residential Collection									
Coming. rec. MRF-sorted (C4)	8.8	0.04	0.9	59.5	2.2	9.7	0	0.9	16.9
Residuals (C7)	11.2	0.06	1.6	$0.1x10^3$	3.4	19.0	0	1.4	33.4
Multifamily Collection									
Commingled Recyclables (C15)	1.4	6.5	0.2	11.4	0.4	1.8	0	0.2	3.2
Residuals (C16)	2.2	14.7	0.4	30.9	0.8	4.9	0	0.3	8.7
Commercial Collection									
Pre-sorted recyclables (C19)	6.2	44.2	1.0	72.3	2.4	11.8	0	1.0	20.5
Residuals (C20)	7.0	42.2	1.1	83.6	2.3	13.4	0	0.9	23.5
Separation									
Mixed waste MRF (S1)	11.1	84.3	33.6	$0.1x10^3$	$0.2x10^3$	22.7	10.7	28.3	62.0
Pre-sorted recyclables MRF (S2)	0.5	10.4	4.7	14.6	24.7	2.2	1.6	3.8	8.2
Commingled recyc. MRF (S3)	2.4	7.5	3.0	10.4	17.6	1.5	1.1	2.7	5.9
Treatment									
Combustion (T3)	27.2	$-2.3x10^3$	$-0.5x10^3$	$-1.1x10^3$	$-2.7x10^3$	$0.3x10^3$	$0.5 x 10^6$	$-0.2x10^3$	$-0.6x10^3$
Disposal									
Landfill (D1)	0.01	0	0	0	0	0	0	0.01	0.02
Ash landfill (D2)	1.6	0.3	0.9	3.8	4.4	2.6	0	1.8	2.8
Transportation	1.01	41.2	8.0	55.0	11.4	54.2	0	6.7	21.5
Recyclable revenues	8.9	-	-	-	-	-	-	-	-
Remanufacturing emissions(1)	-	$-3.4x10^3$	$-0.9x10^3$	$-2.5x10^3$	$-3.2x10^3$	$-7.5x10^3$	$-0.7 x 10^6$	-16.0	$-0.7x10^3$
Net	**71.7**	**$-5.4x10^3$**	**$-1.3x10^3$**	**$-3.1x10^3$**	**$-5.7x10^3$**	**$-7.1x10^3$**	**$-0.2 x 10^6$**	**$-0.2x10^3$**	**$-1.1x10^3$**

Note: (1) Values in this row represent the difference between emissions associated with production from virgin and recycled materials. Negative values indicate avoided emissions attributable to the use of recycled materials for remanufacturing.

Figure 3.1: Mass flows for the minimum cost strategy

(The numbers in parentheses show the mass in tons/year.)

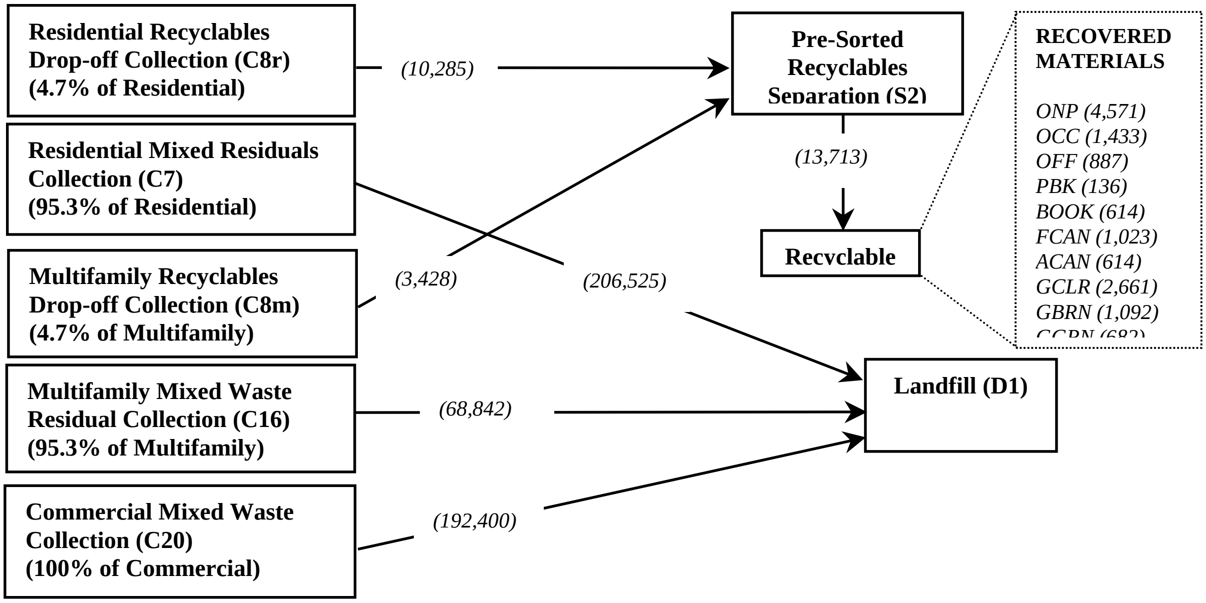
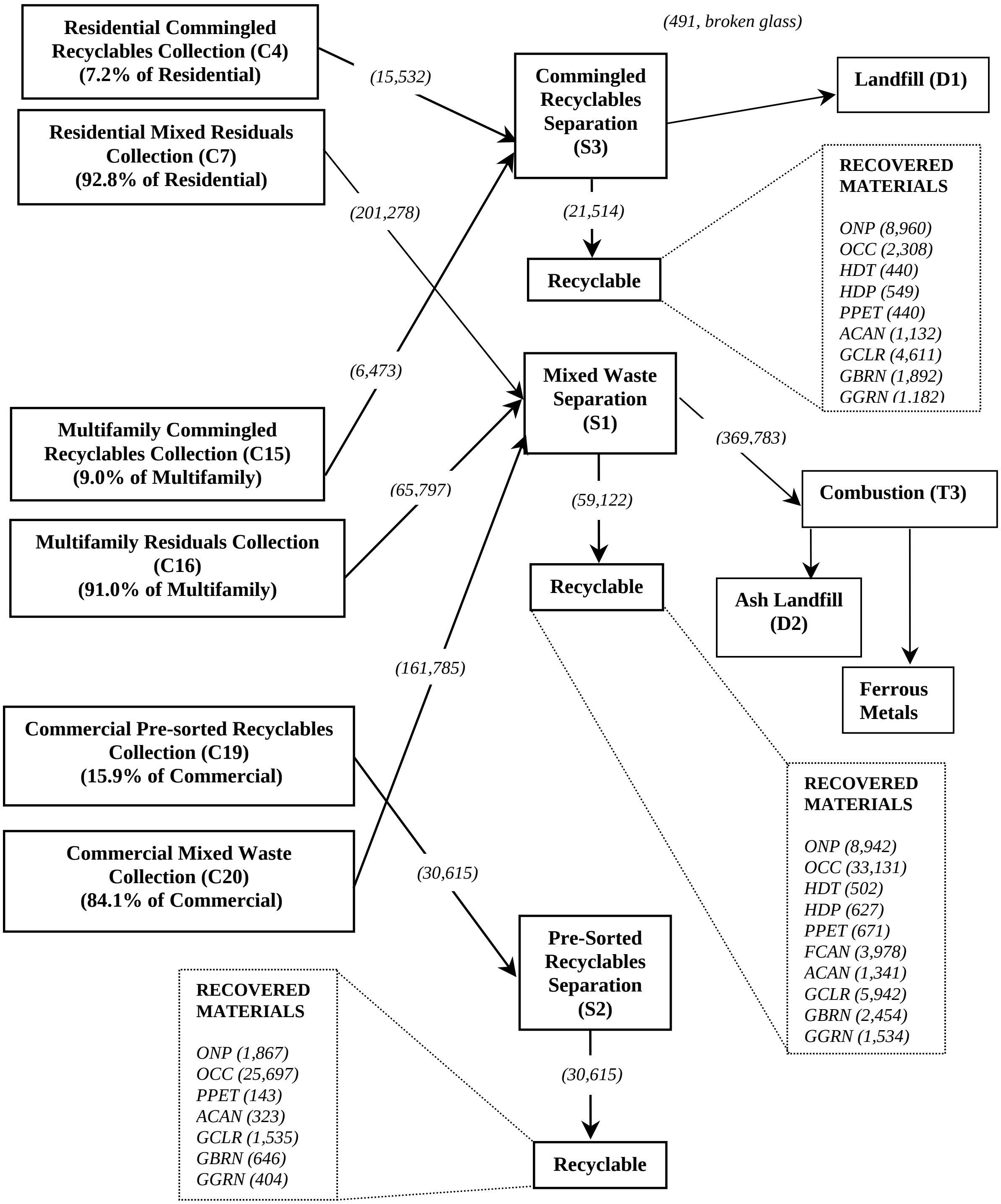


Figure 3.2: Mass flows for the minimum GHE strategy

(The numbers in parentheses show the mass in tons/year)



The minimum cost SWM strategy indicates that the residential and multifamily sectors are served by a recyclable materials drop-off facility and mixed MSW collection for handling the residual waste. Approximately 4.7% of the waste from each of these two sectors is recovered as recyclable material, and the remaining 95.3% of the waste is collected as mixed MSW and disposed of in a landfill. In the commercial sector, all wastes are collected by the mixed MSW collection option and disposed of in a landfill. The cost breakdown shown in Table 3.5 indicates that the collection and landfill costs constitute 71% of the net cost. Since the pre-sorted MRF, which is a relatively inexpensive MRF, is handling only a small amount of waste, the cost associated with that facility is low ($ 0.21 million/yr). The revenue from the recyclables recovered at this MRF is $1.29 million/yr. Although recycling operations are typically more expensive than mixed waste collection, the minimum cost strategy includes the drop-off option for recyclables since it costs very little and is easily offset by the revenue generated from the recyclable materials.

For most environmental parameters, the majority of burdens are associated with collection and landfill activities. For example, collection activities consume the most energy, while CO_2 (fossil and biomass) emissions are greatest from the landfill. The negative values of some environmental parameters associated with “Remanufacturing” indicate reductions in net energy consumption and emissions resulting from offsetting of manufacturing from virgin material by manufacturing using recyclable material.

Compared to approximately 6.5 billion lbs/yr GHE burden in the minimum cost strategy, the minimum GHE strategy (Table 3.6 and Figure 3.2) provides a net reduction of approximately 1.1 billion lbs/yr. The net cost of the minimum GHE strategy, however, is approximately twice that of the minimum cost strategy. Thus, there is a considerable tradeoff between these two policy objectives.

The major portion of the reduction in GHE is achieved through combustion of residual waste to recover energy. Although combustion flue gases contribute to GHE, the offset of fossil fuel-based energy production (coal and natural gas) by the energy generated at a waste-to-energy facility is significantly more than the burden caused by the combustion process. This is in part because emissions from MSW combustion include significant biomass CO_2 that is assigned a weighting factor of zero in equation 3.1. Therefore, a net reduction in GHE is realized. The user may examine the implications of policy decisions associated with including biomass CO_2 in the GHE definition by simply assigning a nonzero weighting factor and resolving the model.

In the minimum GHE scenario, 23.4% of the total waste stream is recovered for recycling relative to 2.8% in the minimum cost scenario. The model selects recycling for both combustible (paper, plastic) and non-combustible (glass, metal) items. The selection of recycling for non-combustible items indicates that the savings at the remanufacturing facility are greater than the emissions associated with recyclables recovery activities. The selection of recycling of combustible items indicates that from a GHE perspective, recycling is more beneficial than combustion with energy recovery in the current case study. Interestingly, a costly mixed waste MRF is selected to recover those recyclables not separated by the waste generator, emphasizing the GHE benefit of recyclable recovery.

3.4 Scenarios to Examine the Effects of Varying Diversion Targets

An array of scenarios was used to examine the effects of imposing different diversion requirements on the SWM system cost and LCI parameter values since diversion is often viewed as an important objective. The ISWM model includes a constraint that represents a specified diversion requirement characterized by a mass fraction of waste generated that is diverted from disposal in a traditional landfill. This constraint ensures that the resulting SWM strategy achieves the diversion target if it is technically possible based on the waste composition and factors, such as participation rates, that limit recycling. Scenarios describing a range of diversion targets were examined.

For illustrative purposes, two different sets of diversion scenarios were considered. In one case, diversion is defined to include only waste diverted via recycling, and in the second case diversion is defined to include recycling, yardwaste composting, and waste combustion. Each case was analyzed for a series of diversion targets.

3.4.1 Diversion through recovery of recyclable material

A set of scenarios was defined to consider diversion of waste from a landfill by recycling. For each scenario, a target diversion rate was specified. This target was represented in the ISWM model as a constraint to limit the amount of waste that can flow into the landfill. As described above, the minimum cost SWM strategy with no specified diversion target yields approximately 2.8% diversion. In addition, diversion targets of 15%, 20%, 25% and 25.9% were modeled. The maximum possible diversion rate that can be achieved by recycling in this case is 25.9%, which was determined by solving the ISWM model while maximizing the diversion rate. This maximum recycling level is determined by numerous user-input parameters involving waste generation and composition, the extent to which waste generators participate in drop-off and curbside collection programs for recycling, and the ability to recover recyclables at a mixed waste MRF. For each diversion target, the ISWM model was solved to determine the most cost-effective SWM strategy.

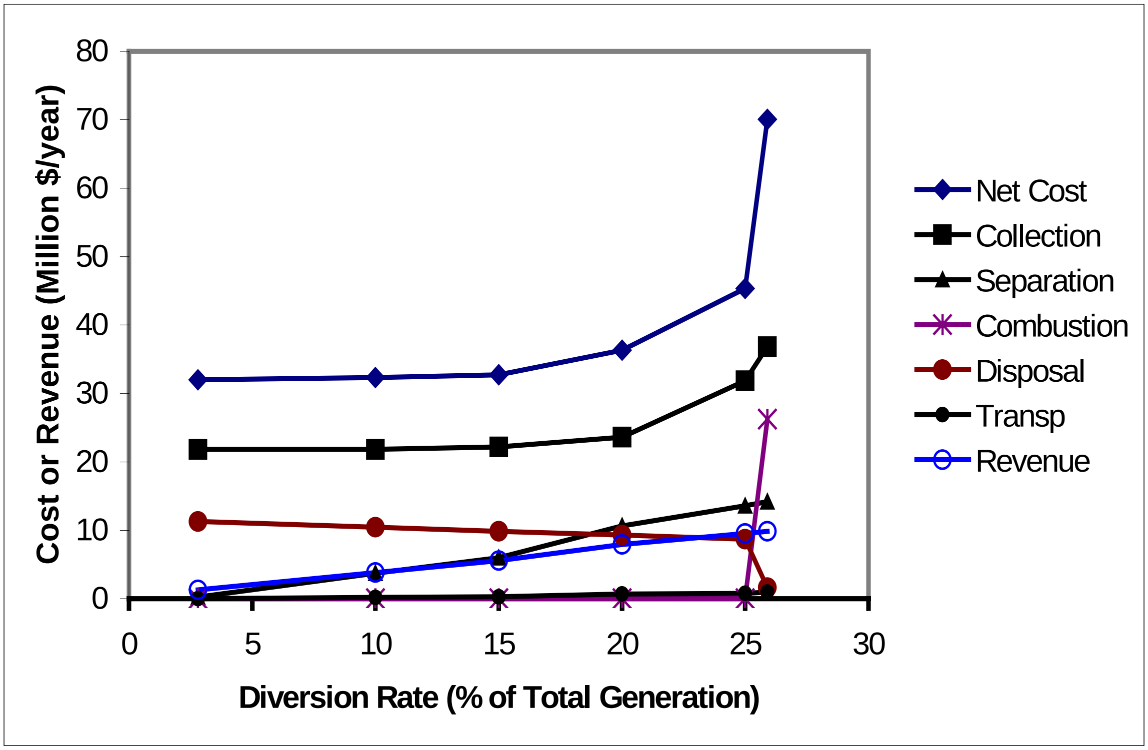
The minimum cost strategy for each diversion target is shown in Table 3.7. This table lists the unit operations selected and the mass handled in each unit operation. As the diversion target begins to increase, the SWM strategies recover more materials from commercial waste that is processed at a mixed waste MRF while there are minimal changes in the residential and multifamily sectors. As the diversion target increases further, the model uses presorted collection from the multifamily and commercial sectors. At higher diversion targets, commingled collection, which yields higher levels of capture, is selected for the residential and multifamily sectors, and the residuals not recycled by the waste generators are processed through a mixed waste MRF to recover more recyclable materials. To maximize diversion, the residue from the mixed waste MRF is processed through a waste-to-energy facility. Even though this is more expensive than landfilling, combustion is selected since the Fe metal recovered from the combustion ash provides additional diversion. It is also interesting to note that residential curbside recycling program is selected after multifamily (C14) and commercial recycling (C19). This is likely due to the higher concentrations of materials available at each location in the non residential sectors.

As expected, the cost of the SWM strategy yielding the maximum diversion rate is relatively high (\$70.1 million/year)--more than twice as much as the minimum cost (\$32.0 million/year) (Table 3.7). These results show that as the diversion target increases, more expensive unit operations that yield higher levels of recyclable recovery are incrementally selected (Figure 3.3). The rapid increase in net cost for diversion levels greater than 20% is associated with greater use of separate collection of recyclables in the commercial and residential sectors. Combustion is added at the 25.9% diversion target to allow Fe metal recovery from the ash. Such tradeoff information might be very useful in selecting cost-effective targets for a local diversion program.

Table 3.7: Optimal SWM strategies for scenarios with different diversion targets (with recycling only)

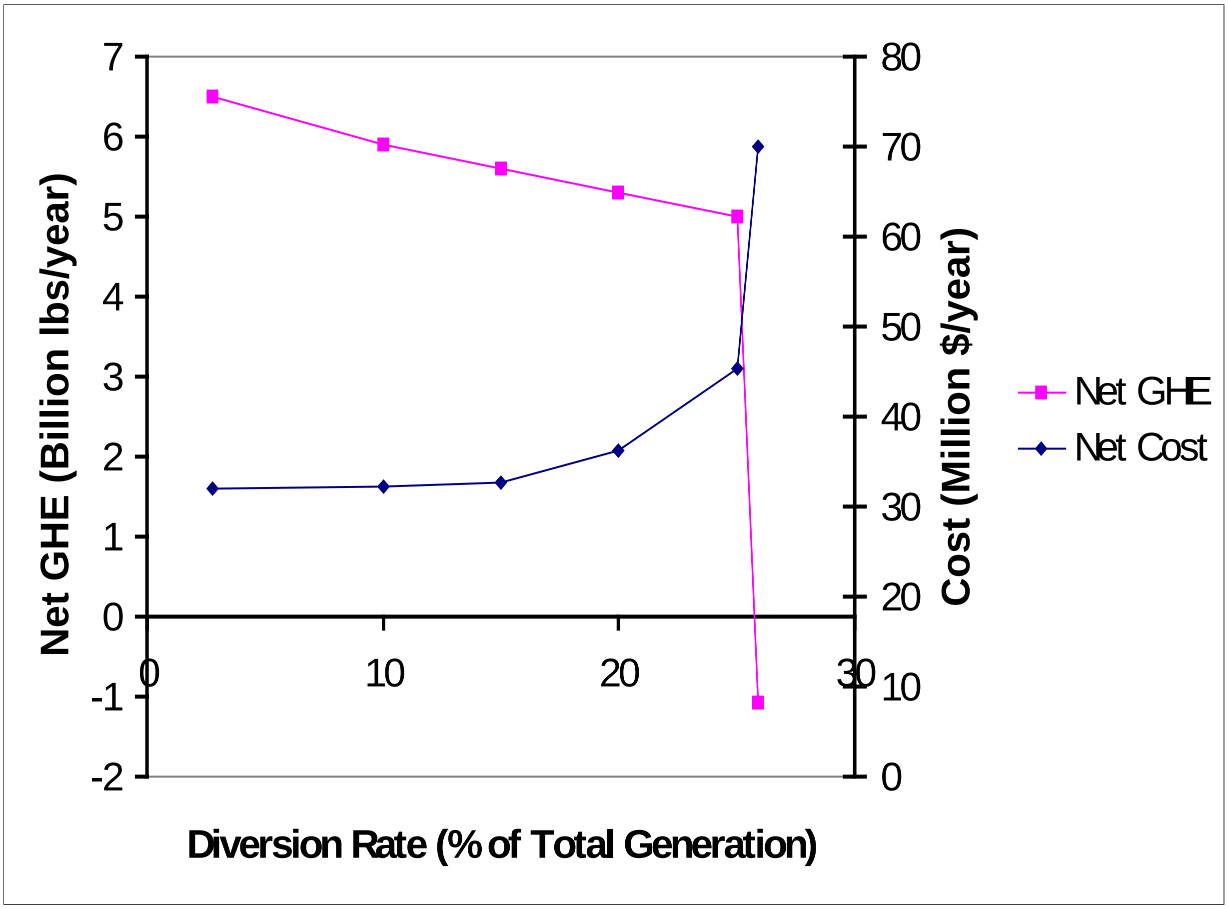
Unit Processes	**Scenarios**									
	Minimum Cost (2.8% recycling)		15% recycling		20% recycling		25% recycling		25.9% (max) recycling	
	Cost (10^6\$/yr)	Mass (10^3tons/yr)	Cost (10^6\$/yr)	Mass (10^3tons/yr)	Cost (10^6\$/yr)	Mass (10^3tons/yr)	Cost (10^6\$/yr)	Mass (10^3tons/yr)	Cost (10^6\$/yr)	Mass (10^3tons/yr)
Residential Collection										
Commingled Recyclables (C4)	-	-	-	-	-		3.55	8.5	9.06	21.8
Residuals (C7)	11.4	207	11.4	207	11.4	207	11.2	202	11.1	195
Recyclables Drop-off (C8r)	0.34	10.3	0.34	10.3	0.34	10.3	0.34	6.7	-	-
Multifamily Collection										
Recyclables Drop-off (C8m)	0.11	3.4	0.05	1.5	-	-	-	-	-	-
Pre-sorted Recyclables (C14)	-	-	0.48	3.9	0.86	6.9	-	-	-	-
Commingled Recyclables (C15)	-	-	-	-	-	-	1.45	9.1	1.45	9.1
Residuals (C16)	2.28	68.8	2.23	66.9	2.19	65.3	2.14	63.2	2.14	63.2
Commercial Collection										
Pre-sorted recyclables (C19)	-	-	-	-	1.29	7.3	6.32	35.8	6.32	35.8
Residuals (C20)	-	-	-	-	1.39	32.0	6.82	156	6.82	157
Mixed waste (C20)	7.73	192	7.73	192	6.15	153	-	-	-	-
Separation										
Mixed waste MRF (S1)	-	-	5.76	192	10.3	391	11.3	421	10.8	415
Pre-sorted recyclables MRF (S2)	0.21	13.7	0.24	15.7	0.39	24.7	0.69	42.5	0.58	35.8
Commingled recyc. MRF (S3)	-	-	-	-	-	-	1.60	17.6	2.81	30.9
Treatment										
Combustion (T3)	-	-	-	-	-	-	-	-	26.2	357
Disposal										
Landfill (D1)	11.3	468	9.86	409	9.28	385	8.70	361	0.02	0.7
Ash landfill (D2)	-	-	-	-	-	-	-	-	1.62	108
Transportation	0	13.7	0.29	208	0.67	416	0.76	482	0.98	590
Recyclable revenues	1.29		5.59		7.90		9.55		9.84	
Net cost	**32.0**		**32.7**		**36.3**		**45.3**		**70.1**	

Figure 3.3: Variation of cost with diversion rate (with recycling only)



GHE values were also calculated for each SWM strategy included in Table 3.7. Figure 3.4 shows the variation of GHE and cost with increasing diversion. This and similar information can be used to examine the cost and environmental implications of diversion. As the diversion rate increases, more recyclable materials are recovered and sent to remanufacturing. This results in increasing GHE reductions from offsetting emissions from manufacturing processes using virgin materials. At the maximum diversion rate, a rapid reduction in GHE is seen. This results from the additional GHE reductions that correspond to energy offsets achieved at the waste-to-energy facility, which is only used at 25.9% diversion. At lower levels of diversion, a significant reduction in GHE can be realized at a relatively small increase in cost; for example, when going from 2.8% to 15% diversion, the GHE reduces by about one billion lbs/year at only a small marginal increase in cost. To achieve a much larger reduction (from 5 to –1.1 billion lbs/yr) in GHE, however, requires a substantial marginal increase in cost.

Figure 3.4: Net cost and net GHE versus diversion rate (with recycling only)



3.4.2 Diversion through recovery of recyclable material, yardwaste composting and waste-to-energy

Another set of scenarios was defined in which required target diversion rates could be achieved via recycling, yardwaste composting and combustion. Again, a diversion target was represented in the ISWM model as a constraint to appropriately limit the mass flowing into the landfill. Diversion targets were set in increments of 20% from 20%, to 78.3%, the maximum possible rate. The maximum rate was determined by using the ISWM model to maximize diversion. For each diversion target, the ISWM model was solved to determine the most cost-effective SWM strategy (Table 3.8).

Table 3.8: Optimal SWM strategies for scenarios with different diversion targets[(a)]

Unit Processes	**Scenarios**									
	Minimum Cost (2.8% recycling)		20% diversion		40% diversion		60% diversion		78.3% (max) diversion	
	Cost ($10^6\$$/yr)	Mass (10^3tons/yr)	Cost ($10^6\$$/yr)	Mass (10^3tons/yr)	Cost ($10^6\$$/yr)	Mass (10^3tons/yr)	Cost ($10^6\$$/yr)	Mass (10^3tons/yr)	Cost ($10^6\$$/yr)	Mass (10^3tons/yr)
Residential Collection										
Commingled Recyclables (C4)	-	-	-	-	-	-	-	-	8.92	20.5
Residuals (C7)	11.4	207	11.4	207	11.4	207	11.4	207	11.1	196
Recyclables Drop-off (C8r)	0.34	10.3	0.34	10.3	0.34	10.3	0.34	10.3	-	-
Multifamily Collection										
Recyclables Drop-off (C8m)	0.11	3.4	0.11	3.4	0.06	1.7	-	-	-	-
Pre-sorted Recyclables (C14)	-	-	-	-	0.43	3.5	0.84	6.8	-	-
Commingled Recyclables (C15)	-	-	-	-	-	-	-	-	1.41	8.6
Residuals (C16)	2.28	68.8	2.28	68.8	2.24	67.1	2.20	65.5	2.15	63.7
Commercial Collection										
Pre-sorted recyclables (C19)	-	-	-	-	-	-	-	-	6.29	35.3
Residuals (C20)	-	-	-	-	-	-	-	-	6.83	157
Mixed waste (C20)	7.73	192	7.73	192	7.73	192	7.73	192	-	-
Separation										
Mixed waste MRF (S1)	-	-	5.76	192	5.76	192	5.76	192	10.9	417
Pre-sorted recyclables MRF (S2)	0.21	13.7	0.21	13.7	0.24	15.4	0.26	17.1	0.58	35.3
Commingled recyc. MRF (S3)	-	-	-	-	-	-	-	-	2.69	29.1
Treatment										
Combustion (T3)	-	-	2.56	36.3	12.1	169	22.3	306	26.7	362
Disposal										
Landfill (D1)	11.3	468	9.04	375	5.79	240	2.46	102	0.01	0.5
Ash landfill (D2)	-	-	0.15	10.4	0.73	49.2	1.38	92.4	1.62	109
Transportation	0.00	13.7	0.31	217	0.39	257	0.48	302	0.99	590
Recyclable revenues	1.29		5.41		5.57		5.73		9.42	
Net cost	**32.0**		**34.4**		**41.6**		**49.4**		**70.7**	

(a) Diversion is defined to include recycling, combustion, and yardwaste composting in three sectors.

Figure 3.5 shows the mass flows for the maximum possible (78.3%) diversion. Compared to the scenarios for diversion with recycling only, a larger percentage of waste can be diverted from the landfill because of the additional options available for diversion. As in the previous case (Table 3.7), in the maximum diversion strategy recyclables are recovered both by commingled recyclables collection and by recovery of recyclables at a mixed waste MRF. Recycling is selected over combustion in strategies that maximize diversion since certain recyclables are not combustible and would thus remain in the ash (e.g., glass), and there is a fraction of the combustible recyclables that will not burn because of inadequate mixing. In addition, each material has some ash. These residuals must be landfilled.

Figure 3.6 shows the behavior of net cost and GHE as incremental levels of diversion are imposed. As the diversion rate approaches the maximum level (78.3%), the cost increases rapidly (approximately 50% for the last increment). Again, an increase in diversion of waste from a landfill leads to increased use of both separate recyclables collection (C4, C19) and the waste-to-energy facility (T3), both of which, in this case, are significantly more expensive than a landfill. At the other extreme, the zero diversion rate also leads to an increase in the cost and GHE compared to those values for the minimum cost strategy, which has a 2.8% diversion rate. When diversion is constrained to 0%, the recyclable materials that were recovered via the drop-off option in the minimum cost strategy now enter the mixed MSW stream and the cost increases. Also, elimination of the recovery of recyclables in this scenario leads to an increase in GHE.

Figure 3.5: Mass flows for the minimum cost strategy for the scenario with a maximum diversion rate of 78.3%

(The numbers in parentheses show the mass in tons/year)

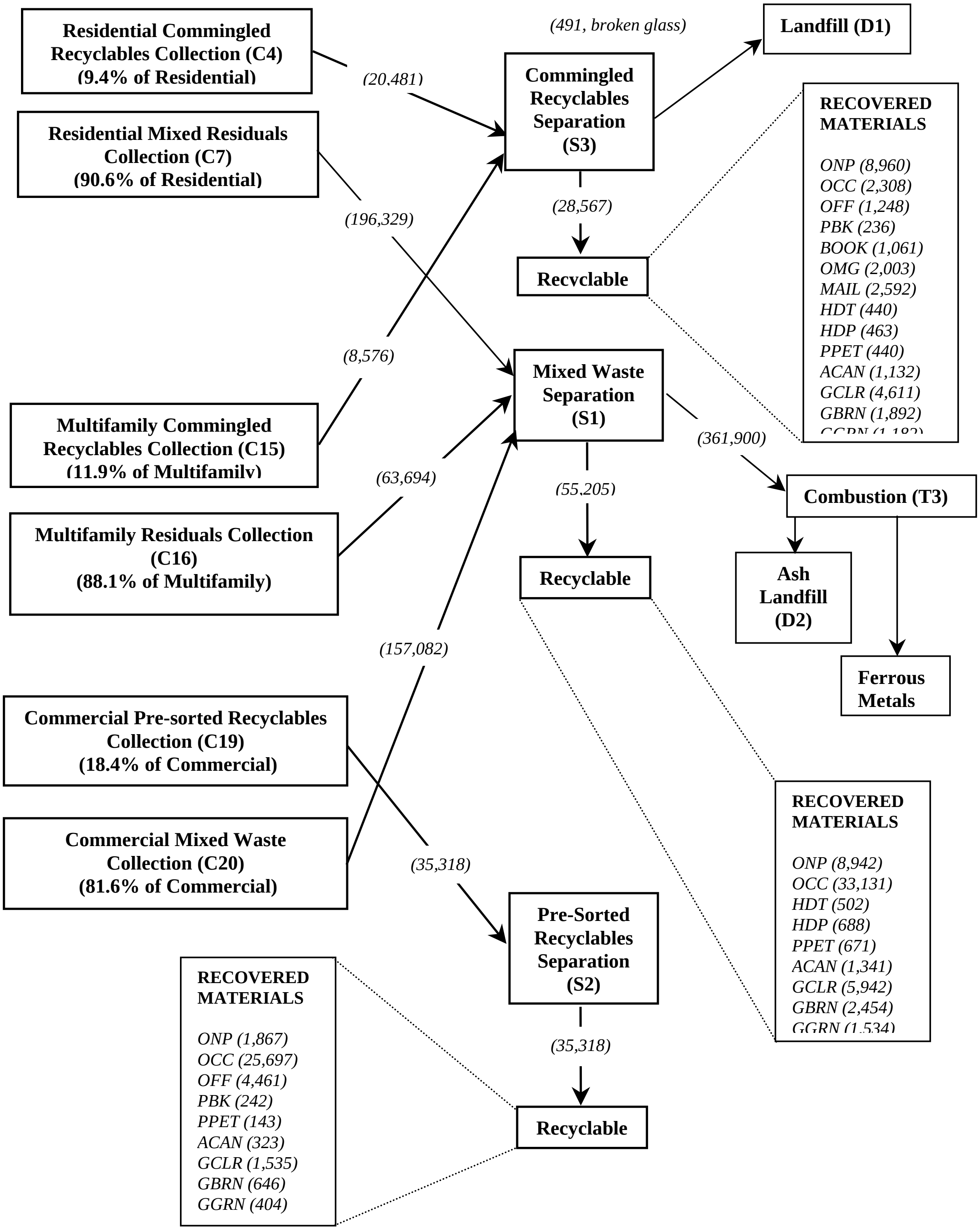
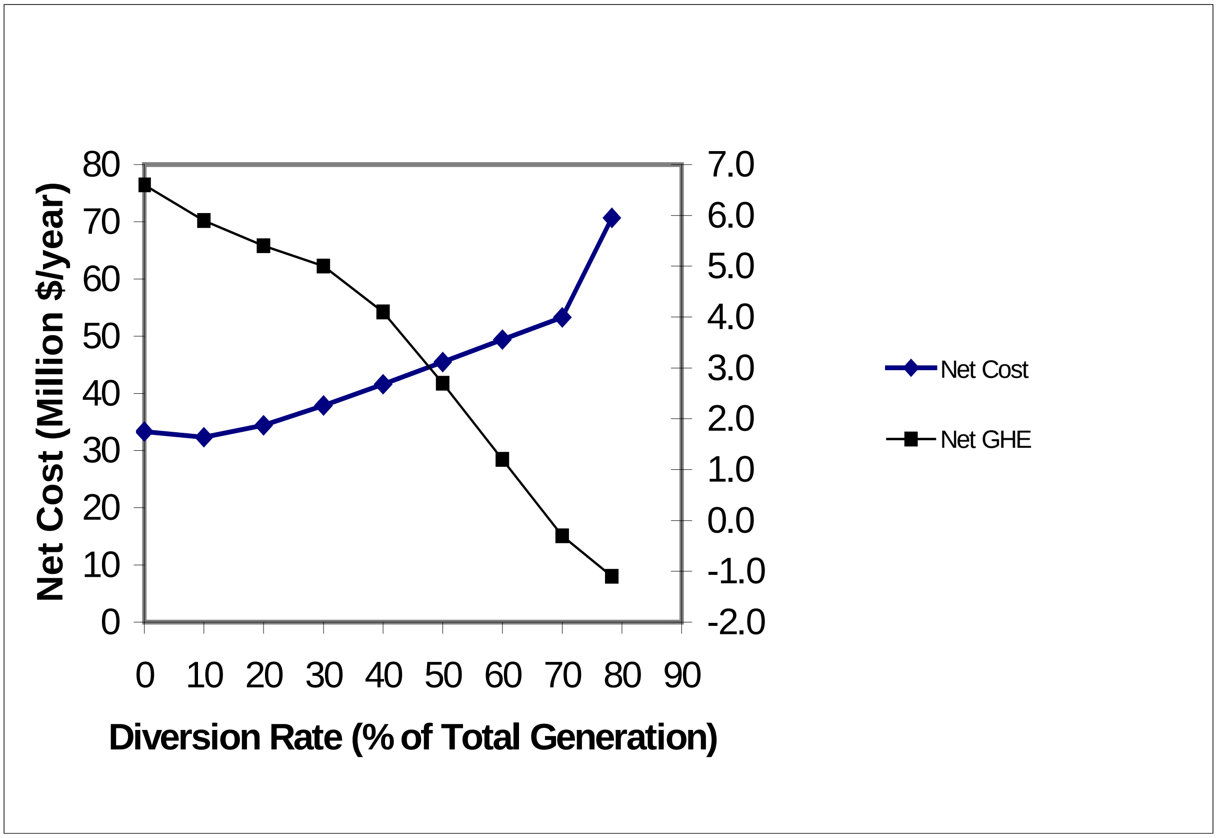


Figure 3.6: Net cost and net GHE versus diversion rate[1]



[1] Diversion includes recycling, yardwaste composting and combustion in all sectors.

Figure 3.7: Comparison of cost versus diversion rate for two definitions of diversion

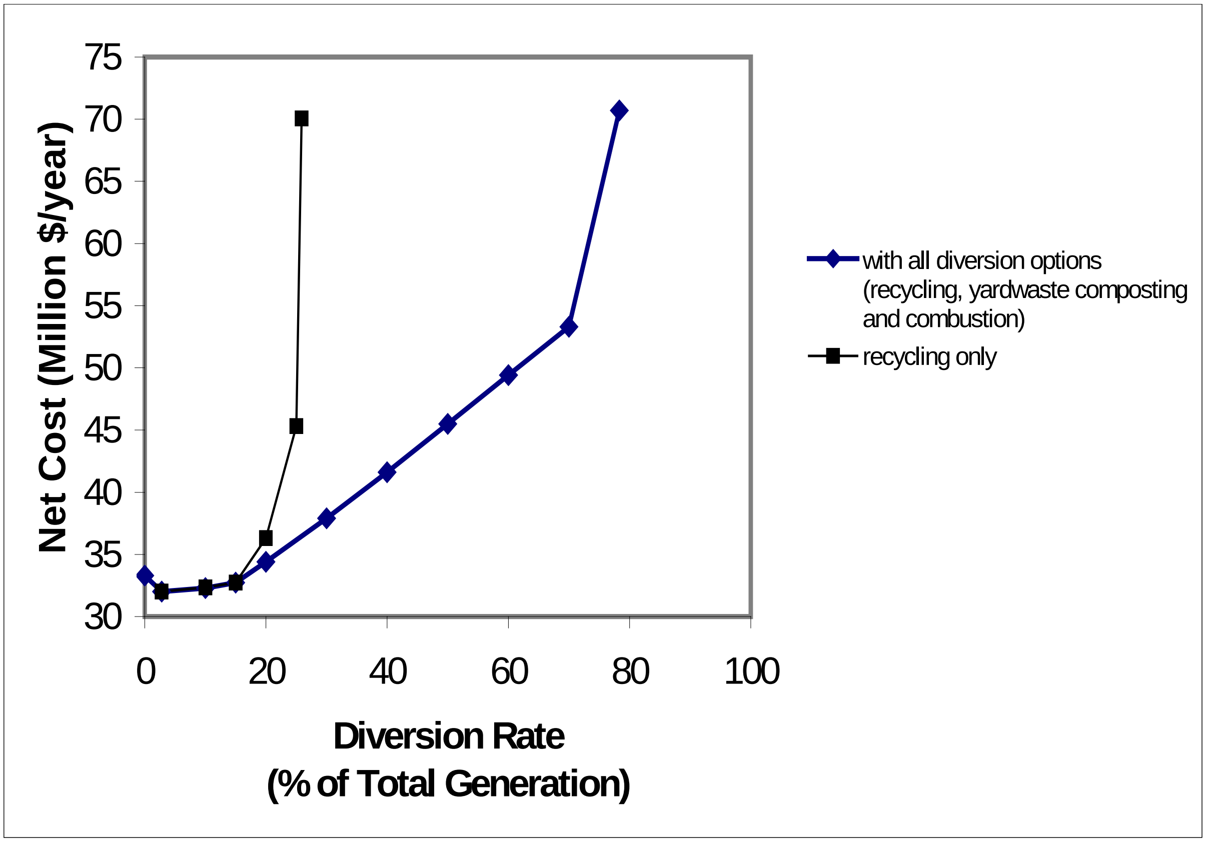
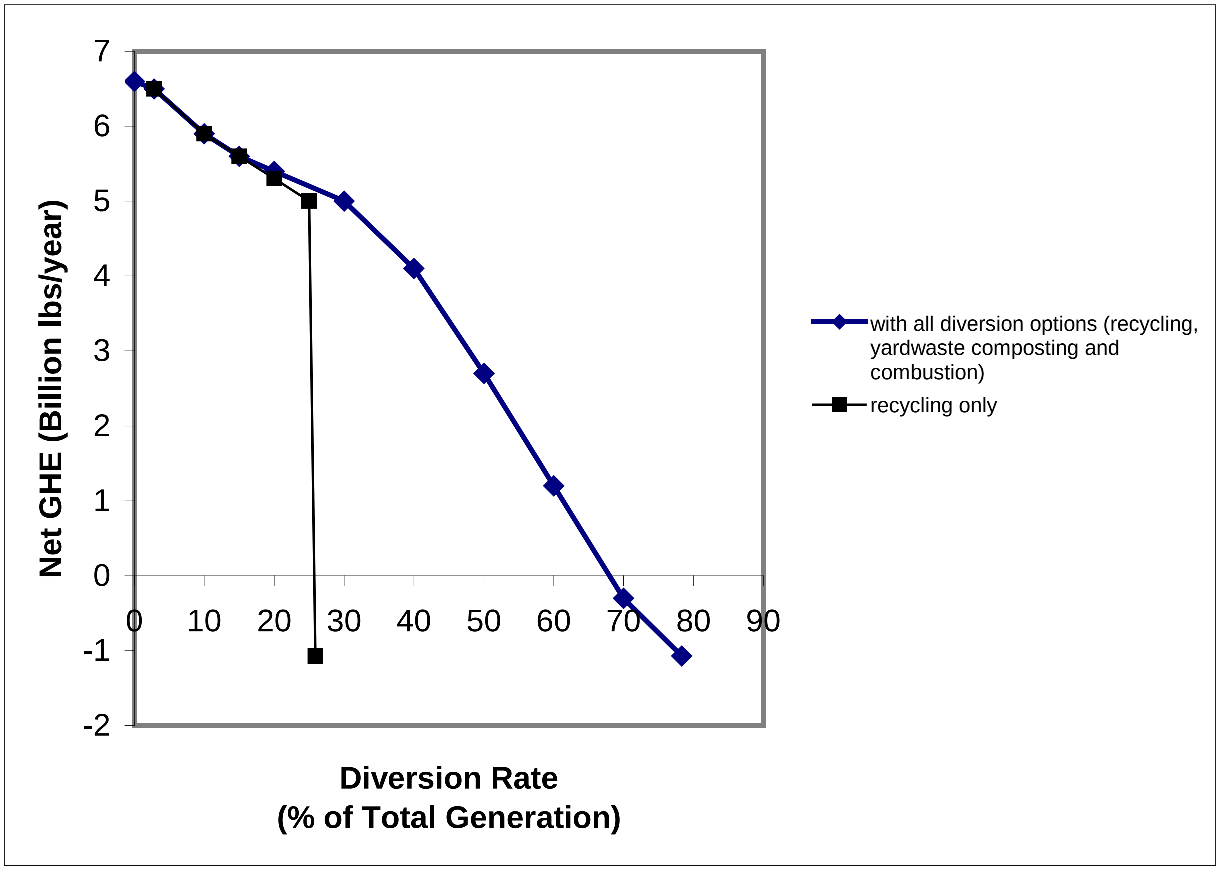


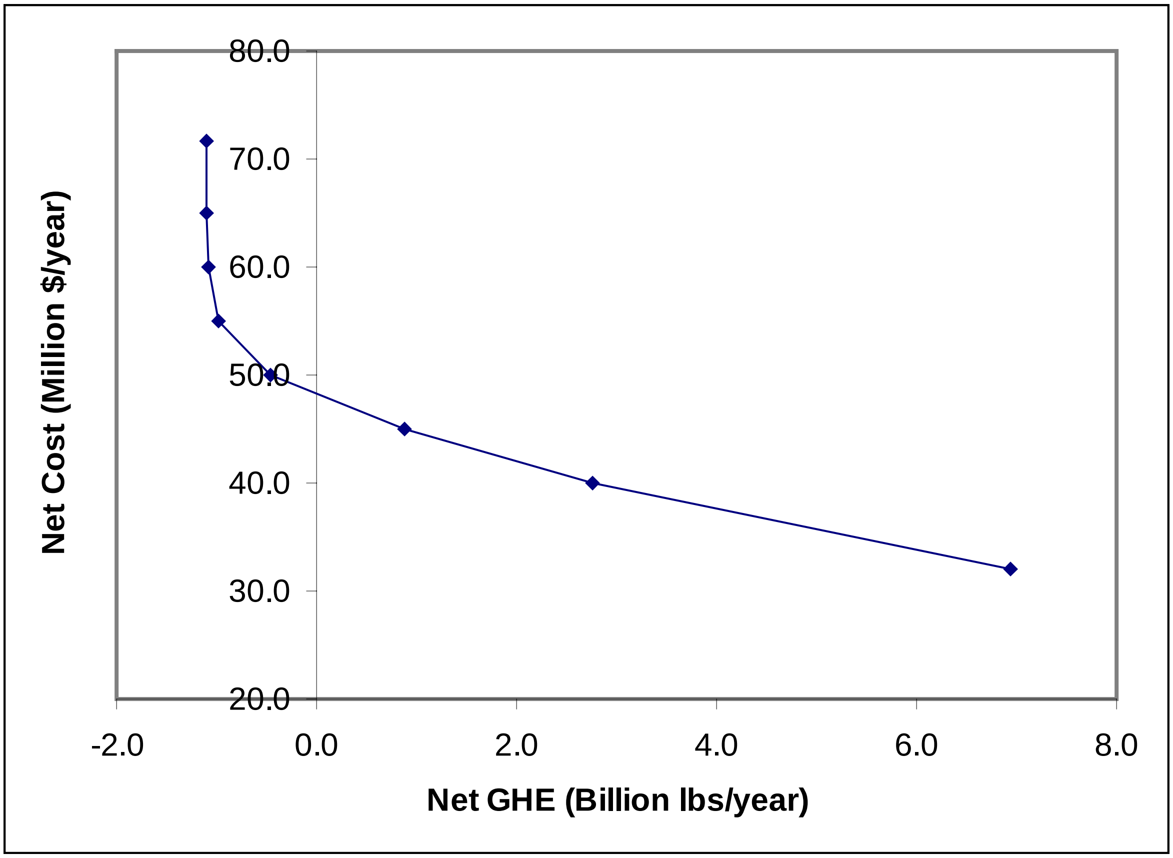
Figure 3.8: Comparison of GHE versus diversion rate for two definitions of diversion



3.5 Scenarios to Examine the Tradeoff between GHE and Cost

Another set of scenarios was defined to generate the tradeoff between GHE and cost. The minimum cost and the minimum GHE scenarios, which are presented in Tables 3.5 and 3.6, range in cost from $32.0 to $71.7 million/yr, respectively. The ISWM model for the minimum GHE scenario was modified by including a cost constraint and solved to find the minimum GHE strategy for a given cost. By varying this cost constraint, the tradeoff curve shown in Figure 3.9 was obtained. This curve indicates that at GHE levels higher than –1 billion lbs/yr, the marginal cost of GHE reduction is almost constant. To achieve lower GHE levels, however, it requires a rapidly increasing cost beyond this point. The ISWM model can be used similarly to generate tradeoff curves among other environmental parameters and cost. Such tradeoff curves may be useful when determining environmental targets for emissions associated with MSW management systems.

Figure 3.9: Trade-off curve between cost and GHE



3.6 Generation of Alternative Minimum Cost SWM Strategies

Using the modeling to generate alternative (MGA) approach (Brill *et al.*, 1982; Chang *et al.*, 1982; Brill *et al.*, 1990), the ISWM model was extended to generate a small set of alternative SWM strategies. These alternatives were driven, using optimization, to be as different as possible with respect to the choices of unit processes and the flows of waste items through them. The goal of analyzing these scenarios is to examine the flexibility, if any, that will be available to a SWM planner in selecting different unit processes and waste management alternatives that will give comparable performance. Given different selections of unit processes and mass flows in these alternatives, they are likely to perform differently with respect to issues and considerations that are not included explicitly in the model. For example, the political implications of locating a suitable site for a combustion facility may be undesirable even if combustion is selected in the optimal strategy. Alternatively, it may be possible to make better use of existing facilities and equipment in implementing one of the alternatives.

For the minimum cost strategy described above, a set of three alternative strategies was generated starting with the minimum cost strategy. The cost of each alternative was limited to be no more than 20% greater than the minimum cost of $32 million/yr (Table 3.5). The ISWM model for the minimum cost scenario was modified by: 1) converting the cost objective to be a constraint (to ensure that the cost does not exceed 120% of the minimum cost), and 2) adding a new objective function that maximizes the differences between the decision variables used in the new alternative strategy and previously generated strategies. This modified ISWM model was solved to generate a set of three SWM alternatives. These alternative strategies and the minimum cost strategy are compared in Table 3.9. The mass flow diagrams for the three alternatives are shown in Figures 3.10-3.12. These figures and the table show a wide range of selections in unit operations and mass flow among the alternatives. For example, each alternative selects a different unit process for multifamily waste collection. Also, the full range of available unit processes is used among the four strategies, indicating the flexibility actually available in selecting unit processes.

These alternatives were evaluated with respect to several performance criteria including diversion rate, energy consumption and emissions of various pollutants (Table 3.10). Although they were not explicitly modeled in these scenarios, the alternatives show diverse performances with respect to some of these criteria. For example, the diversion rates vary from approximately 17% to 23%, NO_x emissions vary from approximately –0.80×10^6 to -1.6×10^6 lbs/yr, and fossil CO_2 emissions vary from 1.6×10^6 lbs/yr to 99.7×10^6 lbs/yr. On the other hand, some emissions (e.g., particulate matter) do not vary significantly. Although these additional criteria can fit into the ISWM model, many other unmodeled issues (e.g., social/political acceptability and practicality) cannot. If unmodeled criteria are considered to be important during decision making, then these alternatives provide a set of choices at relatively similar cost. Also, such analyses provide a convenient way to examine alternative management choices and their performance that could be realized at marginal differences in budget.

Table 3.9: Minimum cost and alternative SWM strategies

Unit Processes	**Scenarios**							
	Minimum Cost		**Alternative 1**		**Alternative 2**		**Alternative 3**	
	Cost (10^6 \$/yr)	**Mass** (10^3 tons/yr)	**Cost** (10^6 \$/yr)	**Mass** (10^3 tons/yr)	**Cost** (10^6 \$/yr)	**Mass** (10^3tons/yr)	**Cost** (10^6 \$/yr)	**Mass** (10^3tons/yr)
Residential Collection								
Mixed Waste (C1)	-	-	11.6	217	-	-	11.6	217
Residuals (C7)	11.4	207	-	-	11.4	207	-	-
Recyclables Drop-off (C8r)	0.3	10.3	-	-	0.3	10.3	-	-
Multifamily Collection								
Recyclables Drop-off (C8m)	0.1	3.4	-	-	-	-	-	-
Mixed Waste (C13)	-	-	2.4	72.3	-	-	-	-
Pre-sorted Recyclables (C14)	-	-	-	-	0.8	6.8	-	-
Commingled Recyclables (C15)	-	-	-	-	-	-	1.3	8.3
Residuals (C16)	2.3	68.8	-	-	2.2	65.5	2.2	64.0
Commercial Collection								
Pre-sorted recyclables (C19)	-	-	6.3	35.7	6.3	35.7	-	-
Residuals (C20)	-	-	6.8	156.7	6.8	157	-	-
Mixed waste (C20)	7.7	192	-	-	-	-	7.7	192
Separation								
Mixed waste MRF (S1)	-	-	4.0	157	4.7	207	5.5	187
Pre-sorted recyclables MRF (S2)	0.2	13.7	0.6	35.7	0.8	52.8	-	-
Commingled recyc. MRF (S3)	-	-	-	-	-	-	0.6	8.3
Treatment								
Combustion (T3)	-	-	2.2	29.7	1.2	15.8	5.2	69.9
Disposal								
Landfill (D1)	11.3	468	9.2	382	9.5	395	8.4	350
Ash landfill (D2)	-	-	0.1	9.6	0.07	4.9	0.3	21.9
Transportation	-	-	0.3	132	0.4	194	0.3	155
Recyclable Revenues	1.3		5.1		6.1		4.7	
Net cost	**32.0**		**38.4**		**38.4**		**38.4**	

Table 3.10: Total diversion and LCI parameters for the alternative SWM strategies

Scenario	Diversion (%)	Cost (10^6 $/ton)	Energy (10^{12} BTU/yr)	PM (10^6 lbs/yr)	NOx (10^6 lbs/yr)	SOx (10^6 lbs/yr)	CO (10^6 lbs/yr)	CO2 Biomass (10^9 lbs/yr)	CO2 Fossil (10^6 lbs/yr)	GHE (10^9 lbs/yr)
Min Cost	2.8	32.0	0.041	-0.097.0	0.21	-0.19	-0.11	0.071	-3.2	6.49
Alt. 1	18.8	38.4	-2.2	-0.47	-1.6	-2.3	-6.2	-0.52	99.7	4.95
Alt. 2	16.9	38.4	-1.5	-0.51	-0.83	-1.7	-3.6	-0.24	1.6	5.36
Alt. 3	23.0	38.4	-2.3	-0.49	-1.5	-2.4	-5.3	-0.39	54.6	4.21

Figure 3.10: Mass flows for SWM Alternative 1

(The numbers in parentheses show the mass in tons/year)

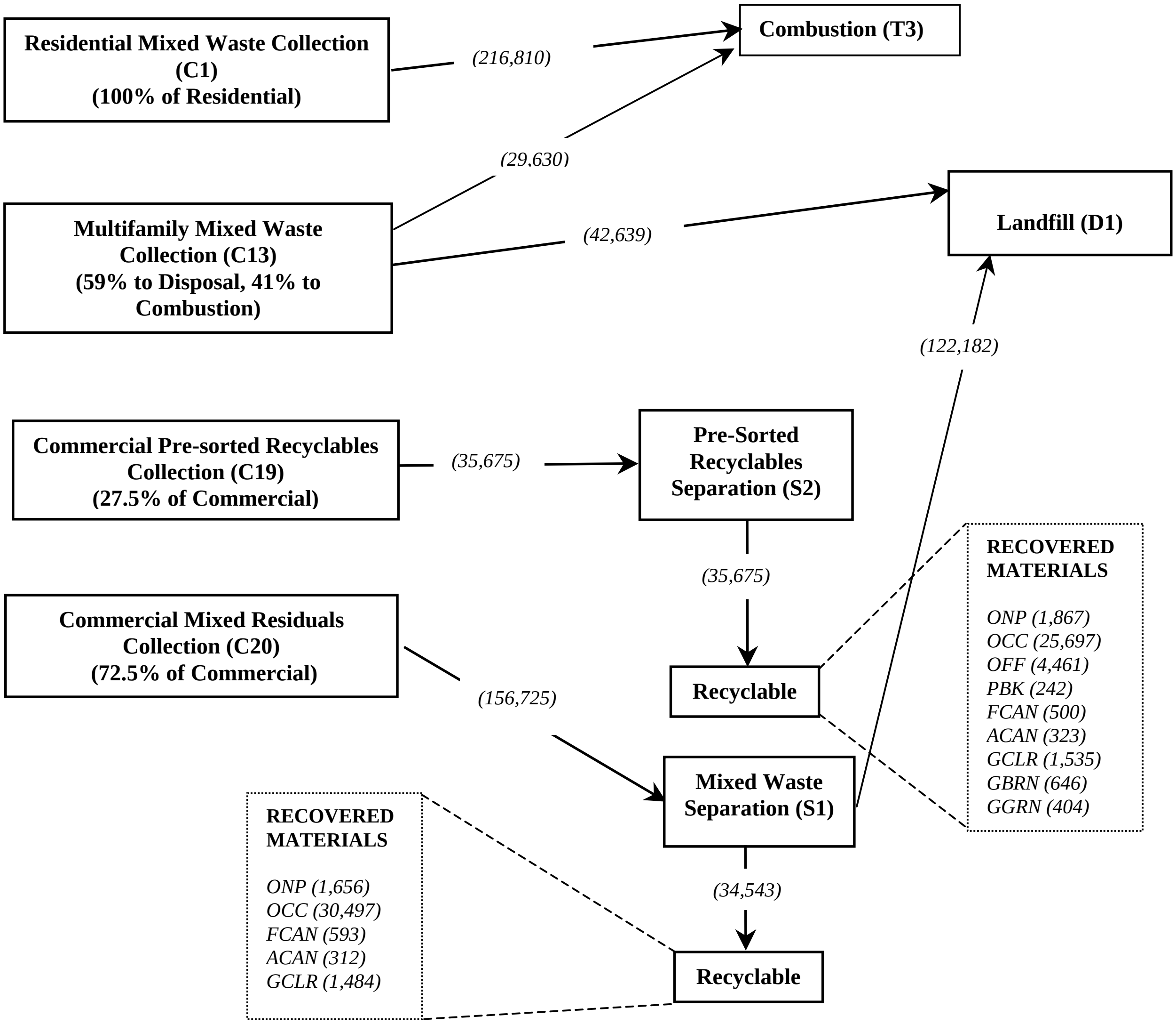


Figure 3.11: Mass flows for SWM Alternative 2

(The numbers in parentheses show the mass in tons/year)

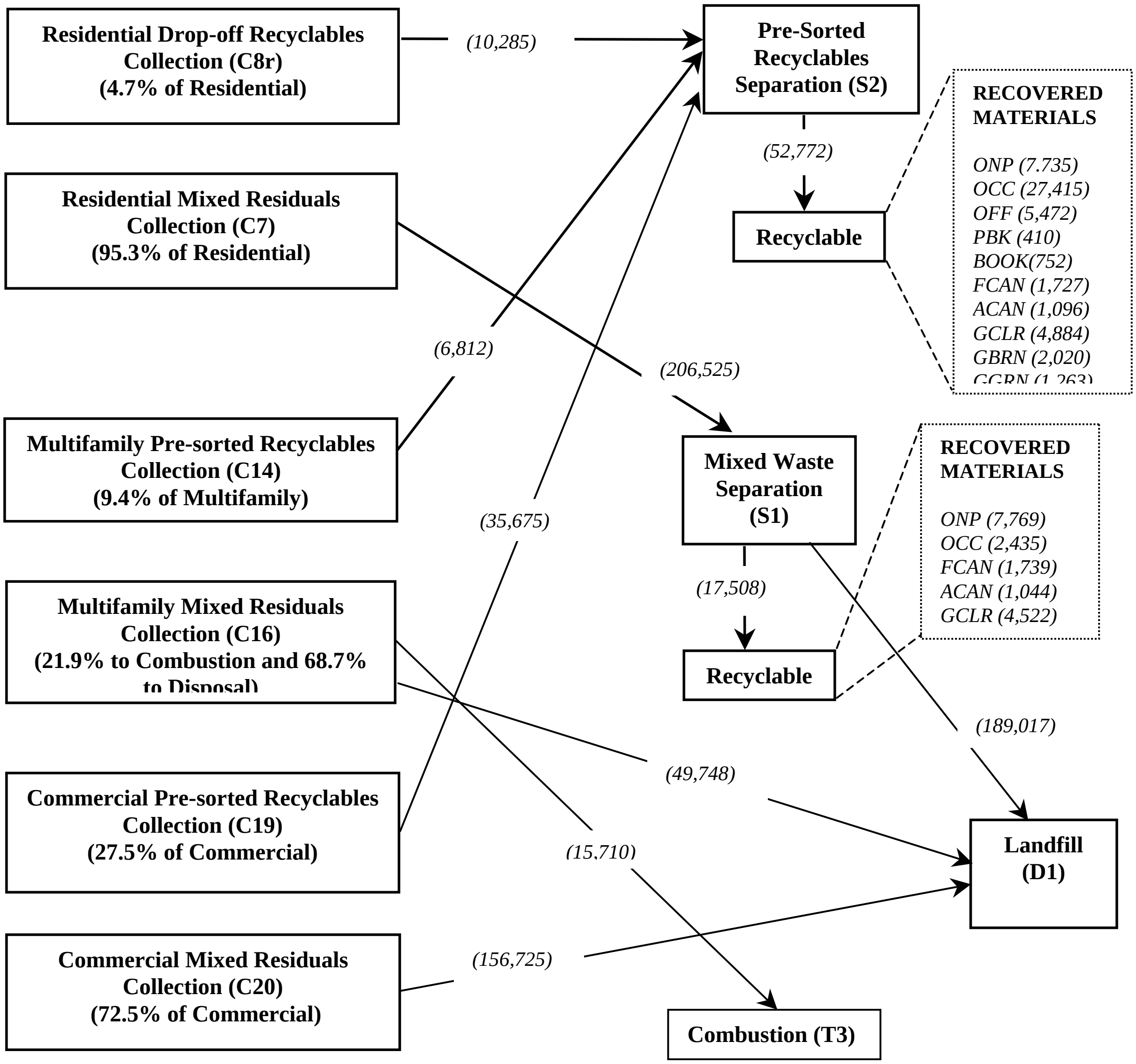
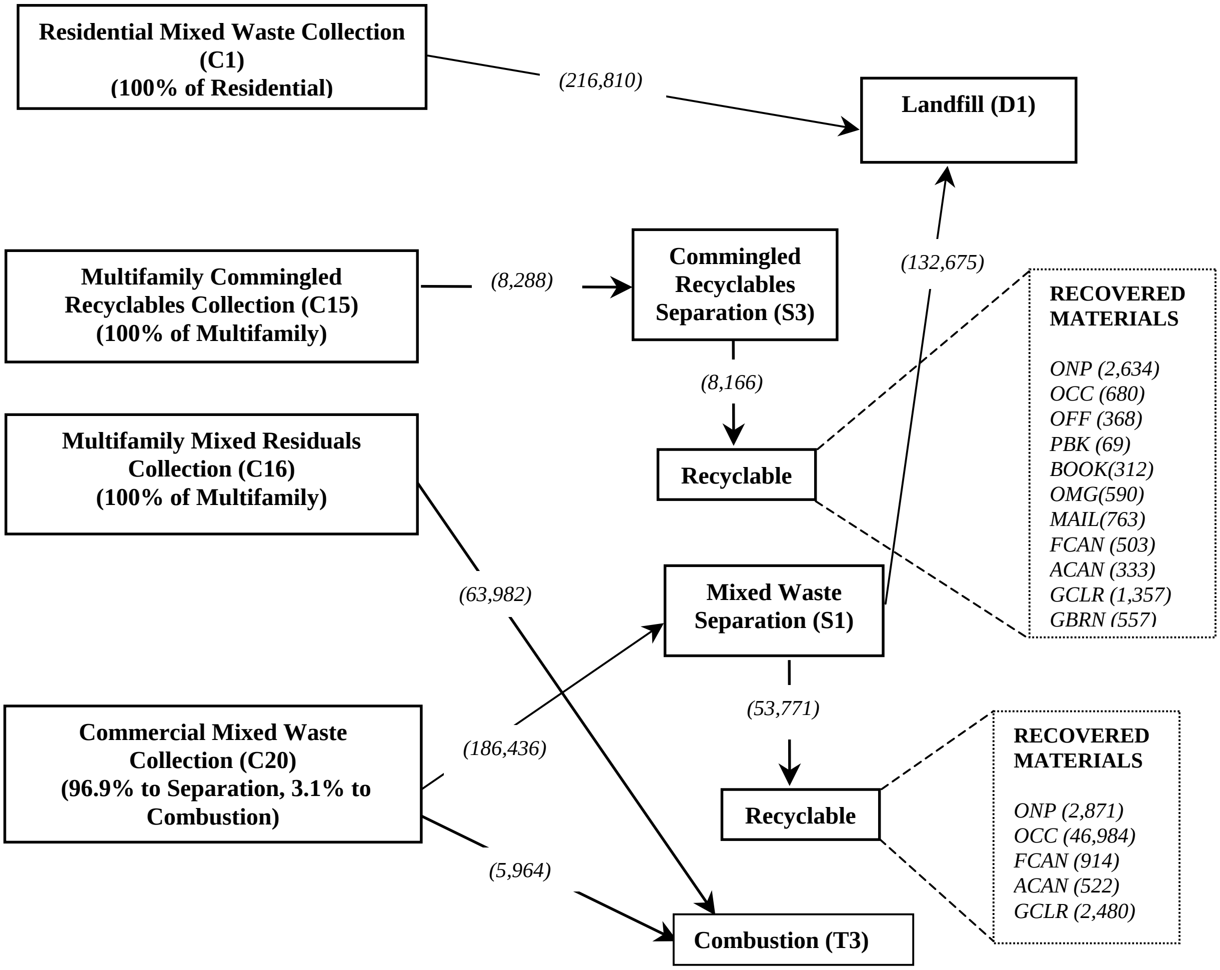


Figure 3.12: Mass flows for SWM Alternative 3

(The numbers in parentheses show the mass in tons/year)



3.7 Summary

This paper illustrates an application of the ISWM model. The use of this model in examining MSW management strategies with consideration of both economic and environmental factors was demonstrated for a realistic, but hypothetical case study for a municipality of medium size. A life-cycle-based methodology was used to calculate emissions of a set of pollutants, including CO, CO2, NOx, SOx, particulate matter, and GHE, and energy consumption. Waste generation from three different sectors and an array of unit processes for waste management were included in the model.

Using this case study, several MSW management and planning scenarios were examined to demonstrate the versatility of the ISWM model. These scenarios considered alternatives for diverting waste from landfills and reducing greenhouse gas emissions. Through these scenarios, the tradeoff between cost and a diversion target as well as the tradeoff between cost and GHE were generated. The ISWM model can easily be extended to carry out similar analyses with the other environmental parameters. Also, the flexible structure of the ISWM model that facilitates site-specific modeling capabilities provides the framework for examining many other scenarios. Under an ongoing contract with USEPA, this model has been integrated into a prototype decision support tool that provides interactive capabilities to allow a user to fully utilize the capabilities of this model in exploring and examining alternative SWM strategies (Harrison et al., 1999).

Although the ISWM model is a very large LP model, the solution times on mid- to high-end MS Windows-based computers are less than 20 seconds. The LP modeling structure required several simplifying assumptions in the linearization of the model. Although these assumptions may be reasonable for the use of this model as a planning and screening tool, any particular solution would need to be examined in more detail as part of an actual design process.

3.8 References

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Chapter 4: Resource Recovery, Landfill Utilization and Environmental Considerations in Integrated Solid Waste Management

4.1 Introduction

Increasing difficulties and problems associated with municipal solid waste (MSW) management have led to several policy and legislative actions by the environmental management agencies in the US and other industrialized nations. For example, with increasing demand for landfill disposal and related concerns about leachate contamination, construction of new landfills are tightly regulated to avoid potential problems in the future. In an effort to reduce the continued demand for landfill space, many cities are actively promoting programs to divert waste from landfills. These programs include increasing efforts in source reduction, recycling, and alternative uses of waste (e.g., waste-to-energy processes).

Depending on the individual needs and severity of the MSW management issues facing the community, each community is experimenting with different solid waste management (SWM) programs and their implementations to address its immediate problems. Typically, these programs are instituted with specific policy goals. For instance, a mandated recycling program may be instituted in a community to achieve either reduced landfill disposal needs or increased recovery of material resources. Lately, federal and local environmental management agencies are concerned about the environmental implication of MSW management activities. This includes net energy consumption and release of environmental emissions resulting directly from each MSW management activity, e.g., NO_x emissions associated with the collection vehicle fleet and facility operation, and CH_4 releases associated with landfill operations. Existing and newer policies are likely to target these new issues as well.

Implementation of an MSW management program typically requires extensive effort and funds. Therefore, prior to implementation, evaluation of a program's potential effectiveness in achieving the targeted policy goals is important. Although the true long-term effectiveness of a program can be evaluated only by implementing that program and monitoring performance indices, prior estimates at the preliminary stage of program design can be used to make relative comparisons of alternative programs. The primary purpose of this paper is to describe a quantitative framework for examining and comparing alternative MSW management programs with respect to meeting specified policy goals. This framework is based on the application of the Integrated Solid Waste Management (ISWM) model, a linear programming (LP) model for integrated MSW management, which is described in Chapter 2. Illustrative applications are described for several alternative programs aimed at achieving a set of policy goals within the context of a realistic, but hypothetical case study.

4.2 Alternative Policy Goals and Considerations

In this paper, alternative MSW management programs and their effectiveness with respect to resource recovery, landfill utilization, and environmental emissions are examined. Although this is not a complete list, these policy goals are selected as a representative list for illustration and demonstration.

Resource Recovery

With growing problems with MSW management and increased local and national attention, many municipalities are viewing some components of MSW as recoverable resources. Recyclable materials recovered from the waste stream are not only a source of revenue, but they are also instrumental in replacing valuable virgin material in many manufacturing processes. A related benefit is the reduced demand on electric energy that results from avoidance of virgin material mining and extraction processes, and some manufacturing processes. Further, modern waste-to-energy processes provide a mechanism to recover energy from MSW, thereby replacing electric energy demand from the supply grid. On a smaller scale, composting processes are used to generate compost by converting waste into a product and diverting the waste from landfills. In general, as a means for meeting the policy goal of maximizing resource recovery, municipalities continue to implement different MSW management programs that target a combination of the recycling, combustion and composting options described above.

In this study, resource recovery level is estimated on the basis of the mass fraction of MSW that is recovered as recyclable materials for use in remanufacturing processes. This is represented by the resource recovery index R_{RES} ($0 \leq R_{RES} \leq 1$), that is calculated as a mass ratio of the actual amount of recyclable materials recovered to the amount of recyclable materials that are in the MSW stream.

Landfill Utilization

Limited space availability for landfill disposal and growing negative public opinion towards landfills and their operations are continuing to be of concern. In some regions and municipalities, MSW management agencies are exploring options that will minimize the demand for landfill utilization. With his goal in mind, several MSW management programs are being tested to divert as much waste as possible from landfills. For example, recycling programs and waste to energy recovery programs divert certain components of MSW from flowing into a landfill, and thereby reducing landfill needs. Also, tax and incentive schemes can be instituted to affect the flow of MSW away from landfills.

In this study, landfill utilization is estimated on the basis of the mass fraction of MSW that requires disposal in a dry landfill. This is represented by the landfill utilization index, R_{LU} ($0 \leq R_{LU} \leq 1$), which is estimated as a mass ratio of the amount of waste disposed in a traditional landfill to the total amount of waste generated.

Environmental Implications

Recent efforts to study and understand the cross-media effects of environmental management in one medium on the others have led to interest in characterizing environmental implications arising from activities associated with MSW management. For example, the operation of a fleet of collection vehicles and heavy earth moving vehicles at landfills, which are integral components of MSW operations, result in emissions of several air pollutants that potentially contribute to air quality problems. Other examples are the generation of pollutants in flue gases from waste-to-energy operations and methane and CO_2 gas production at landfills. In addition, energy consumption by almost all MSW management operations contributes environmental emissions that are associated with energy production. As collective environmental management with cross-media considerations becomes increasingly important, it is anticipated that existing and new policies will be reexamined to target environmental emissions from MSW management activities. Thus, new and existing MSW management programs will likely be restructured to meet these new goals.

Although environmental emissions of numerous species are tracked in the ISWM model (Chapter 2), this study will focus only on greenhouse gas emissions, which is expressed in terms of greenhouse gas equivalents (GHE). GHE is represented as a weighted sum of CO_2 (fossil), CO_2 (biomass), CH_4, and NO_x emissions (in lbs/yr) as given below. The weight for CO_2 (biomass) is assumed to be zero in this study.

$$GHE = CO_2\,(\text{fossil}) + 63\ CH_4 + 270\ NO_x \qquad \textbf{(Eq. 4.1)}$$

Emission estimates represent the sum of emissions from all unit operations used in an MSW management strategy. Emissions in each unit operation are allocated by individual waste item that enters that unit operation. These emissions are estimated using a life cycle methodology, resulting in a life cycle inventory (LCI) of emissions. For example, NO_x emissions include those associated with: combustion of diesel fuel in collection vehicles, production and transport of that fuel (referred to as pre-combustion emissions), and production and delivery of electricity used in the collection facilities (e.g., offices and garages). In cases where recyclable materials are recovered or waste is used to generate electricity, an offset approach is used to estimate the net LCI. For example, the LCI associated with remanufacture of aluminum represents the difference between the emissions resulting from the remanufacturing processes for production of ingot from recycled aluminum and the emissions associated with the production of ingot from virgin material. Similarly, when electricity is recovered via combustion or landfill gas, the corresponding emissions associated with the generation of an equivalent amount of electricity by a utility are subtracted from the total LCI.

In this study, a GHE index R_{GHE} ($0 \leq R_{GHE} \leq 1$) is computed as the ratio of the GHE that is saved by an MSW management strategy to the maximum possible GHE that can be saved.

$$R_{GHE} = [GHE_{max} - GHE_{Strategy}] / [GHE_{max} - GHE_{min}] \qquad \textbf{(Eq. 4.2)}$$

where: $GHE_{Strategy}$ is the net GHE for a given strategy, and GHE_{min} and GHE_{max} are the minimum and the maximum amounts, respectively, of net GHE that can be attained for the case study. The ISWM model is used to identify the MSW management strategies that yield the maximum and minimum amounts of GHE.

4.3 Description of the Case Study

A hypothetical case study representing an urban region of medium size was defined. Waste generation rates and compositions were categorized by three separate sectors: a single family home sector, a multi family home sector and a commercial sector. The key parameters that define this case study are listed in Tables 4.1 and 4.2. The case study definition also required the values of many other site-specific input parameters (e.g., distances among waste processing facilities, collection frequencies, level of participation of households in different collection programs, etc.). The reader is referred to the appendix for the full list. Only a subset of the complete set of unit operations was included in this case study as listed in Table 4.3. The waste items that are considered for recycling are indicated in Table 4.1.

The ISWM model, which was implemented using the above information for the case study, was used to investigate the following base scenarios: minimum cost, maximum recyclable materials recovery, minimum GHE, and minimum landfill utilization. The resource recovery index (R_{RES}), landfill utilization index (R_{LU}), and GHE index (R_{GHE}) were estimated for the MSW management strategies generated for each scenario. These scenarios and the resulting strategies are described in the following sub-section.

Table 4.1: Waste stream composition (by wet weight) (1)

Item	Abbreviation	Residential (%)	Multifamily (%)	Commercial (%)
Yard Trimmings, Leaves	YTL	5.6	5.6	n/a
Yard Trimmings, Grass	YTG	9.3	9.3	n/a
Yard Trimmings, Branches	YTB	3.7	3.7	n/a
Old Newsprint *	ONP	6.7	6.7	2.2
Old Corrugated Cardboard*	OCC	2.1	2.1	36.0
Office Paper *	OFF	1.3	1.3	7.2
Phone Books *	PBK	0.2	0.2	0.3
Books *	BOOK	0.9	0.9	n/a
Old Magazines *	OMG	1.7	1.7	n/a
3rd Class Mail *	MAIL	2.2	2.2	2.3
Paper - Non-recyclable	PNR	17.1	17.1	n/a
CCCR Other (2)	CCR_O	n/a	n/a	1.9
HDPE - Translucent *	HDT	0.4	0.4	n/a
HDPE - Pigmented *	HDP	0.5	0.5	n/a
PET Beverage Containers *	PPET	0.4	0.4	0.2
Plastic - Non-Recyclable	PLNR	9.9	9.9	n/a
CCNR Other (3)	CNR_O	n/a	n/a	4.1
Ferrous Cans *	FCAN	1.5	1.5	0.7
Ferrous - Non-recyclable	FNR	3.2	3.2	n/a
Aluminum Cans *	ACAN	0.9	0.9	0.4
Al - Non-recyclable	ANR	0.5	0.5	n/a
Glass - Clear *	GCLR	3.9	3.9	1.9
Glass - Brown *	GBRN	1.6	1.6	0.8
Glass - Green *	GGRN	1.0	1.0	0.5
Glass - Non-recyclable	GNR	0.7	0.7	n/a
CNNR Other (4)	NNR_O	n/a	n/a	2.4
Food Waste	FW	4.9	4.9	n/a
CCCN Other (5)	CCN_O	n/a	n/a	17.1
Miscellaneous combustible (6)	MIS_CNN	7.5	7.5	n/a
CCNN Other (7)	CNN_O	n/a	n/a	11.3
Miscellaneous (8)	MIS_NNN	12.3	12.3	n/a
CNNN Other (9)	NNN_O	n/a	n/a	10.7

* denotes an item considered for recycling in this case study

Notes:

(1) The waste composition was adopted from USEPA (1997).

(2) CCCR-Other represents commercial wastes that are combustible, compostable and recyclable.

(3) CCNR-Other represents commercial wastes that are combustible, non-compostable and recyclable.

(4) CNNR-Other represents commercial wastes that are non-combustible, non-compostable and recyclable.

(5) CCCN-Other represents commercial wastes that are combustible, compostable and non- recyclable.

(6) Miscellaneous-combustible represents wastes from the residential and multifamily sectors that are combustible but non-recyclable.

(7) CCNN-Other represents commercial wastes that are combustible, non-compostable and non- recyclable.

(8) Miscellaneous represents wastes from the residential and multifamily sectors that are non-combustible and non-recyclable.

(9) CNNN-Other represents commercial wastes that are non-combustible, non-compostable and non- recyclable.

Table 4.2: Solid waste generation

Sector Name	Population	Residents per home	Units (1)	Waste generation (2)	Total generation (tons/year)
Residential	450,000	2.63	171,103	2.64	216,810
Multifamily	150,000	N/A	750	2.64	72,270
Commercial	N/A	N/A	2,000	3,700	192,400

(1) For the residential sectors: houses; for the multifamily sectors: storage points; for the commercial sector: commercial locations.

(2) Expressed in lbs/person/day for the Residential and Multifamily sectors and in lbs/location/week for the commercial sector.

Table 4.3: Unit operations used in the case study

Operation	Code	Description
Residential Collection	C0	Collection of yard trimmings for aerobic composting
	C1	Collection of mixed MSW in one truck prior to separation of any component
	C2	Collection of commingled recyclables (sorted at the point of collection by the collection crew)
	C3	Collection of pre-sorted recyclables
	C4	Collection of commingled recyclables (to be sorted at a MRF); ONP in separate compartment
	C5	Co-collection of MSW and recyclables in a single-compartment truck
	C7	Collection of mixed MSW after removal of recyclables or yard waste
	C8r	Recyclables drop-off by the generator
	C11	Collection of wet, dry and recyclable fractions in three different compartments
Multi-Family Collection	C8m	Recyclables drop-off by the generator
	C13	Collection of mixed MSW
	C14	Collection of pre-sorted recyclables (multiple bins)
	C15	Collection of commingled recyclables (two bins, ONP separate)
	C16	Collection of MSW after removal of recyclables via C14 or C15
	C17	Collection of wet, dry and recyclable fractions in three different compartments
Commercial Collection	C19	Collection of pre-sorted recyclables
	C20	Collection of mixed MSW (before or after recyclables removal)
Transfer	TR1	Transfer of mixed MSW
	TR2	Transfer of commingled recyclables (not in bags)
	TR5	Transfer of pre-sorted recyclables
	RT1	Rail transfer of MSW from collection vehicles
	RT2	Rail transfer of MSW from trains to haul vehicles at landfill D1
Separation	S1	Sorting of mixed refuse
	S2	Processing of pre-sorted recyclables collected via C2 and C3
	S3	Sorting of commingled recyclables collected via C4
	S4	Sorting of co-collected recyclables collected via C5
Treatment	T1	Aerobic composting of yard waste
	T3	Combustion with electric power generation
Disposal	D1	Landfill
	D2	Ash Landfill

4.3.1 Base Scenarios

The ISWM model was solved (using the CPLEX LP solver) to identify the minimum cost MSW management strategy. The unit operations and the waste flow paths are shown in Figure 4.1. The breakdown of cost and mass of waste by unit operations are shown in Table 4.4. Although no recycling requirements were imposed, the minimum cost strategy includes recovery of recyclables via co-collection for the residential sector and pre-sorted collection for the multifamily sector because these options are cost-effective for this case. The objective function in the ISWM model was then modified to identify the best MSW management strategies for the maximum recycling, minimum GHE and minimum landfill utilization scenarios. Again, the cost and mass flow by unit operations for these strategies are listed in Table 4.4.

Figure 4.1: Mass flows in the minimum cost strategy

(The numbers in parentheses show the mass in tons/year.)

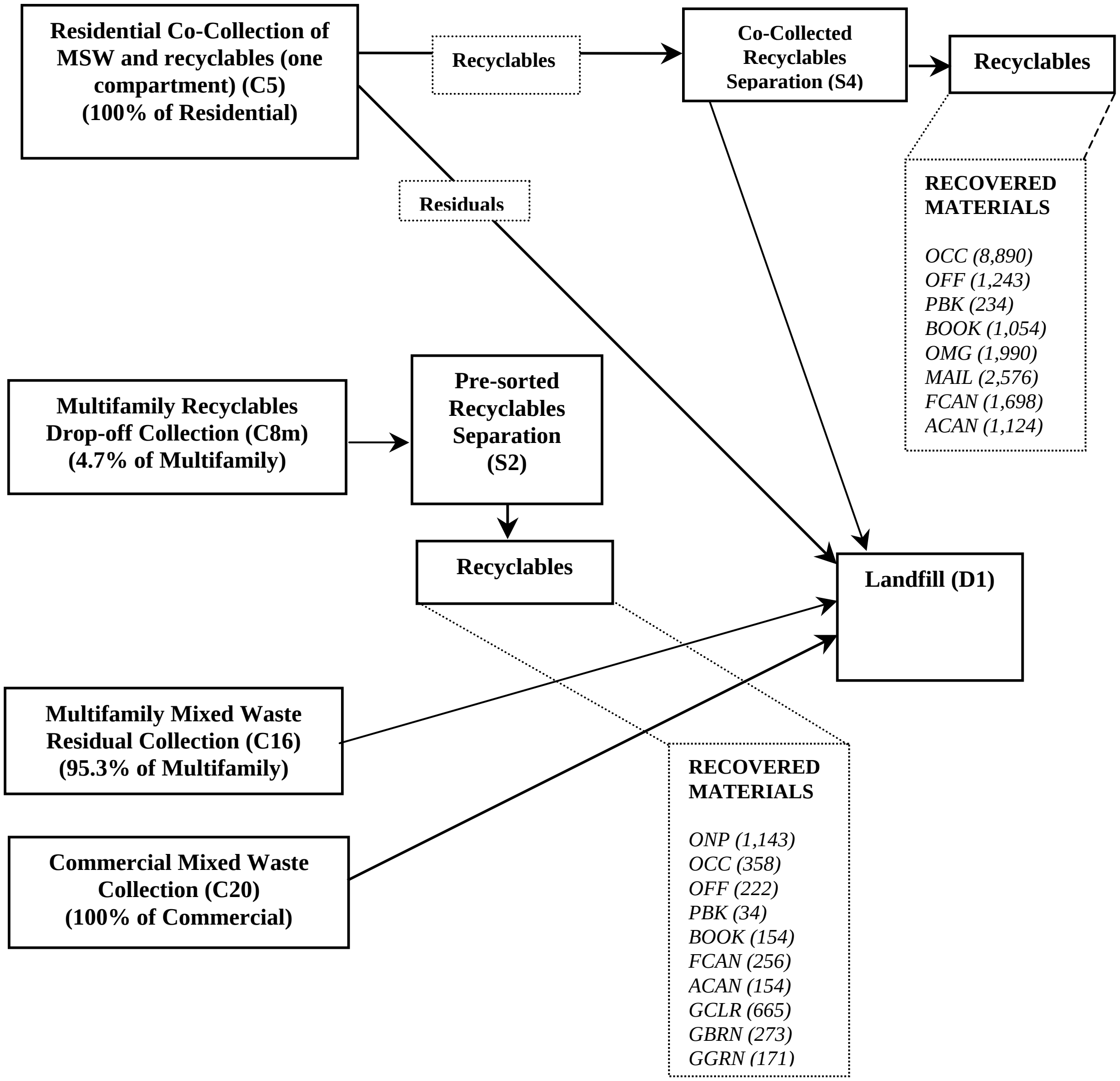


Table 4.4: Cost and mass flows for the base scenarios

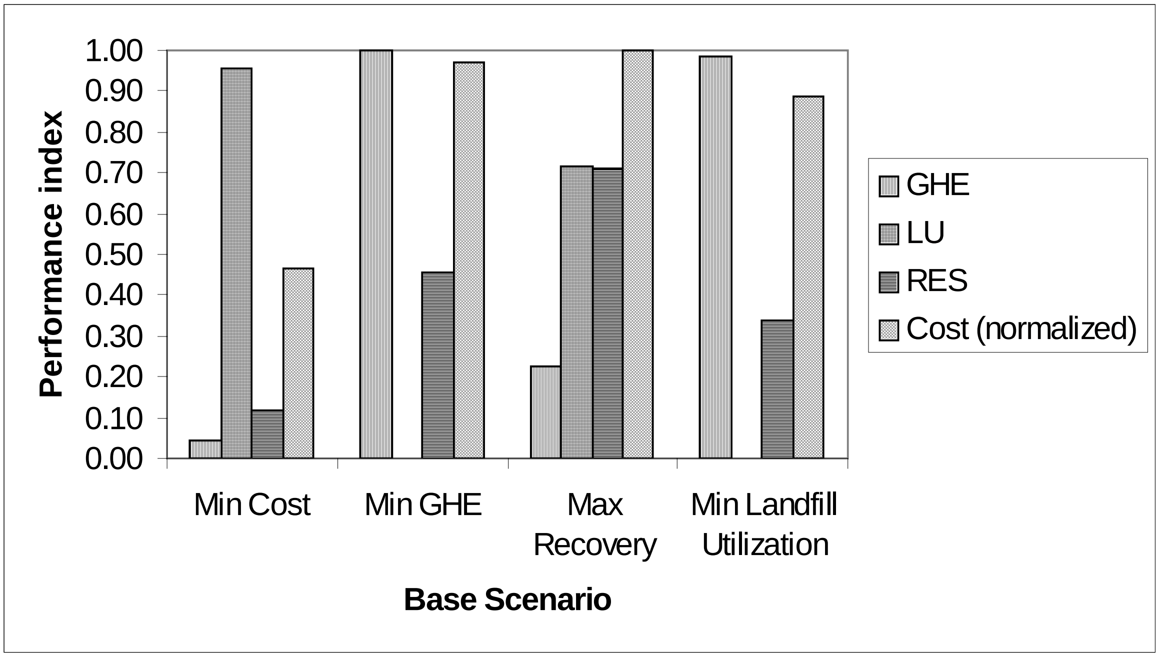
Unit Processes	**Scenarios**							
	Minimum Cost		Minimum GHE		Maximum recovery		Minimum landfill utilization	
	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)
Residential Collection								
Co-collection in single comp. (C5)	7.4	217	7.4	217	-	-	7.4	217
Wet-dry-recyclables (C11)	-	-	-	-	29.6	216	-	-
Multifamily Collection								
Recyclables Drop-off (C8m)	0.1	3	-	-	-	-	0.1	3
Pre-sorted Recyclables (C14)								
Commingled Recyclables (C15)	-	-	1.4	7	-	-	-	-
Residuals (C16)	2.3	69	2.2	66	-	-	2.3	69
Wet-dry-recyclables (C17)	-	-	-	-	4.6	72	-	-
Commercial Collection								
Pre-sorted recyclables (C19)	-	-	6.2	31	6.3	36	-	-
Residuals (C20)	-	-	7.0	162	6.8	157	-	-
Mixed waste (C20)	7.7	192	-	-	-	-	7.7	192
Separation								
Mixed waste MRF (S1)	-	-	6.0	228	7.9	323	5.8	192
Pre-sorted recyclables MRF (S2)	0.05	3	0.5	30.6	0.6	36	0.1	3
Commingled recyc. (S3)	-	-	0.7	6.5	5.0	55	-	-
Co-collected recyc. MRF (S4)	1.3	21	1.4	5.4	-	-	-	-
Treatment								
Combustion (T3)	-	-	29.3	398	-	-	31.0	422
Disposal								
Landfill (D1)	11.1	459	0.02	0.7	8.3	346	-	-
Ash landfill (D2)	-	-	1.8	123	-	-	2.0	131
Transportation	0.00	24	0.7	393	0.6	414	0.6	327
Recyclable revenues ($10^6\$$/yr)	2.6		7.3		10.8		4.4	
Net cost ($10^6\$$/yr)	**27.3**		**57.2**		**59.0**		**52.4**	
Resource Recovery (10^3ton/yr)	**22**		**87**		**135**		**64**	
Landfill utilization (10^3ton/yr)	**459**		**1**		**346**		**0**	
GHE (10^9ton/yr)	**6.3**		**-1.1**		**4.9**		**-1.0**	

4.3.2 Performance Comparison

The key performance criteria (i.e., resource recovery, landfill utilization, and GHE) described in Section 4.2 were estimated for the best strategy corresponding to each base scenario. They are listed in Table 4.4. These values provide the benchmarks for each criterion for this specific case study. To enable relative comparisons among these strategies, the indices R_{RES}, R_{LU}, and R_{GHE} were also computed. The net cost normalized by the maximum cost is also computed. They are summarized in Figure 4.2.

Figure 4.2: Performance comparison of the strategies for the base scenarios

(Best values for GHE, LU and RES are1,0,1, respectively)



4.4 Alternative MSW Management Programs for Meeting Policy Goals

For the case study, the results in Table 4.4 and Figure 4.2 show the full range of performance one may expect to achieve with respect to the policy goals of maximizing resource recovery, minimizing landfill utilization and minimizing environmental (GHE) emissions. Municipalities and MSW management agencies attempt various MSW management programs to best achieve these goals. For instance, direct regulations that require a specified material recovery rate can be instituted to divert MSW away from landfills. This could be achieved, for example, via a commingled recyclable collection program or a recyclable drop-off program. Alternatively, a landfill tax or pay-as-you-throw system could be imposed to achieve the same goal. Further, incentive schemes could be instituted to subsidize the market prices for recyclable materials, thus enhancing resource recovery and reducing landfill utilization. A large number of similar alternative programs are available, each potentially yielding a different level of performance with respect to stipulated policy goals. Identifying the best MSW management program given tradeoff among the policy goals is the challenge faced by municipalities.

The ISWM model provides a tool to address this problem. This model can be employed to represent different approaches that municipalities may typically examine. For example, a fee-based approach that imposes an additional fee for disposal can be easily represented by adjusting the landfill tipping fee accordingly. In a more indirect and complex approach, such as a federal incentive scheme for recovery of recyclable material from the waste stream, the ISWM model can be implemented with adjustments in appropriate parameters according to how the incentives are returned to the MSW management system. For instance, if the incentives are used by the municipalities for recycling-related public awareness campaigns, then the factors that represent the level of participation of public in existing recycling programs should be adjusted to reflect expected increases in recyclable materials set out by each household.

A range of MSW management programs were examined and their performances with respect to meeting the goals of maximizing resource recovery, minimizing landfill utilization, and minimizing GHE were evaluated and compared for the case study. Table 4.5 shows a template that is used to represent within the ISWM model each program described in the subsequent sections.

Table 4.5: Template of table representing an MSW management program

Program name	A symbolic name of the program.
Program description	A short description program, its main purpose and its important characteristics.
ISWM Model objective	The criterion that is used to identify the MSW management strategy.
ISWM Model set-up and special constraints	List of special constraints that will be needed to model a specific program. Unit processes and collection combination options that will be enabled.
Changes in parameters settings	Modifications to input and model parameters.

4.5 Direct Regulation for MSW Management

4.5.1 Recycling Programs

While many communities continue to implement recycling programs on a voluntary basis, some municipalities directly regulate the recycling rate. In this study, the recycling rate is defined in terms of the ratio of total mass of recycled materials recovered to the total mass of MSW generated. For example, achieving a 10% recycling rate from a total MSW generation of 100,000 tons/year means that 10,000 tons of waste will be recovered as recyclable materials. Many alternative recycling programs can be used to meet these regulations. A set of scenarios were modeled and solved to identify the most cost effective way for a municipality to achieve a range of target recycling rates for the case study (Table 4.6).

Table 4.6: Mandated recycling programs

Program name	RECYCLING_# (1)
Program description	Determine minimum cost strategy to meet a minimum recycling target. Recyclable material may be recovered from all three sectors. All collection options are enabled. Includes one residential sector, one multifamily sector, and one commercial sector.
ISWM Model objective	Minimize cost.
ISWM Model set-up and special constraints	Enable all recycling collection options. Include a constraint for recycling target. Solve repeatedly for different recycling targets.
Changes in parameters settings	None.

(1) Set of scenarios RECYCLING_1, RECYCLING_2, etc, with different recycling targets.

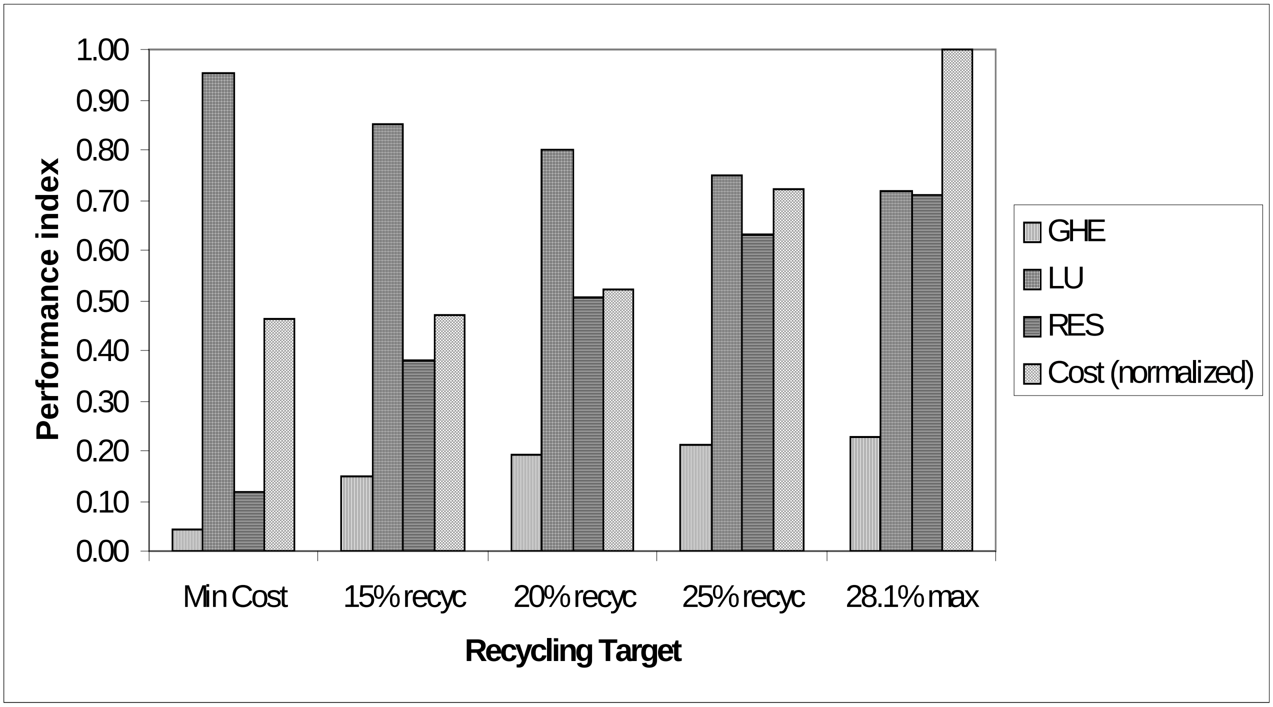
These strategies for the recycling programs were then evaluated with respect to how well they achieve the three policy goals. The estimates for R_{RES}, R_{LU} and R_{GHE} for each strategy are provided in Table 4.7. The relative performance of these strategies compared to the minimum cost strategy is shown in Figure 4.3.

Table 4.7: Cost and mass flows for the cost-effective strategies for recycling programs and minimum cost strategy

Unit Processes	**Scenarios**									
	Minimum Cost (4.6% recycling)		15% recycling		20% recycling		25% recycling		28.1% (max) recycling	
	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)
Residential Collection										
Co-collection in single comp. (C5)	7.39	217	7.39	217	7.39	217	0.04	1.3	-	-
Residuals (C7)	-	-	-	-	-	-	11.3	205	-	-
Recyclables Drop-off (C8r)	-	-	-	-	-	-	0.56	10.9	-	-
Wet-dry-recyclables (C11)	-	-	-	-	-	-	-	-	29.6	216
Multifamily Collection										
Recyclables Drop-off (C8m)	0.11	3.4	0.11	3.4	-	-	-	-	-	-
Pre-sorted Recyclables (C14)	-	-	-	-	0.86	6.9	-	-	-	-
Residuals (C16)	2.28	68.8	2.28	68.8	2.19	65.3	-	-	-	-
Wet-dry-recyclables (C17)	-	-	-	-	-	-	4.60	72.3	4.60	72.3
Commercial Collection										
Pre-sorted recyclables (C19)	-	-	-	-	4.88	27.7	6.32	35.8	6.32	35.8
Residuals (C20)	-	-	-	-	5.27	121	6.82	157	6.82	157
Mixed waste (C20)	7.73	192	7.73	192	1.76	43.7	-	-	-	-
Separation										
Mixed waste MRF (S1)	-	-	5.10	173	4.46	165	10.9	403	7.92	323
Pre-sorted recyclables MRF (S2)	0.05	3.4	0.05	3.4	0.56	34.6	0.76	46.7	0.58	35.8
Commingled Recyc. MRF (S3)	-	-	-	-	-	-	1.25	13.7	5.00	54.7
Co-collected recyc. MRF (S4)	1.25	20.9	1.25	20.9	1.76	24.1	0.01	0.1	-	-
Treatment	-	-	-	-	-	-	-	-	-	-
Disposal										
Landfill (D1)	11.1	459	9.86	409	9.28	385	8.70	361	8.33	346
Transportation	0.00	24.3	0.26	198	0.26	223	0.72	463	0.59	414
Recyclable revenues (10^6\$/yr)	2.56		6.26		7.96		9.55		10.8	
Net cost (10^6\$/yr)	**27.3**		**27.8**		**30.7**		**42.4**		**59.0**	
Resource Recovery (10^3ton/yr)	**22.2**		**72.2**		**96.3**		**120**		**135**	
Landfill utilization (10^3ton/yr)	**459**		**409**		**385**		**361**		**346**	
GHE (10^9ton/yr)	**6.3**		**5.5**		**5.2**		**5.0**		**4.9**	

Figure 4.3: Comparison of cost effective strategies for recycling programs and the minimum cost strategy

(Best values for GHE, LU and RES are1,0,1, respectively)



The R_{RES} index shows the gradual increase of resource recovery up to a value of approximately 0.71. This indicates that about 29% of the potentially recyclable material can not be recovered by even the most aggressive recycling target. This non-recovered fraction is due to less than 100% participation by households, less than perfect disposal of recyclable materials by participating households, and less than 100% efficiency of sorting at material recovery facilities. The R_{LU} index shows that the most aggressive recycling target results in about 70% (i.e. $R_{LU} \approx 0.7$) landfill utilization. This indicates that for this case study, a recycling program alone will not achieve high levels of reductions in landfill utilization. Similarly, a comparison of the R_{GHE} index shows that less than 25% of the maximum potential reduction in GHE is achieved by a recycling program for this case study.

4.5.2 Yardwaste Management Programs

Yardwaste constitutes a significant fraction of the MSW stream in many communities. Local issues, such as landfill space limitations or pressure from environmental groups to convert biomass to useful products, can typically lead to special yardwaste management programs. For example, yardwaste could be banned from landfills, requiring households to take care of yardwaste they generate. Alternatively, a dedicated yardwaste collection and central composting program could accompany such a ban. By setting different mandatory targets for yardwaste diversion from the landfill, such programs are modeled using the ISWM model for the case study (Table 4.8). This model is solved to identify the minimum cost strategy to implement these programs.

These strategies are evaluated with respect to how well they achieve the three policy goals. These values are listed in Table 4.9. The relative performance of these strategies compared to the minimum cost strategy is shown in Figure 4.4. The impact of these programs on all performance indices is minimal. While the landfill utilization and GHE may change, the overall landfill utilization remains high and GHE remains low.

Table 4.8: Mandated yardwaste management programs

Program name	YARDWASTE_# (1)
Program description	Determine minimum cost strategy to meet a minimum yardwaste diversion target. Diverted yardwaste may be composted or combusted. All collection options are enabled. Includes one residential sector, one multifamily sector, and one commercial sector.
ISWM Model objective	Minimize cost.
ISWM Model set-up and special constraints	Enable all collection options. Include a constraint for yardwaste diversion target. Solve repeatedly for different yardwaste diversion targets.
Changes in parameters settings	None.

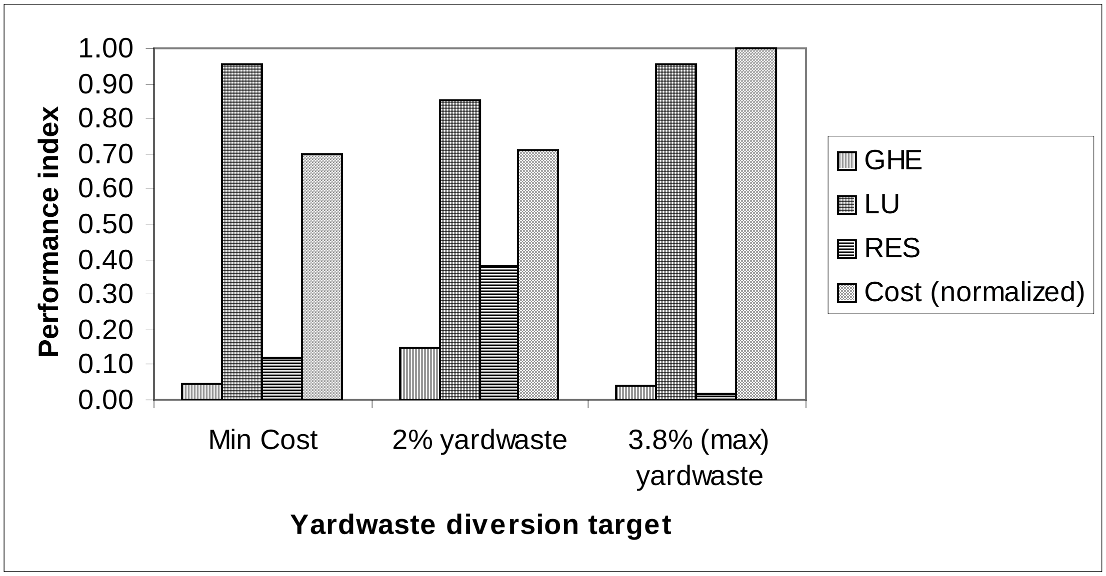
(1) Set of scenarios YARDWASTE_1, YARDWASTE_2, etc, with different yardwaste diversion targets

Table 4.9: Cost and mass flows for the cost-effective strategies for yardwaste programs and the minimum cost strategy

Unit Processes	**Scenarios**					
	Minimum Cost		2% yardwaste diversion		3.8% (max) yardwaste diversion	
Cost or Mass (1)	Cost $(10^{6}\$$ /yr	Mass $(10^{3}$ton /yr)	Cost $(10^{6}\$$ /yr	Mass $(10^{3}$ton /yr)	Cost $(10^{6}\$$ /yr	Mass $(10^{3}$ton /yr)
Residential Collection						
Yardwaste collection (C0)	-	-	3.63	9.6	6.86	18.1
Co-collection in single comp. (C5)	7.39	217	3.47	102	-	-
Residuals (C7)	-	-	5.91	105	11.1	199
Multifamily Collection						
Recyclables Drop-off (C8m)	0.11	3.4	0.11	3.4	0.11	3.4
Residuals (C16)	2.28	68.8	2.28	68.8	2.28	68.8
Commercial Collection						
Mixed waste (C20)	7.73	192	7.73	192	7.73	192
Separation						
Pre-sorted recyclables MRF (S2)	0.05	3.4	0.05	3.4	0.05	3.4
Co-collected recyc. MRF (S4)	1.25	20.9	0.59	9.8	-	-
Treatment						
Yardwaste composting (T1)	-	-	0.13	9.6	0.25	18.1
Disposal						
Landfill (D1)	11.1	459	11.1	460	11.1	460
Transportation	0.00	24.3	0.01	22.9	0.02	21.6
Recyclable revenues (10^{6}\$/yr)	2.56		1.37		0.32	
Net cost (10^{6}\$/yr)	**27.3**		**33.6**		**39.2**	
Resource Recovery (10^{3}ton/yr)	**22.2**		**12.3**		**3.4**	
Landfill utilization (10^{3}ton/yr)	**459**		**460**		**460**	
GHE (10^{9}ton/yr)	**6.3**		**6.3**		**6.3**	

Figure 4.4: Comparison of cost effective strategies for yardwaste programs and the minimum cost strategy

(Best values for GHE, LU and RES are 1,0,1, respectively)



4.5.3 Alternative Outcomes under Direct Regulations

The previous sections present the most cost-effective outcomes that would be expected if different direct regulations are implemented. Although the resulting MSW management strategies are "optimal" for the modeled system, they may not necessarily be the best for the real system since the model may not capture all issues. Thus, local issues that are not explicitly modeled may drive two similar municipalities to implement two distinctly different SWM strategies costing approximately the same. The effectiveness in achieving the policy goals, however, may vary significantly among these different strategies. This should be considered when evaluating the effectiveness of an MSW management program. One approach is to examine different outcomes that may potentially result for a given program. The modeling to generate alternatives (MGA) approach (Brill *et al.*, 1982; Chang *et al.*, 1982; Brill *et al.*, 1990) provides an efficient approach to generate a small set of distinctly different MSW management strategies that have a cost within a specified range. Being different in the choices of unit operations and the mass flows in the alternative strategies, they are likely to perform differently with respect to different policy objectives. Therefore, these alternatives provide a means to estimate the range of performance of a given MSW management program.

The two programs for direct regulations described above were reexamined. The MGA approach was applied to the ISWM model for each program to generate a small set of alternative MSW management strategies. These alternatives were then evaluated and compared with respect to the three policy goals considered in this study.

4.5.3.1 Alternative Outcomes for the 20% Recycling Program

The ISWM model for the 20% recycling program was modified to implement a corresponding MGA model in which a cost constraint was added. In this constraint, the cost was relaxed by 20% (which was arbitrarily chosen; any other level of relaxation can be modeled similarly) of the cost of the minimum cost strategy ($ 30.7 million/year). Four alternative strategies were generated. They are summarized in Table 4.10. A comparison of the performance of these strategies is shown in Figure 4.5.

Table 4.10: Cost and mass flows for the cost-effective strategies for the 20% recycling scenario and its alternative solutions

Unit Processes	**Scenarios**									
	20% Recycling		Alternative 1		Alternative 2		Alternative 3		Alternative 4	
Cost or Mass (1)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)
Residential Collection										
Co-collection in single comp. (C5)	7.39	217	7.39	217	7.39	217	-	-	7.39	217
Residuals (C7)	-	-	-	-	-	-	11.3	206	-	-
Recyclables Drop-off (C8r)	-	-	-	-	-	-	0.46	10.7	-	-
Multifamily Collection										
Pre-sorted Recyclables (C14)	0.86	0.9	-	-	0.96	7.2	-	-	-	-
Commingled Recyclables (C15)	-	-	-	-	-	-	1.27	8.7	-	-
Residuals (C16)	2.19	65.3	-	-	2.2	65.1	2.15	63.6		
Wet-dry-recyclables (C17)	-	-	4.60	72.3	-	-	-	-	4.60	72.3
Commercial Collection										
Pre-sorted recyclables (C19)	4.88	27.7	6.32	35.8	4.05	23.0	-	-	6.32	35.8
Residuals (C20)	5.27	121	6.82	157	4.37	100	-	-	6.82	157
Mixed waste (C20)	1.76	43.7	-	-	2.77	69.0	7.73	192	-	-
Separation										
Mixed waste MRF (S1)	4.46	165	2.79	107	4.87	169	10.9	399	3.42	157
Pre-sorted recyclables MRF (S2)	0.56	34.6	0.58	35.8	0.49	30.2	0.17	10.7	0.58	35.8
Commingled recyc. MRF (S3)	-	-	1.25	13.7	-	-	0.73	8.7	1.25	13.7
Co-collected recyc. MRF (S4)	1.76	24.1	2.02	25.0	2.02	25.0	-	-	2.02	25.0
Treatment										
Combustion (T3)	-	-	4.75	64.2	8.35	118.3	0.03	0.4	3.94	53.5
Disposal										
Landfill (D1)	9.28	385	7.74	321	6.44	267	9.27	385	7.99	332
Ash landfill (D2)	-	-	0.36	24.4	0.51	34.5	0.002	0.1	0.31	20.5
Transportation	0.26	223	0.23	206	0.34	259	0.68	418	0.29	235
Recyclable revenues ($10^6\$$/yr)	7.96		7.96		7.85		7.85		8.03	
Net cost ($10^6\$$/yr)	**30.73**		**36.9**		**36.9**		36.9		36.9	
Resource Recovery (10^3ton/yr)	**96.3**		**96.3**		**96.3**		**96.3**		**96.3**	
Landfill utilization (10^3ton/yr)	**385**		**346**		**267**		**385**		**332**	
GHE (10^9ton/yr)	**5.2**		**3.7**		**4.6**		**5.3**		**3.9**	

Figure 4.5: Comparison of cost-effective strategies for the 20% recycling scenario and its alternative scenarios

(Best values for GHE, LU and RES are1,0,1, respectively)

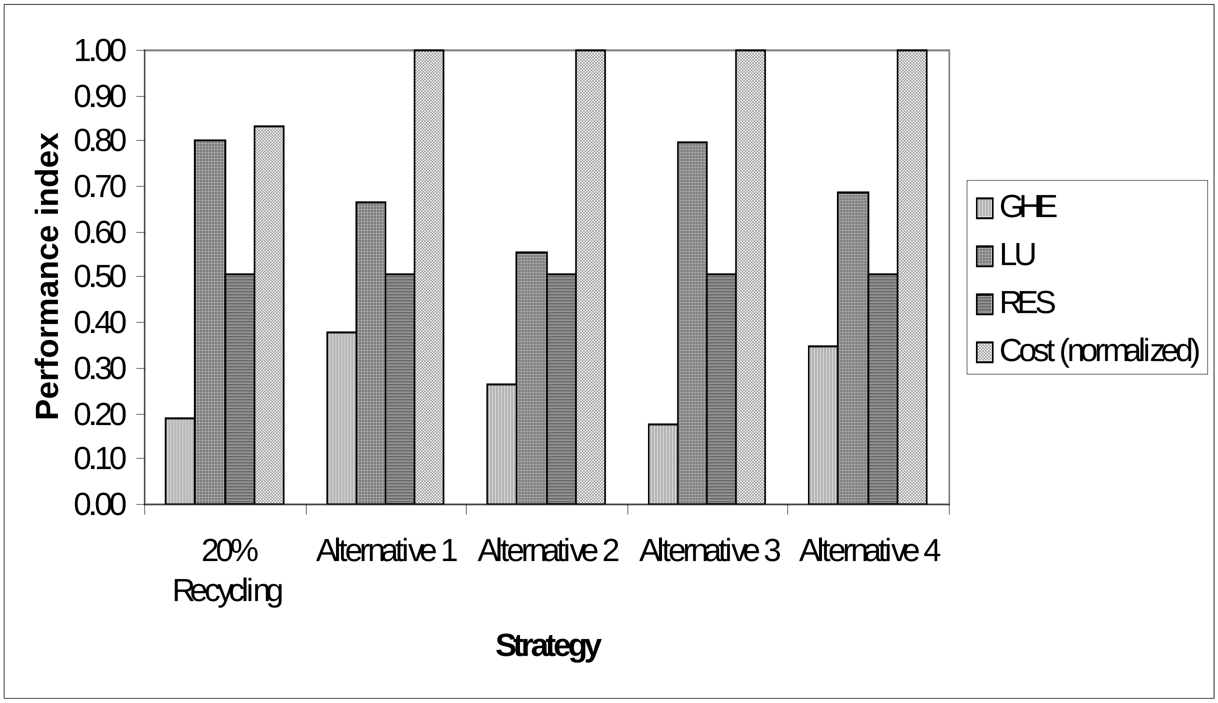


Table 4.10 shows that all unit processes were selected among these alternatives, resulting in unique and different strategies. This indicates that a municipality looking to implement a cost-effective MSW management strategy to require 20% recycling could select a wide range of strategies. Their performance comparison shows a significant variation with respect to GHE and landfill utilization. This comparison provides an insight into the degree of variation in attaining different policy goals that could result from different implementation plans when a recycling target is mandated. It also suggests that such a planning tool could be used by designers to develop effective strategies for a given case.

4.5.3.2 Alternative Outcomes for Yardwaste Management Program

The ISWM model for the maximum yardwaste management program was modified to implement a corresponding MGA model in which a cost constraint was added. In this constraint, the cost was relaxed by 20% (again arbitrarily chosen) of the cost of the maximum yardwaste management strategy ($ 39.2 million/year). Four alternative strategies were generated. They are summarized in Table 4.11. A comparison of the performance of these strategies is shown in Figure 4.6.

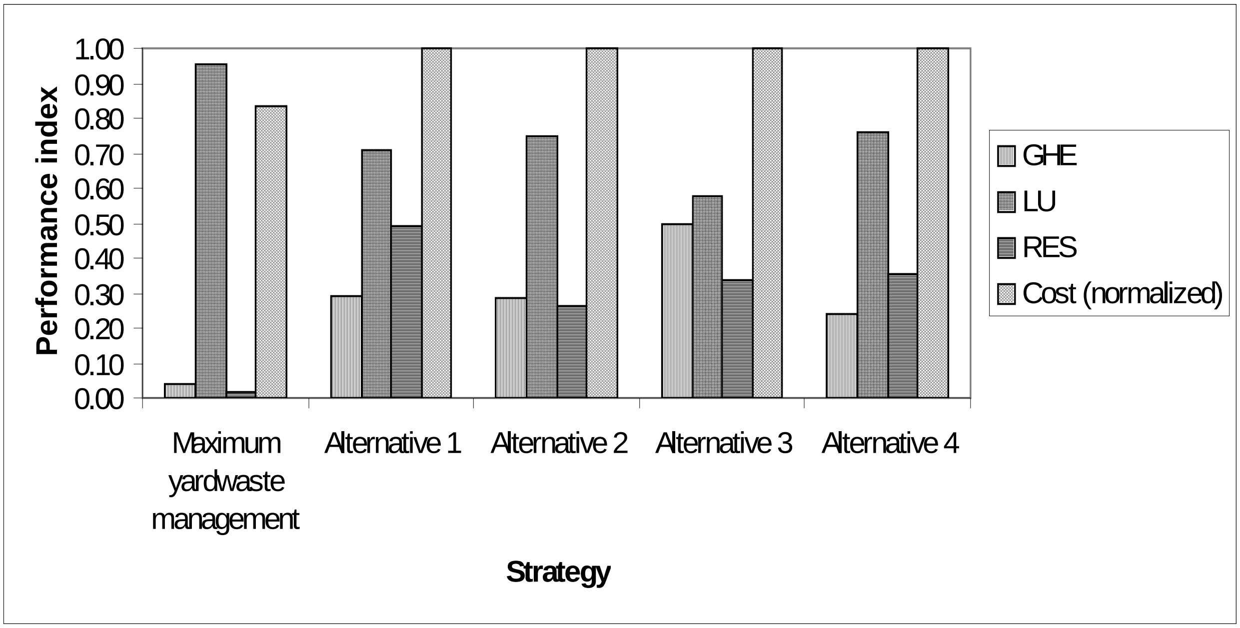
Table 4.11: Cost and mass flows for the cost-effective strategies for the maximum yardwaste management scenario and its alternative solutions

Unit Processes	**Scenarios**									
	Maximum yardwaste management		Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)
Residential Collection										
Yardwaste (C0)	6.86	18.1	6.86	18.1	6.86	18.1	6.86	18.1	6.86	18.1
Residuals (C7)	11.14	198.6	11.14	198.6	11.14	198.6	11.14	198.6	11.14	198.6
Multifamily Collection										
Recyclables Drop-off (C8m)	0.11	3.4	-	-	-	-	-	-	-	-
Mixed waste (C13)	-	-	2.37	72.3	-	-	-	-	2.37	72.3
Pre-sorted Recyclables (C14)	-	-	-	-	-	-	0.84	6.8	-	-
Residuals (C16)	2.28	68.8	-	-	-	-	2.20	65.5	-	-
Wet-dry-recyclables (C17)	-	-	-	-	4.60	17.0	-	-	-	-
Commercial Collection										
Pre-sorted recyclables (C19)	-	-	6.29	35.7	6.29	35.7	-	-	6.29	35.7
Residuals (C20)	-	-	6.82	156.7	6.82	156.7	-	-	6.82	156.7
Mixed waste (C20)	7.73	192.4	-	-	-	-	7.73	192.4	-	-
Separation										
Mixed waste MRF (S1)	-	-	9.12	355.3	-	-	5.66	192.4	6.95	270.9
Pre-sorted recyclables MRF (S2)	0.05	3.4	0.58	35.7	0.58	35.7	0.11	6.8	0.58	35.7
Commingled recyc. MRF (S3)	-	-	-	-	1.25	13.7	-	-	-	-
Treatment										
Yardwaste composting (T1)	0.25	18.1	0.25	18.1	0.25	18.1	0.25	18.1	0.25	18.1
Combustion (T3)	-	-	2.19	29.3	3.95	53.7	9.24	124.0	2.18	29.2
Disposal										
Landfill (D1)	11.08	459.2	8.22	340.9	8.68	360.2	6.68	277.1	8.85	367.1
Ash landfill (D2)	-	-	0.14	9.5	0.31	20.7	0.63	42.5	0.13	9.0
Transportation	0.02	21.6	0.67	418.6	0.07	88.3	0.40	259.8	0.55	333.7
Recyclable revenues (10^6\$/yr)	0.32		7.66		3.80		4.74		5.98	
Net cost (10^6\$/yr)	**39.22**		**47.00**		**47.00**		**47.00**		**47.00**	
Resource Recovery (10^3ton/yr)	**3.4**		**93.5**		**49.6**		**64.1**		**67.2**	
Landfill utilization (10^3ton/yr)	**459.2**		**340.9**		**360.2**		**277.1**		**367.1**	
GHE (10^9ton/yr)	**6.3**		**4.4**		**4.4**		**2.8**		**4.8**	

Similar to the results for mandated recycling program, these results show that all unit processes were selected among these alternatives. The maximum diversion of 3.8% was achieved via yardwaste collection in all strategies, but each strategy includes a unique and different set of other unit processes. These strategies result in significant differences in their effectiveness in achieving the three policy goals; suggesting again that there is a wide range of optima in designing a strategy.

Figure 4.6: Comparison of cost-effective strategies for the maximum yardwaste management scenario and its alternative scenarios

(Best values for GHE, LU and RES are1,0,1, respectively)



4.6 Fee-Based Programs

4.6.1 Tipping Fees

Additional tipping fees on mixed waste entering the facility can be used to control landfill utilization. These fees may be designed to achieve a lower landfill utilization rate by encouraging the municipalities to find alternative cost-effective ways, such as combustion and recycling, to manage MSW. A few tipping fee-based scenarios (Table 4.12) were examined using the ISWM model. These include different scenarios with tipping fees at \$30/ton, \$45/ton, and \$60/ton were modeled (the tipping fee for the base scenario is $23.8/ton). The resulting MSW management strategies are listed in Table 4.13 and their performances are compared in Figure 4.7.

Table 4.12: Disposal fees

Program name	DISPOSAL_CHARGES_# (1)
Program description	All collection options are enabled. Includes one residential sector, one multifamily sector, and one commercial sector.
ISWM Model objective	Minimize cost.
ISWM Model set-up and special constraints	Enable all collection options. The landfill tipping fee will be adjusted to reflect an additional fee.
Changes in parameters settings	None.

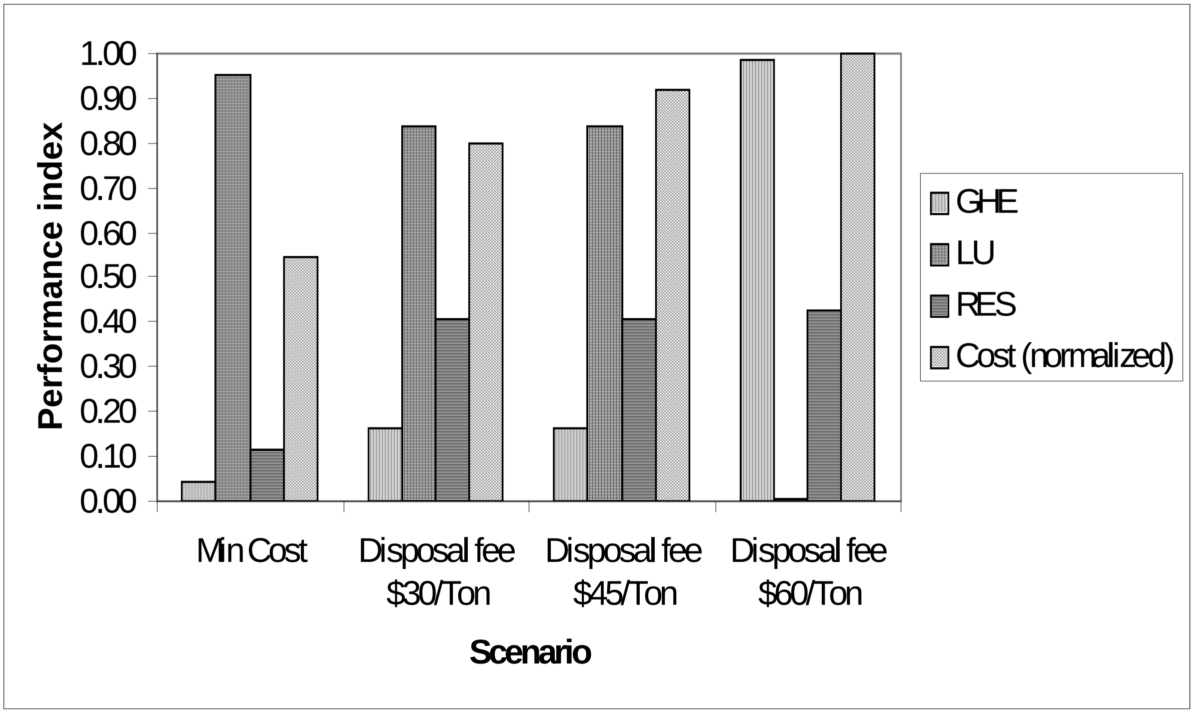
(1) Set of scenarios: DISPOSAL_CHARGES_1, DISPOSAL_CHARGES_2, with incremental values for disposal charges in $/ton.

Table 4.13: Cost and mass flows for the cost-effective strategies for disposal fee scenarios

Unit Processes	Scenarios							
	Minimum Cost		$30/ton landfill tip tax		$45/ton landfill tip fee		$60/ton landfill tip fee	
	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)	Cost (10^6\$ /yr	Mass (10^3ton /yr)
Residential Collection								
Co-collection in single comp. (C5)	7.39	216.8	7.39	216.8	7.39	216.8	7.39	216.8
Multifamily Collection								
Recyclables Drop-off (C8m)	0.11	3.4	0.11	3.4	0.11	3.4	0.11	3.4
Residuals (C16)	2.28	68.8	2.28	68.8	2.28	68.8	2.28	68.8
Commercial Collection								
Mixed waste (C20)	7.73	192.4	7.73	192.4	7.73	192.4	7.73	192.4
Separation								
Mixed waste MRF (S1)	-	-	5.66	192.4	5.66	192.4	5.76	192.4
Pre-sorted recyclables MRF (S2)	0.05	3.4	0.05	3.4	0.05	3.4	0.05	3.4
Co-collected recyc. MRF (S4)	1.25	20.9	1.25	20.9	1.25	20.9	1.25	20.9
Treatment								
Combustion (T3)	-	-	-	-	-	-	29.5	400.6
Disposal								
Landfill (D1)	11.07	459.2	21.84	403.8	27.9	403.8	0.18	2.1
Ash landfill (D2)	-	-	-	-	-	-	1.90	127.5
Transportation	0.00	24.3	0.29	216.7	0.29	216.7	0.55	344.2
Recyclable revenues (10^6\$/yr)	2.56		6.66		6.61		6.69	
Net cost (10^6\$/yr)	**27.33**		**39.96**		**46.01**		**50.00**	
Resource Recovery (10^3ton/yr)	**22.2**		**77.7**		**77.7**		**81.1**	
Landfill utilization (10^3ton/yr)	**459.2**		**403.8**		**403.8**		**2.1**	
GHE (10^9ton/yr)	**6.3**		**5.4**		**5.4**		**-1.0**	

Figure 4.7: Comparison of cost-effective strategies for disposal fee scenarios

(Best values for GHE, LU and RES are 1,0,1, respectively)



With increasing tipping fees, an increasing amount of waste is diverted from the landfill. At $30/ton and $45/ton tipping fees, the most cost-effective way to divert waste is through a mixed waste MRF where recyclables are recovered and the residual is sent to a landfill. At higher tipping fees, it becomes more cost-effective to combust this residual waste.

4.6.2 Alternative Outcomes for Tipping Fee-Based Program

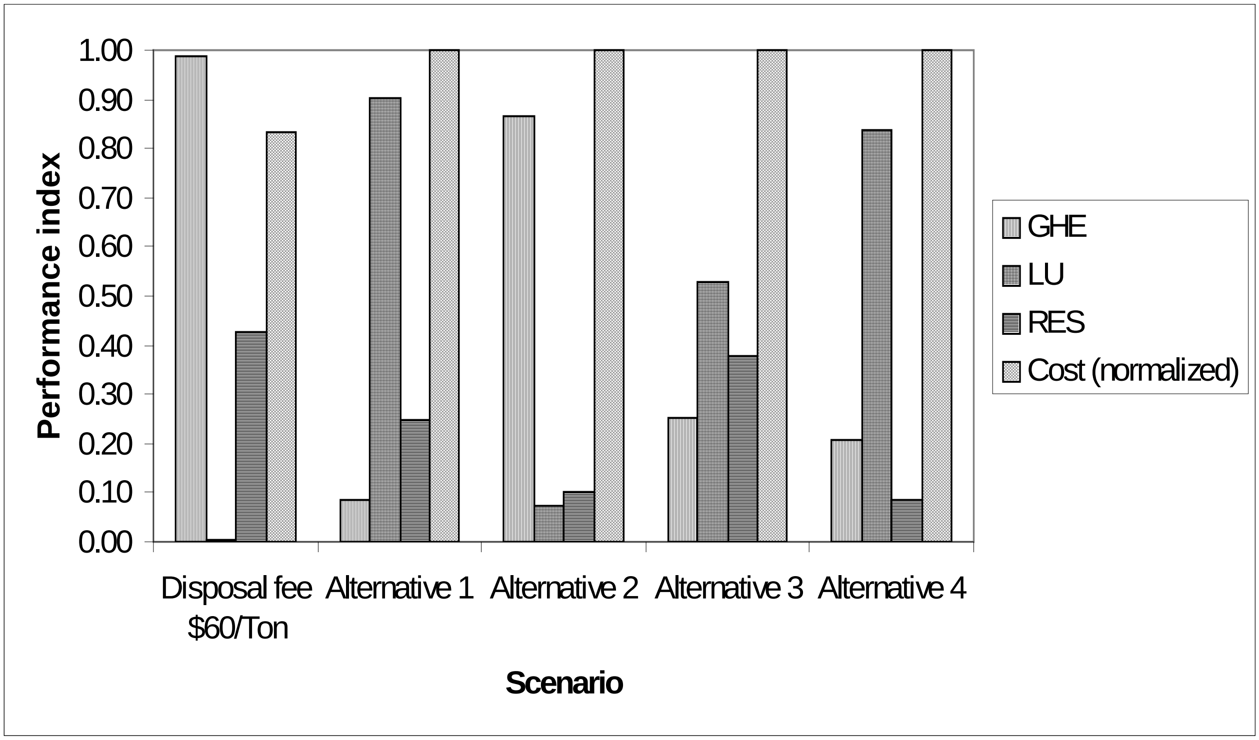
The ISWM model for the \$60/ton tipping fee was modified to implement a corresponding MGA model in which a cost constraint was added. In this constraint, the cost was relaxed by 20% of the \$50 million/year cost of the strategy for the \$60/ton scenario. Four alternative strategies were generated. They are summarized in Table 4.14. A comparison of the performances of these strategies is shown in Figure 4.8. The results are similar to those of the previous MGA cases in that all unit processes were selected among the alternatives. A range of combinations of recycling collection and combustion is used to find cost-effective ways to manage MSW at a high tipping fee. The corresponding differences in their effectiveness in achieving the three policy goals is significant. Notably, the high level of landfill utilization associated with a couple of the alternatives is inconsistent with achieving one primary goal, i.e., minimizing landfill utilization by using a disposal fee. There is also considerable variation in the GHE across the alternatives. These tradeoffs could be explored further in designing an actual strategy for a given case.

Table 4.14: Cost and mass flows for the cost-effective strategies for the $60/Ton disposal fee and its alternative scenarios

Unit Processes	**Scenarios**									
	$60/Ton disposal fee		Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	Cost (10^6\$ /yr	Mass (10^{3}ton /yr)	Cost (10^6\$ /yr	Mass (10^{3}ton /yr)	Cost (10^6\$ /yr	Mass (10^{3}ton /yr)	Cost (10^6\$ /yr	Mass (10^{3}ton /yr)	Cost (10^6\$ /yr	Mass (10^{3}ton /yr)
Residential Collection										
Mixed waste (C1)	-	-	-	-	10.5	196	-	-	7.78	145
Co-collection in single comp. (C5)	7.39	216.8	1.37	40.1	0.72	21.0	0.83	24.2	2.44	71.7
Residuals (C7)	-	-	9.25	168	-	-	10.1	184	-	-
Recyclables Drop-off (C8r)	-	-	0.27	8.4	-	-	0.30	9.1	-	-
Multifamily Collection										
Recyclables Drop-off (C8m)	0.11	3.4								
Mixed Waste (C13)	-	-	2.37	72.3	-	-	-	-	-	-
Pre-sorted Recyclables (C14)			-	-	-	-	0.86	6.9	-	-
Commingled Recyclables (C15)			-	-	-	-	-	-	1.27	8.7
Residuals (C16)	2.28	68.8	-	-	-	-	2.19	65.3	2.15	63.6
Wet-dry-recyclables (C17)			-	-	4.60	72.3	-	-	-	-
Commercial Collection										
Pre-sorted recyclables (C19)	-	-	6.29	35.7	-	-	6.29	35.7	-	-
Residuals (C20)	-	-	6.82	156.7	-	-	6.82	157	-	-
Mixed waste (C20)	7.73	192	-	-	7.73	192	-	-	7.73	192
Separation										
Mixed waste MRF (S1)	5.76	192	-	-	-	-	4.29	184	-	-
Pre-sorted recyclables MRF (S2)	0.05	3.4	0.71	44.1	-	-	0.83	51.7	-	-
Commingled recyc. MRF (S3)	-	-	-	-	1.25	13.7	-	-	0.73	8.7
Co-collected recyc. MRF (S4)	1.25	20.9	0.23	3.9	0.12	2.0	0.14	2.3	0.55	7.8
Treatment										
Combustion (T3)	29.5	401	-	-	31.3	430	11.1	157	4.75	63.6
Disposal										
Landfill (D1)	0.18	2.1	-	-	3.04	36.2	21.3	254	33.8	402
Ash landfill (D2)	1.90	128	36.5	434	1.90	128	0.62	41.9	0.30	20.0
Transportation			0.00	47.9	0.27	143	0.44	279	0.04	36.4
Recyclable revenues (10^6\$/yr)	6.69		3.81		1.41		6.10		1.57	
Net cost (10^6\$/yr)	**50.0**		**60.0**		**60.0**		**60.0**		**60.0**	
Resource Recovery (10^{3}ton/yr)	**81.1**		**47.5**		**19.4**		**71.8**		**16.0**	
Landfill utilization (10^{3}ton/yr)	**2.1**		**434**		**36.2**		**254**		**402**	
GHE (10^{9}ton/yr)	**-1.0**		**6.0**		**-0.06**		**4.7**		**5.0**	

Figure 4.8: Comparison of cost effective strategies for the $60/ton disposal fee scenario and its alternative scenarios

(Best values for GHE, LU and RES are 1,0,1, respectively)



4.7 Incentive Programs

4.7.1 Incentives for Recycling Programs

The government can provide loans or grants to municipalities to help them achieve higher levels of recycling. These grants may be used by the municipalities to create additional recycling educational programs or to improve existing recycling facilities or technologies. Public awareness of recycling and its potential benefits may be improved through education programs, leading to improved public participation. Inputs to the ISWM model were modified to illustrate such scenarios. Table 4.15 summarizes the scenarios (representing a middle and a high level of responsiveness to a public awareness program) implemented for these cases, and the illustrative changes in household participation, which is represented by the participation factor that is defined as the fraction of households that set out recyclables for each collection cycle, in recycling programs are listed in Table 4.16.

Table 4.15: Recycling incentive programs for improving participation rates

Program name	PARTICIP_# (1)
Program description	All recyclable collection options are enabled. one residential sector, one multifamily sector, and one commercialsector.
ISWM Model objective	Minimize cost.
ISWM Model set-up and special constraints	Enable all collection options.
Changes in parameters settings	Assume the participation rates in the recycling programs to be a high percentage in proportion to the level of incentives; these will be sector specific.

(1) This is a set of scenarios: PARTICIP_1, PARTICIP_2, etc, each one representing different levels of incentives.

Table 4.16: Participation rates for the recycling collection unit processes for the different recycling incentive scenarios

Collection options	**Scenarios (Participation rates)**		
	Base	PARTICIP_1	PARTICIP_2
Residential: C2-C4	65%	85%	90%
Residential: C0-C3	50%	70%	75%
Residential: C8r	40%	60%	70%
Multifamily: C14-C15	80%	85%	90%
Multifamily: C8m	40%	60%	70%
Commercial: C19	70%	85%	90%

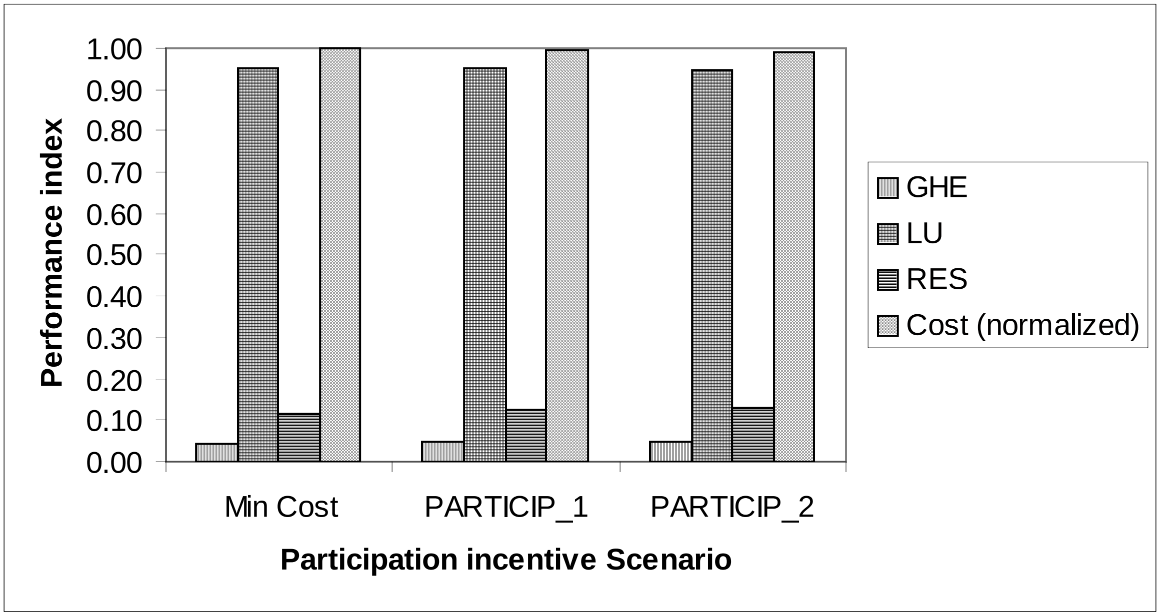
The resulting MSW management strategies are summarized in Table 4.17. The corresponding performance metrics are shown in Figure 4.9. In this case the different scenarios have little impact on the strategies and their performances. In this illustration, a public awareness program would have minimal effect on these performance measures. Of course, the result could be different for other cases or if other performance measures are considered.

Table 4.17: Cost and mass flows for the cost-effective strategies for the scenarios with incentives in participation rates

Unit Processes	**Scenarios**					
	Minimum Cost		PARTICIP_1		PARTICIP_2	
	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)
Residential Collection						
Co-collection in single comp. (C5)	7.39	217	7.39	217	7.39	217
Multifamily Collection						
Recyclables Drop-off (C8m)	0.11	3.4	0.17	5.1	0.20	6.0
Residuals (C16)	2.28	68.8	2.24	67.1	2.22	66.3
Commercial Collection						
Mixed waste (C20)	7.73	192	7.73	192	7.73	192
Separation						
Pre-sorted recyclables MRF (S2)	0.05	3.4	0.08	5.1	0.09	6.0
Co-collected recyc. MRF (S4)	1.25	20.9	1.25	20.9	1.25	20.9
Treatment	-	-	-	-	-	-
Disposal						
Landfill (D1)	11.07	459	11.03	458	11.00	457
Transportation	0.00	24.3	0.00	26.0	0.00	26.9
Recyclable revenues ($10^6\$$/yr)	2.56		2.76		2.81	
Net cost ($10^6\$$/yr)	**27.3**		**27.2**		**27.0**	
Resource Recovery (10^3ton/yr)	**22.2**		**24.0**		**24.8**	
Landfill utilization (10^3ton/yr)	**459**		**458**		**457**	
GHE (10^9ton/yr)	**6.3**		**6.3**		**6.3**	

Figure 4.9: Comparison of cost-effective strategies for the scenarios with incentives in participation rates

(Best values for GHE, LU and RES are 1,0,1, respectively)



4.7.2 Alternative Outcomes for the Incentive Program

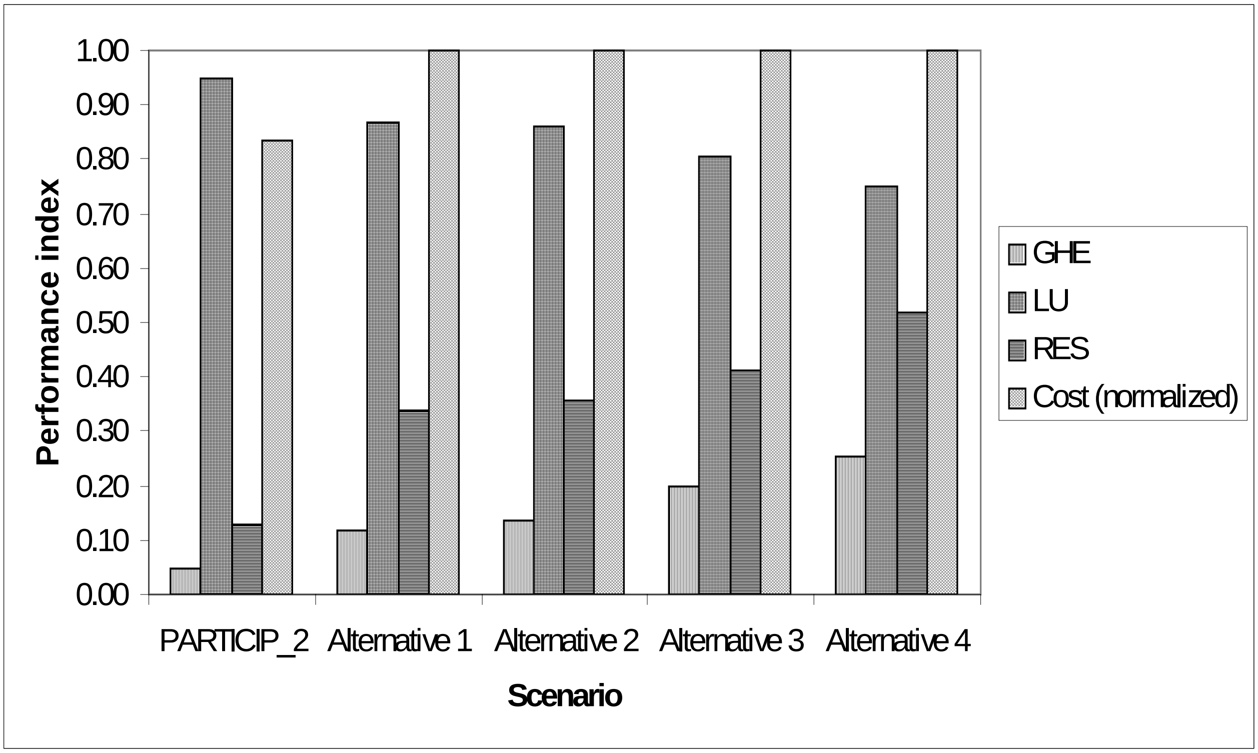
The ISWM model for the scenario with the highest participation levels, PARTICIP_2, was modified to implement a corresponding MGA model in which a cost constraint was added. In this constraint, the cost was relaxed by 20% of the $27.1 million/year cost of the strategy for that scenario). Four alternative strategies were generated. They are summarized in Table 4.18. A comparison of the performance of these strategies is shown in Figure 4.10. Interestingly, all recycling collection unit processes are selected among these alternatives, while the effectiveness of all strategies are quite similar. This indicates that although considerable flexibility is available in selecting different unit processes under this program, it results in a robust performance with respect the three policy goals. Of course, these results are specific to the case study, and may not be applicable in general.

Table 4.18: Cost and mass flows for the cost-effective strategies for the recycling incentive program to improve participation and its alternatives

Unit Processes	**Scenarios**									
	PARTICIP_2		Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)	Cost ($10^6\$$ /yr	Mass (10^3ton /yr)
Residential Collection										
Mixed waste (C1)	-	-	-	-	8.90	166.1	-	-	-	-
Co-collection in single comp. (C5)	7.39	217	2.01	59.0	1.73	50.7	7.39	217	7.39	217
Residuals (C7)	-	-	8.12	145	-	-	-	-	-	-
Recyclables Drop-off (C8r)	-	-	0.43	13.1	-	-	-	-	-	-
Multifamily Collection										
Recyclables Drop-off (C8m)	0.20	6.0	-	-	-	-	-	-	-	-
Mixed waste (C13)	-	-	2.37	72.3	-	-	-	-	2.37	72.3
Pre-sorted Recyclables (C14)	-	-	-	-	0.86	7.7	-	-	-	-
Residuals (C16)	2.22	66.3	-	-	2.18	64.6	-	-	-	-
Wet-dry-recyclables (C17)	-	-	-	-	-	-	4.60	72.3	-	-
Commercial Collection										
Pre-sorted recyclables (C19)	-	-	6.76	45.9	-	-	6.76	45.9	6.76	45.9
Residuals (C20)	-	-	6.56	147	-	-	6.56	147	6.56	147
Mixed waste (C20)	7.73	192	-	-	7.73	192	-	-	-	-
Separation										
Mixed waste MRF (S1)	-	-	-	-	5.66	192	-	-	4.81	197
Pre-sorted recyclables MRF (S2)	0.09	6.0	0.95	59.0	0.12	7.7	0.75	45.9	0.75	45.9
Commingled recyc. MRF (S3)	-	-	-	-	-	-	1.25	13.7	-	-
Co-collected recyc. MRF (S4)	1.25	20.9	0.34	5.7	0.29	4.9	1.25	20.9	1.25	20.9
Treatment										
Combustion (T3)	-	-	-	-	-	-	1.19	16.3	1.61	21.6
Disposal										
Landfill (D1)	11.00	457	10.06	417	9.98	414	9.32	387	8.71	361
Ash landfill (D2)	-	-	-	-	-	-	0.10	6.5	0.10	7.0
Transportation	0.00	26.9	0.00	64.7	0.29	205	0.01	87.0	0.36	271
Recyclable revenues ($10^6\$$/yr)	2.81		5.20		5.34		6.79		8.27	
Net cost ($10^6\$$/yr)	**27.0**		**32.4**		**32.4**		**32.4**		**32.4**	
Resource Recovery (10^3ton/yr)	**24.8**		**64.1**		**67.5**		**78.3**		**98.9**	
Landfill utilization (10^3ton/yr)	**457**		**417**		**414**		**387**		**361**	
GHE (10^9ton/yr)	**6.3**		**5.7**		**5.6**		**5.1**		**4.7**	

Figure 4.10: Comparison of cost-effective strategies for the recycling incentive program to improve participation and its alternatives

(Best values for GHE, LU and RES are 1,0,1, respectively.)



4.8 Discussion and Conclusions

This paper presented a quantitative approach to examine different MSW management programs. The effectiveness of each program at achieving specified policy goals was compared using quantitative performance measures. The ISWM model was used to formulate and represent the scenarios for a hypothetical, but realistic case study. The policy goals of maximizing resource recovery, minimizing landfill utilization and minimizing emissions associated with GHE were considered. To better characterize the effectiveness of an MSW management program, different MSW management strategies that were similar with respect to cost were generated. These are meant to be representative of the range of strategies that different municipalities may select to achieve the same MSW management objective. Since these strategies are different in their choice of unit processes and mass flow, they may perform quite differently with respect to different criteria. This approach, therefore, suggests a range of strategies that can be considered in an actual planning process in selecting one that is effective from an overall point of view.

The flexible structure of the ISWM model enables such an examination of a wide range of scenarios. Simple modifications can be made as illustrated. Although this paper presents only a small number of scenarios, the ISWM model offers a convenient framework for carrying out quantitative studies for a broader set of MSW management scenarios.

The results for the case study do indicate some interesting results: while some MSW management programs, such as direct regulations and disposal fees, are effective in meeting the targeted policy goal(s), others, such as an incentive scheme, were less responsive. Also, in several cases a range of good alternative MSW management strategies were available for implementing a program, and they resulted in significantly different levels of effectiveness in meeting the targeted policy goal(s). This indicates that the overall effectiveness of an MSW management program should be studied carefully before implementation. The ISWM model was shown to be a flexible tool that can be used to support such studies.

4.9 References

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Chapter 5: Summary

The research described in this dissertation focuses on the development of an integrated solid waste management (ISWM) model and illustrates its use in examining a range of SWM scenarios. An integrated solid waste management system was defined and described in Chapter 2. The SWM system includes a set of unit processes for collection, transfer, separation, treatment and final disposal of wastes. It also defines a set of key parameters to characterize the solid waste stream categorized by single family, multi family and commercial sectors in a given community. This system is represented using a linear programming model that would assist in identifying efficient SWM strategies that meet cost, energy, and environmental emissions goals and targets. A series of unit process models, which were developed by other researchers as part of a collective research effort, were used as the basis for characterizing and quantifying these objectives. Each unit process model computes the cost and the life-cycle inventories of energy consumption and environmental emissions of numerous pollutants. The ISWM model enables a user to optimize or set constraints on cost, energy consumption, and emissions of CO, CO_2 (biomass), CO_2 (fossil), NO_x, SO_x, greenhouse gases represented as greenhouse gas equivalents, total particulates and PM_{10}. The primary set of constraints in the model represents the mass flows through the unit processes and the mass balances for each waste item at each unit process. Additional constraints can be introduced to represent site-specific management issues, such as diversion requirements, cost restrictions, and targets on management goals.

A major challenge of this research was in representing the MSW system as an LP model. The difficulties with representing the system as a linear programming model were fundamentally caused by the complexity arising due to the presence of a large number of elements (waste items, unit processes, generation sectors and optimizable parameters) and their interrelationships that exist in a comprehensive MSW system. Previous attempts by other researchers to model the system as an LP had limited success in representing some of the mass flows using only linear equations. For example, suppose that a municipality collects recyclables through a recycling collection program. The residuals must be collected by a residuals MSW collection option. Further, assume that the model solution selects to send part of this residual waste to a combustion facility and the rest to a landfill. In such a case, the composition of the residual stream entering the combustion facility should be the same as the composition of the residual stream sent to the landfill. This composition is a variable since the materials recovered for recycling are decision variables whose values will be known only after solving the model. Therefore, the amount of each waste item leaving a facility as part of residual MSW is an unknown in the model, also is the fraction of that residual stream going to each of the downstream facilities. Thus, the expression for the amount of each waste item entering a downstream facility contains a term that is a product of these two variables. This causes the nonlinearity in such a modeling approach. A unique approach was developed to overcome this problem and to enable an LP formulation. In this approach, every possible mass flow path that a waste item could take within the limits of the defined system was represented as a set of variables. Feasible combinations of all collection unit processes and the waste flow alternatives to downstream unit processes were explicitly defined. This enabled the formulation of the constraints and objective functions as a set of linear mathematical expressions. Although this approach requires the definition of a large set of decision variables, the structure of the model makes the search process sufficiently efficient. For example, models of MSW systems representing typical municipalities have on the order of 10,000 decision variables and that many constraints. The solution time for these cases is on the order of 10-20 seconds on a Pentium II 450 MHz computer with 256 MB of main memory.

In Chapter 3, a hypothetical case study representing an urban region was defined and analyzed to test the ISWM model. Two base scenarios were analyzed: one to obtain the minimum cost solution and the other to obtain the minimum greenhouse gas emissions. Additional scenarios were tested to examine the effects of imposing different diversion rates. Diversion of wastes from landfill could include recycling, yardwaste composting and combustion. Two different definitions of diversion were used: one including only recycling and the other including all three options. The least cost solution shows a 2.8% diversion rate without any constraint. The results for the diversion rate scenarios showed interesting cost tradeoff with diversion target (with recycling only). The marginal costs were very low at diversion levels less than 15%, but increased rapidly beyond that point. The maximum diversion rate (with recycling only) that can be achieved is 25.9%. Such information could be useful in deciding appropriate diversion goals by local municipalities. The LCI estimates for GHE indicate that the greenhouse gas emissions decrease with increasing diversion rate. This is due to emissions offsets from manufacturing processes that use recycled materials. For the scenarios where diversion was defined as the combination of recycling, combustion and composting activities, the maximum diversion rate is 78.3%. The additional diversion is achieved through combustion of waste. This contributes to greater reductions in greenhouse gas emissions through additional offsets from energy production at the combustion facility. The use of the model in developing the tradeoff between GHE and cost was also demonstrated. Again, interesting cost versus GHE tradeoff is observed—the marginal costs of additional reductions in greenhouse gas emissions remain almost constant for a wide range of emissions, but at the highest levels of emissions reductions the marginal costs increase rapidly.

An extended model was developed and tested for generating alternative SWM strategies. An MGA approach was used to obtain alternative solutions that are as different as possible with respect to the choices of unit processes. For the case presented in this dissertation, several alternatives, which were able to achieve similar performance by using distinctly different combinations of unit processes and mass flows, were found. This indicates that for this case considerable amount of flexibility is available in choosing a good SWM strategy, allowing a decision maker to address unmodeled issues such as social and political considerations, practicality of using existing equipment and facilities and the workforce trained to operate them.

The ISWM model was also applied to examine the effectiveness of SWM programs, such as recycling, yard waste composting, and fee and incentive programs, in achieving their intended goals. In Chapter 4, several SWM programs were modeled and analyzed and their effectiveness was compared with respect to the following goals: maximizing resource recovery; minimizing landfill utilization; and minimizing environmental emissions. Using the flexibility of the ISWM model, several scenarios for each SWM program were formulated. Each one of these scenarios was modeled and analyzed through unique implementations of the LP model for a medium size urban region. The results from these scenarios indicate that some SWM programs yielded a wide range of performance with respect to the three criteria, while some others were invariant. To examine the variation in the strategies that may arise from implementing a program, the MGA models of the ISWM were solved to identify different SWM strategies that are of similar cost. Interestingly, several programs resulted in distinctly different SWM strategies, indicating that each municipality could choose a different SWM strategy to meet the intended goals of an SWM program. Although the primary goal of a program was met by all alternative strategies, some performed differently with respect to other goals. In such cases, the individual municipalities have the flexibility to examine the tradeoff among these different criteria and choose a strategy. The capabilities and versatility of the ISWM model to examine a wide range of scenarios is demonstrated through these studies.

This model is intended for planning, or screening, purposes and there are limitations to the existing implementation. The LP modeling structure required several simplifying assumptions in the linearization of the model. Although these assumptions may be reasonable for the use of this model as a planning and screening tool, any particular solution would need to be examined in more detail as part of an actual design process. One simplification, for instance, is that economies of scale cannot be represented. The model is implemented in an interactive decision support system to allow trial-and-error modifications, however, so that some experimentation with alternative solutions can be carried out. For instance, if a small and impractical size for a facility is selected in the model solution, then the model can be modified to eliminate that facility or to constrain it to be no smaller than a specified capacity. This trial-and-error capability allows a user to explore the effects of economies of scale. Similarly, other simplifications can be addressed to some degree by modifying constraints or parameters to examine an issue more closely. In addition, of course, more detailed procedures would be needed to produce the final design for actual implementation of an SWM system in any given case.

Appendix

All the default information was taken from Version 1.2 of the ISWM-DST model. Only the input values that were changed are included in this Appendix.

Part A: Common Pre-processor Input Data

TABLE A1: RESIDENTIAL COLLECTION CHARACTERISTICS (CAPTURE RATES)

DESCRIPTION									
	C1	C7	C5	C11	C2	C3	C4	C0	C8
Yard Trimmings, Leaves	1.00	1.00	▨	1.00	▨	▨	▨	0.90	▨
Yard Trimmings, Grass	1.00	1.00	▨	1.00	▨	▨	▨	0.90	▨
Yard Trimmings, Branches	1.00	1.00	▨	1.00	▨	▨	▨	0.90	▨
Old News Print	1.00	1.00	0.68	1.00	0.67	0.62	0.67	▨	0.59
Old Corr. Cardboard	1.00	1.00	0.56	1.00	0.55	0.52	0.55	▨	0.59
Office Paper	1.00	1.00	0.49	1.00	0.48	0.46	0.48	▨	0.59
Phone Books	1.00	1.00	0.60	1.00	0.59	0.45	0.59	▨	0.59
Books	1.00	1.00	0.60	1.00	0.59	0.55	0.59	▨	0.59
Old Magazines	1.00	1.00	0.60	1.00	0.59	0.55	0.59	▨	0.59
3rd Class Mail	1.00	1.00	0.60	1.00	0.59	0.55	0.59	▨	0.59
Pallets	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Paper Other #1	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Paper Other #2	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Paper Other #3	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Paper Other #4	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Paper Other #5	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
CCCR Other	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Mixed Paper	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
HDPE - Translucent	1.00	1.00	0.56	1.00	0.55	0.52	0.55	▨	0.59
HDPE - Pigmented	1.00	1.00	0.56	1.00	0.55	0.52	0.55	▨	0.59
PET	1.00	1.00	0.56	1.00	0.55	0.52	0.55	▨	0.59
Plastic - Other #1	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Plastic - Other #2	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Plastic - Other #3	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Plastic - Other #4	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Plastic - Other #5	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
Mixed Plastic	1.00	1.00	0.00	1.00	0.00	0.00	0.00	▨	0.00
CCNR Other	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Ferrous Cans	1.00	1.00	0.58	1.00	0.57	0.52	0.57	▨	0.59
Ferrous Metal - Other	1.00	1.00	0.58	1.00	0.57	0.52	0.57	▨	0.59
Aluminum Cans	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
Aluminum - Other #1	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
Aluminum - Other #2	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
Glass - Clear	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
Glass - Brown	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
Glass - Green	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
Mixed Glass	1.00	1.00	0.64	1.00	0.63	0.59	0.63	▨	0.59
CNNR Other	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Paper - Non-recyclable	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Food Waste	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
CCCN Other	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Plastic - Non-Recyclable	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Misc.	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
CCNN Other	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Ferrous - Non-recyclable	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Al - Non-recyclable	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Glass - Non-recyclable	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
Misc.	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨
CNNN Other	1.00	1.00	▨	1.00	▨	▨	▨	▨	▨

Fraction of households served by collection option	1	1	1	1	1	1	1	1	1
Participation Factor	1.0	1.0	1.0	1.0	0.65	0.50	0.65	0.50	0.40

TABLE A2: MULTI-FAMILY COLLECTION CHARACTERISTICS (CAPTURE RATES)

DESCRIPTION	MULTIFAMILY COLLECTION OPTIONS						
	C 13	C 16	C 17	C 18	C 14	C 15	C 8
Yard Trimmings, Leaves	1.00	1.00	1.00	1.00	▨	▨	▨
Yard Trimmings, Grass	1.00	1.00	1.00	1.00	▨	▨	▨
Yard Trimmings, Branches	1.00	1.00	1.00	1.00	▨	▨	▨
Old News Print	1.00	1.00	1.00	1.00	0.63	0.68	0.59
Old Corr. Cardboard	1.00	1.00	1.00	1.00	0.53	0.56	0.59
Office Paper	1.00	1.00	1.00	1.00	0.46	0.49	0.59
Phone Books	1.00	1.00	1.00	1.00	0.56	0.60	0.59
Books	1.00	1.00	1.00	1.00	0.56	0.60	0.59
Old Magazines	1.00	1.00	1.00	1.00	0.56	0.60	0.59
3rd Class Mail	1.00	1.00	1.00	1.00	0.56	0.60	0.59
Pallets	1.00	1.00	1.00	1.00	▨	▨	▨
Paper Other #1	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Paper Other #2	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Paper Other #3	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Paper Other #4	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Paper Other #5	1.00	1.00	1.00	1.00	0.00	0.00	0.00
CCCR Other	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Mixed Paper	1.00	1.00	1.00	1.00	0.00	0.00	0.00
HDPE - Translucent	1.00	1.00	1.00	1.00	0.53	0.56	0.59
HDPE - Pigmented	1.00	1.00	1.00	1.00	0.53	0.56	0.59
PET	1.00	1.00	1.00	1.00	0.53	0.56	0.59
Plastic - Other #1	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Plastic - Other #2	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Plastic - Other #3	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Plastic - Other #4	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Plastic - Other #5	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Mixed Plastic	1.00	1.00	1.00	1.00	0.00	0.00	0.00
CCNR Other	1.00	1.00	1.00	1.00	▨	▨	▨
Ferrous Cans	1.00	1.00	1.00	1.00	0.53	0.58	0.59
Ferrous Metal - Other	1.00	1.00	1.00	1.00	0.53	0.58	0.59
Aluminum Cans	1.00	1.00	1.00	1.00	0.60	0.64	0.59
Aluminum - Other #1	1.00	1.00	1.00	1.00	0.60	0.64	0.59
Aluminum - Other #2	1.00	1.00	1.00	1.00	0.60	0.64	0.59
Glass - Clear	1.00	1.00	1.00	1.00	0.60	0.64	0.59
Glass - Brown	1.00	1.00	1.00	1.00	0.60	0.64	0.59
Glass - Green	1.00	1.00	1.00	1.00	0.60	0.64	0.59
Mixed Glass	1.00	1.00	1.00	1.00	0.60	0.64	0.59
CNNR Other	1.00	1.00	1.00	1.00	▨	▨	▨
Paper - Non-recyclable	1.00	1.00	1.00	1.00	▨	▨	▨
Food Waste	1.00	1.00	1.00	1.00	▨	▨	▨
CCCN Other	1.00	1.00	1.00	1.00	▨	▨	▨
Plastic - Non-Recyclable	1.00	1.00	1.00	1.00	▨	▨	▨
Misc.	1.00	1.00	1.00	1.00	▨	▨	▨
CCNN Other	1.00	1.00	1.00	1.00	▨	▨	▨
Ferrous - Non-recyclable	1.00	1.00	1.00	1.00	▨	▨	▨
Al - Non-recyclable	1.00	1.00	1.00	1.00	▨	▨	▨
Glass - Non-recyclable	1.00	1.00	1.00	1.00	▨	▨	▨
Misc.	1.00	1.00	1.00	1.00	▨	▨	▨
CNNN Other	1.00	1.00	1.00	1.00	▨	▨	▨

Fraction of households served by collection option	1	1	1	1	1	1	1
Participation Factor	1.0	1.0	1.0	1.0	0.80	0.80	0.40

TABLE A3: COMMERCIAL COLLECTION CHARACTERISTICS (CAPTURE RATES)

DESCRIPTION	COMMERCIAL COLLECTION OPTIONS	
	C 19	C 20
Yard Trimmings, Leaves	▨	▨
Yard Trimmings, Grass	▨	▨
Yard Trimmings, Branches	▨	▨
Old News Print	0.63	▨
Old Corr. Cardboard	0.53	▨
Office Paper	0.46	▨
Phone Books	0.60	▨
Books	▨	▨
Old Magazines	▨	▨
3rd Class Mail	0.60	▨
Pallets	0.60	▨
Paper Other #1	0.00	▨
Paper Other #2	0.00	▨
Paper Other #3	0.00	▨
Paper Other #4	▨	▨
Paper Other #5	▨	▨
CCCR Other	0.00	▨
Mixed Paper	0.00	▨
HDPE - Translucent	▨	▨
HDPE - Pigmented	▨	▨
PET	0.53	▨
Plastic - Other #1	▨	▨
Plastic - Other #2	▨	▨
Plastic - Other #3	▨	▨
Plastic - Other #4	▨	▨
Plastic - Other #5	▨	▨
Mixed Plastic	0.00	▨
CCNR Other	0.00	▨
Ferrous Cans	0.53	▨
Ferrous Metal - Other	0.50	▨
Aluminum Cans	0.60	▨
Aluminum - Other #1	▨	▨
Aluminum - Other #2	▨	▨
Glass - Clear	0.60	▨
Glass - Brown	0.60	▨
Glass - Green	0.60	▨
Mixed Glass	0.60	▨
CNNR Other	0.00	▨
Paper - Non-recyclable	▨	▨
Food Waste	▨	▨
CCCN Other	▨	▨
Plastic - Non-Recyclable	▨	▨
Misc.	▨	▨
CCNN Other	▨	▨
Ferrous - Non-recyclable	▨	▨
Al - Non-recyclable	▨	▨
Glass - Non-recyclable	▨	▨
Misc.	▨	▨
CNNN Other	▨	▨

Participation Factor	0.70	1.0

Part B: Material Recovery Facility Pre-processor Input data

TABLE B1: SORTING EFFICIENCIES FOR MATERIAL RECOVERY FACILITIES

WASTE ITEM	VARIABLE NAME	Mixed Waste S1	Presorted Recyc. S2	Commingled Recyc. S3	Bags in 1 compart. S4
Yard Trimmings, Leaves	YTL				
Yard Trimmings, Grass	YTG				
Yard Trimmings, Branches	YTB				
Old News Print	ONP	0.70	1.00	1.00	0.90
Old Corr. Cardboard	OCC	0.70	1.00	1.00	0.90
Office Paper	OFF	0.70	1.00	1.00	0.90
Phone Books	PBK	0.70	1.00	1.00	0.90
Books	BOOK	0.70	1.00	1.00	0.90
Old Magazines	OMG	0.70	1.00	1.00	0.90
3rd Class Mail	MAIL	0.70	1.00	1.00	0.90
Paper Other #1	PAOT1		1.00	1.00	0.90
Paper Other #2	PAOT2		1.00	1.00	0.90
Paper Other #3	PAOT3		1.00	1.00	0.90
Paper Other #4	PAOT4		1.00	1.00	0.90
Paper Other #5	PAOT5		1.00	1.00	0.90
CCCR Other	CCR_O		1.00		
Mixed Paper	PMIX		1.00	1.00	0.90
HDPE - Translucent	HDT	0.70	1.00	1.00	0.90
HDPE - Pigmented	HDP	0.70	1.00	1.00	0.90
PET	PPET	0.70	1.00	1.00	0.90
Plastic - Other #1	PLOT1		1.00	1.00	0.90
Plastic - Other #2	PLOT2		1.00	1.00	0.90
Plastic - Other #3	PLOT3		1.00	1.00	0.90
Plastic - Other #4	PLOT4		1.00	1.00	0.90
Plastic - Other #5	PLOT5		1.00	1.00	0.90
Mixed Plastic	PLMIX		1.00	1.00	0.90
CCNR Other	CNR_O		1.00		
Ferrous Cans	FCAN	0.70	1.00	1.00	0.90
Ferrous Metal - Other	FMOT	0.70	1.00	1.00	0.90
Aluminum Cans	ACAN	0.70	1.00	1.00	0.90
Aluminum - Other #1	ALOT1	0.70	1.00	1.00	0.90
Aluminum - Other #2	ALOT2	0.70	1.00	1.00	0.90
Glass - Clear	GCLR	0.70	1.00	0.94	0.85
Glass - Brown	GBRN	0.70	1.00	0.94	0.85
Glass - Green	GGRN	0.70	1.00	0.94	0.85
Mixed Glass	GMIX	0.70	1.00	0.94	0.85
CNNR Other	NNR_O		1.00		
Paper - Non-recyclable	PANR				
Food Waste	FW				
CCCN Other	CCN_O				
Plastic - Non-Recyclable	PLNR				
Miscellaneous	MIS_CNN				
CCNN Other	CNN_O				
Ferrous - Non-recyclable	FNR				
Al - Non-recyclable	ANR				
Glass - Non-recyclable	GNR				
Miscellaneous	MIS_NNN				
CNNN Other	NNN_O				