Life-Cycle-based Solid Waste Management. II: Illustrative Applications

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Abstract: A companion paper described the development of the integrated solid waste management (ISWM) model that considers cost, energy, and environmental releases associated with management of municipal solid waste. This paper demonstrates the application of the ISWM model to a hypothetical, but realistic, case study. Several solid waste management (SWM) scenarios are studied, including the variation in energy and environmental emissions among alternate SWM strategies; the effect of mandated waste diversion (through recycling and other beneficial uses of waste such as combustion to recover energy) on environmental releases and cost; the tradeoff between cost and the level of waste diversion; and the tradeoff between cost and greenhouse gas emissions. In addition, the flexibility of the model is illustrated by the identification of alternate SWM strategies that meet approximately the same objectives using distinctly different combinations of unit processes. This flexibility may be of importance to local solid waste management planners who must implement new SWM programs. Use of the model illustrates the potential impact of solid waste management policies and regulations on global environmental emissions.

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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 the collection of mixed waste together with or separate from recyclables and yard waste, materials recovery facilities (MRFs) for recyclables recovery, yard and mixed waste composing, 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. 2002) 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 waste diversion targets. 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 waste items. The ISWM model, which is structured as a linear programming (LP) model, varies in size depending on the MSW system. A typical implementation of the model is expected to have 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 a typical model using the CPLEX® software package on an MS Windows-based PII-450 personal computer with 258 MB RAM takes 10–20 s. 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 that is recovered.

The purpose of this paper is to illustrate the use of the ISWM model for examining 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 trade off among these

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Table 1. Waste Stream Composition (By Wet Weight)

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[a]	ONP	6.7	6.7	2.2
Old corrugated cardboard[a]	OCC	2.1	2.1	36.0
Office paper[a]	OFF	1.3	1.3	7.2
Phone books[a]	PBK	0.2	0.2	0.3
Books[a]	BOOK	0.9	0.9	N/A
Old magazines[a]	OMG	1.7	1.7	N/A
3rd class mail[a]	MAIL	2.2	2.2	2.3
Paper-nonrecyclable	PNR	17.1	17.1	N/A
CCCR-other[b]	CCR O	N/A	N/A	1.9
HDPE-translucent[a]	HDT	0.4	0.4	N/A
HDPE-pigmented[a]	HDP	0.5	0.5	N/A
PET beverage containers[a]	PPET	0.4	0.4	0.2
Plastic-nonrecyclable	PLNR	9.9	9.9	N/A
CCNR-other[c]	CNR O	N/A	N/A	4.1
Ferrous cans[a]	FCAN	1.5	1.5	0.7
Ferrous-nonrecyclable	FNR	3.2	3.2	N/A
Aluminum cans[a]	ACAN	0.9	0.9	0.4
Al-nonrecyclable	ANR	0.5	0.5	N/A
Glass-clear[a]	GCLR	3.9	3.9	1.9
Glass-brown[a]	GBRN	1.6	1.6	0.8
Glass-green[a]	GGRN	1.0	1.0	0.5
Glass-nonrecyclable	GNR	0.7	0.7	N/A
CNNR-other[d]	NNR_O	N/A	N/A	2.4
Food waste	FW	4.9	4.9	N/A
CCCN-other[e]	CCN_O	N/A	N/A	17.1
Miscellaneous combustible[f]	MIS_CNN	7.5	7.5	N/A
CCNN other[g]	CNN_O	N/A	N/A	11.3
Miscellaneous[h]	MIS_NNN	12.3	12.3	N/A
CNNN-other[i]	NNN_O	N/A	N/A	10.7

Note: The waste composition was adopted from [USEPA 1997].

[a] denotes an item considered for recycling in this case study.

[b] CCCR-other represents commercial wastes that are combustible, compostable, and recyclable.

[c] CCNR-other represents commercial wastes that are combustible, noncompostable, and recyclable.

[d] CNNR-other represents commercial wastes that are noncombustible, noncompostable and recyclable.

[e] CCCN-other represents commercial wastes that are combustible, compostable, and nonrecyclable.

[f] Miscellaneous combustible represents wastes from the residential and multifamily sectors that are combustible but nonrecyclable.

[g] CCNN-other represents commercial wastes that are combustible, noncompostable, and nonrecyclable.

[h] Miscellaneous represents wastes from the residential and multifamily sectors that are noncombustible and nonrecyclable.

[i] CNNN-other represents commercial wastes that are noncombustible, noncompostable, and nonrecyclable.

objectives. The use of the model to generate alternative strategies is also demonstrated.

Description of Case Study

A hypothetical case representing an urban region of medium size was defined. Waste generation rates and compositions were categorized in three sectors: residential, multifamily, and commercial. The key parameters and waste composition that define this case are summarized in Tables 1 and 2. The MSW system definition also required specification of many other input parameters (e.g., distances between waste processing facilities, collection frequencies, recycling participation factors) that are described elsewhere (Solano 1999). The unit processes included in this case are: C0-C7, C8r, C8m, C13-16, C19-20, TR1-2, TR5, RT1-2, S1-3, T1, T3, and D1-2, and the following collection combinations are included: C1, C0/C7, C2/C7, C3/C7, C4/C7, and C8r/C7 for the residential sector, C13, C8m/C16, C14/C16, and C15/C16 for the multifamily sector, and C20 and C19/C20 for the commercial sector [the codes are defined in Table 1 in the companion paper by Solano et al. 2002]. Items that are considered for recycling are indicated in Table 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 2. Solid Waste Generation Data

Sector name	Population	Residents per home	Units[a]	Waste generation[b]	Total generation (metric ton/year)
Residential	450,000	2.63	171,103	1.2	196,687
Multifamily	150,000	N/A	750	1.2	65,562
Commercial	N/A	N/A	2,000	1678	174,542

[a] For residential sectors: houses; for multifamily sectors: storage points; for commercial sector: commercial locations.

[b] Expressed in kg/person/day for residential and multifamily sectors and in kg/location/week for commercial sector.

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 carbon equivalents. GHE, an optimizable environmental parameter in the ISWM model, is defined as a weighted sum of CO_2 and CH_4 emissions as follows:

$$\mathrm{GHE}=(12/44)*\{E[\mathrm{CO_2(fossil)}]+63E[\mathrm{CH_4}]\} \tag{1}$$

where $E[\mathrm{CO_2(fossil)}]$ and $E[\mathrm{CH_4}]$=emissions (in kg/year) of fossil-derived CO_2 and CH_4, respectively. Biomass derived CO_2 was assigned a weighting factor of zero and is not shown in Eq. (1). The user may adjust these weighting factors. Other optimizable environmental parameters that were calculated for each scenario include: CO, CO_2 (fossil derived), CO_2 (biomass derived), NO_x, SO_x, particulate matter (PM), and energy. The base 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. The resulting optimal SWM strategies for the minimum cost and minimum GHE scenarios are summarized in Tables 3 and 4, respectively, and the corresponding waste flows are shown in Figs. 1 and 2.

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 5% of the waste from each of these two sectors is recovered as recyclable material, and the remaining 95% of the waste is collected as mixed MSW and disposed of in a landfill. In the commercial sector, approximately 26% of waste is collected as presorted recyclable material, while the rest is collected as mixed MSW and disposed of in a landfill. The cost breakdown shown in Table 3 indicates that the collection and landfill costs constitute 83% of the net cost. Although recycling operations are typically more expensive than mixed waste collec-

Table 3. Cost and Emissions for Minimum Cost Solid Waste Management Strategy

Unit Process	Cost (10^6 \$/year)	Energy (10^9 BTU/year)	PM (10^3 kg/year)	NO_x (10^3 kg/year)	SO_x (10^3 kg/year)	CO (10^3 kg/year)	CO_2 biomass (10^6 kg/year)	CO_2 fossil (10^6 kg/year)	GHE (carbon equivalents) (10^6 kg/year)
Residential collection									
Residuals ($C7$)	11.7	61	0.69	55	4.6	9.0	1.1×10^{-3}	1.3	0.36
Recyclables drop off ($C8$)	0.3	1.5×10^{2}	4.8	26	10	73	2.5×10^{-3}	1.1	0.31
Multifamily collection									
Recyclables drop off ($C8$)	0.1	1.6	3.3×10^{-2}	1.1	0.12	0.47	2.8×10^{-5}	2.7×10^{-2}	7.5×10^{-3}
Residuals ($C16$)	2.4	15	0.18	15	1.1	2.4	2.6×10^{-4}	0.34	9.4×10^{-2}
Commercial collection									
Presorted recyclables ($C19$)	2.0	17	0.20	16	1.3	2.6	3.1×10^{-4}	0.38	0.10
Residuals ($C20$)	6.7	37	0.43	34	2.8	5.6	6.5×10^{-4}	0.81	0.22
Separation									
Presorted recyclables MRF ($S2$)	1.0	20	5.9	18	28	2.1	9.1×10^{-4}	4.6	1.3
Treatment	—	—	—	—	—	—	—	—	—
Disposal									
Landfill ($D1$)	10.0	1.9×10^{2}	14	40	13	3.5×10^{2}	3.5×10^{2}	2.1	18
Transportation	0	9.2	0.83	5.8	1.6	5.7	1.6×10^{-4}	0.67	0.18
Recyclable revenues	6.3	—	—	—	—	—	—	—	—
Remanufacturing emissions[a]	—	-1.2×10^{3}	−61	-2.8×10^{2}	-3.9×10^{2}	-6.7×10^{2}	47	−15	−4.3
Net	27.9	-7.4×10^{2}	−34	−65	-3.3×10^{2}	-2.2×10^{2}	4.0×10^{2}	−3.6	8.2

[a] Values in this row represent difference between emissions associated with production from virgin and recycled materials. Negative values indicate avoided emissions attributable to use of recycled materials for remanufacturing.

Table 4. Cost and Emissions for Minimum GHE Solid Waste Management Strategy

Unit process	Cost (10^6 \$/year)	Energy (10^9 BTU/year)	PM (10^3 kg/year)	NO_X (10^3 kg/year)	SO_x (10^3 kg/year)	CO (10^3 kg/year)	CO_2 biomass (10^6 kg/year)	CO_2 fossil (10^6 kg/year)	GHE (carbon equivalents) (10^6 kg/year)
Residential collection									
Yard waste ($C0$)	7.1	40	0.39	27	3.0	4.6	7.0×10^{-4}	0.72	0.20
Commingled recyclables ($C4$)	9.2	37	0.37	26	2.8	4.4	6.4×10^{-4}	0.68	0.19
Residuals ($C7$)	11.2	57	0.64	51	4.3	8.3	1.0×10^{-3}	1.2	0.34
Multifamily collection									
Presorted recyclables ($C14$)	0.9	5.9	6.2×10^{-2}	4.7	0.44	0.77	1.0×10^{4}	0.12	3.2×10^{-2}
Residuals ($C16$)	2.3	14	0.17	14	1.1	2.3	2.5×10^{-4}	0.33	9.2×10^{-2}
Commercial collection									
Presorted recyclables ($C19$)	1.1	7.4	7.3×10^{-2}	5.2	0.55	0.87	1.3×10^{-4}	0.14	3.8×10^{-2}
Residuals ($C20$)	7.9	46	0.53	43	3.4	7.1	8.0×10^{-4}	1.0	0.28
Separation									
Mixed waste MRF ($S1$)	6.9	47	12	39	56	6.1	1.9×10^{-3}	9.7	2.7
Presorted recyclables MRF ($S2$)	0.2	2.7	0.77	2.4	3.7	0.29	1.2×10^{-4}	0.60	0.17
Commingled recyclables MRF ($S3$)	1.8	4.6	1.4	4.1	6.5	0.46	2.1×10^{-4}	1.1	0.30
Treatment									
Combustion ($T3$)	33.2	-2.8×10^{3}	-2.9×10^{2}	-6.2×10^{2}	-1.5×10^{3}	1.5×10^{2}	3.2×10^{2}	-1.6×10^{2}	-46
Disposal									
Landfill ($D1$)	∼0	1.8×10^{-1}	1.6×10^{-3}	1.8×10^{-2}	3.3×10^{-3}	6.8×10^{-3}	3.2×10^{-7}	1.3×10^{-3}	3.6×10^{-4}
Ash landfill ($D2$)	1.3	10	0.29	3.1	0.53	1.1	5.3×10^{-5}	0.22	6.1×10^{-2}
Transportation	0.8	16	1.4	9.7	2.8	9.6	2.7×10^{-4}	1.1	0.31
Recyclable revenues	5.4	—	—	—	—	—	—	—	—
Remanufacturing emissions[a]	—	-1.9×10^{3}	-1.7×10^{2}	-1.8×10^{-2}	-4.1×10^{2}	-2.5×10^{2}	30	-55	-16
Net	78.3	-4.3×10^{3}	-4.5×10^{2}	-5.7×10^{2}	-1.8×10^{3}	-54	3.5×10^{2}	-2.0×10^{2}	-57

[a] Values in this row represent difference between emissions associated with production from virgin and recycled materials. Negative values indicate avoided emissions attributable to use of recycled materials for remanufacturing.

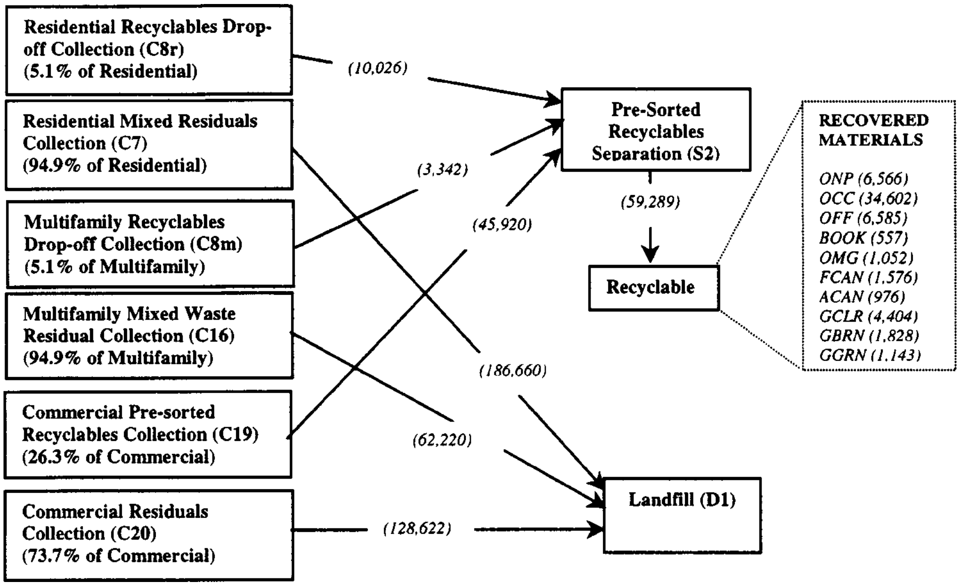

Fig. 1. Mass flows for minimum cost strategy (*the numbers in parentheses show mass in metric ton/year*)

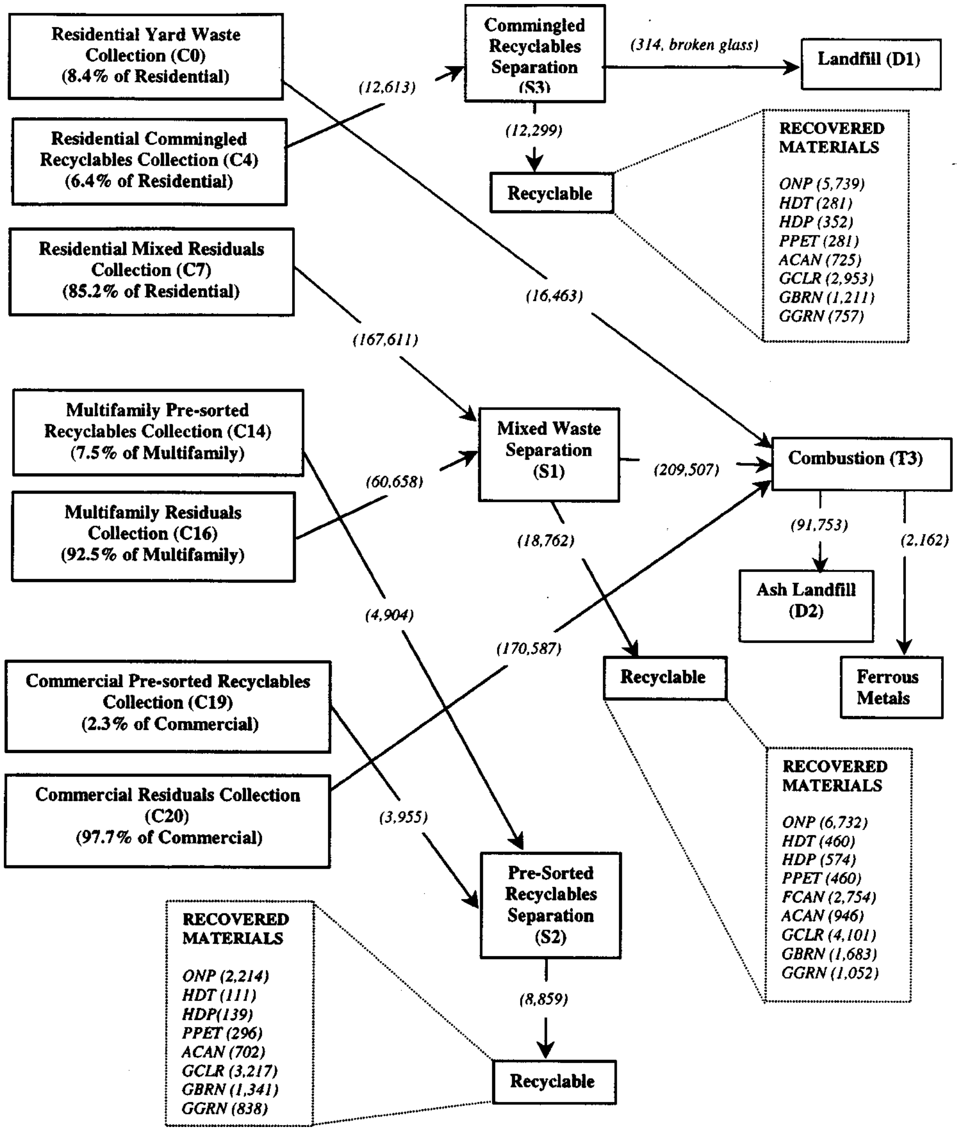

Fig. 2. Mass flows for minimum GHE strategy (*numbers in parentheses show mass in metric ton/year*)

tion, 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, where landfill gas was assumed to be collected and flared. 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 with recyclable material.

Compared to approximately 8 million kg/year GHE burden in the minimum-cost strategy, the minimum GHE strategy (Table 4 and Fig. 2) provides a net reduction of approximately 57 million kg/year. The net cost of the minimum GHE strategy, however, is approximately three times 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 Eq. (1). The user may examine the implications associated with including biomass CO_2 in the GHE definition by assigning a nonzero weighting factor and resolving the model.

In the minimum GHE scenario, the model selects recycling for some combustible (paper, plastic) and noncombustible (glass, metal) items. The selection of recycling for noncombustible items indicate that the emissions savings at the remanufacturing facility are greater than the emissions associated with recyclables recovery activities. The selection of recycling of combustible items indicate that from a GHE perspective, recycling of these specific items 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.

Table 5. Minimum Cost Solid Waste Management Strategies at Different Diversion (Recycling Only) Targets

	SCENARIOS									
	Minimum cost (13.6% recycling)		15% Recycling		20% Recycling		25% Recycling		Maximum Recycling (26.5%)	
Unit Processes	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)
Residential collection										
Commingled recyclables ($C2$)	—	—	—	—	—	—	—	—	9.7	17.9
Residuals ($C7$)	11.8	186.7	11.8	186.7	11.7	186.3	11.7	186.3	11.5	178.8
Recyclables drop off ($C8r$)	0.3	10.0	0.3	10.0	0.5	10.4	0.5	10.4	—	—
Multifamily collection										
Recyclables drop off ($C8m$)	0.1	3.3	0.1	3.3	—	—	—	—	—	—
Presorted recyclables ($C14$)	—	—	—	—	0.9	6.8	0.9	6.9	—	—
Commingled recyclables ($C15$)	—	—	—	—	—	—	—	—	1.4	7.5
Residuals ($C16$)	2.4	62.2	2.4	62.2	2.3	58.7	2.3	58.7	2.2	58.1
Commercial collection										
Presorted recyclables ($C19$)	2.0	45.9	2.0	46.0	2.1	46.1	2.1	46.1	2.1	46.1
Residuals ($C20$)	6.7	128.6	6.7	128.6	6.7	128.4	6.7	128.4	6.7	128.4
Separation										
Mixed waste MRF ($S1$)	—	—	0.9	34.2	3.7	132.7	10.4	363.0	10.8	365.3
Presorted recyclables MRF ($S2$)	1.0	59.3	1.0	59.3	1.1	63.3	1.1	63.4	1.1	64.0
Commingled recyclables MRF ($S3$)	—	—	—	—	—	—	—	—	0.9	7.5
Treatment										
Combustion ($T3$)	—	—	—	—	—	—	—	—	27.2	321.5
Disposal										
Landfill ($D1$)	10.0	377.5	9.8	371.3	9.2	349.4	8.7	327.6	0.003	0.1
Ash landfill ($D2$)	—	—	—	—	—	—	—	—	1.2	82.3
Transportation	0	59.3	0.07	93.6	0.3	196.1	0.8	426.4	1.0	519.9
Recyclable revenues	6.3	—	7.0	—	9.3	—	12.2	—	12.7	—
Net cost	27.9	—	28.1	—	29.2	—	32.9	—	63.0	—

Scenarios to Examine 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 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, yard waste composting, and waste combustion. Each case was analyzed for a series of diversion targets.

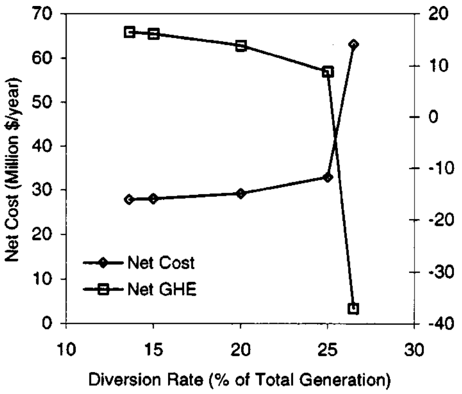

Fig. 3. Net cost and net GHE versus diversion (recycling only) rate

Table 6. Minimum Cost Solid Waste Management Strategies at Different Diversion Targets[a]

	SCENARIOS									
	Minimum cost (13.6% diversion)		20% Diversion		40% Diversion		60% Diversion		Maximum Diversion (82.3%)	
Unit Processes	Cost (10^6 $/year)	Mass (10^3 metric ton/year)	Cost (10^6 $/year)	Mass (10^3 metric ton/year)	Cost (10^6 $/year)	Mass (10^3 metric ton/year)	Cost (10^6 $/year)	Mass (10^3 metric ton/year)	Cost (10^6 $/year)	Mass (10^3 metric ton/year)
Residential collection										
Yard waste ($C0$)	—	—	—	—	—	—	—	—	7.1	16.5
Commingled recyclables ($C2$)	—	—	—	—	—	—	—	—	9.7	16.8
Residuals ($C7$)	11.8	186.7	11.7	186.5	11.7	186.3	11.7	186.4	11.1	163.4
Recyclables drop off ($C8r$)	0.3	10.0	0.4	10.2	0.5	10.4	0.4	10.3	—	—
Multifamily collection										
Recyclables drop off ($C8m$)	0.1	3.3	—	—	—	—	—	—	—	—
Presorted recyclables ($C14$)	—	—	0.9	6.8	0.9	6.8	0.9	6.6	0.9	6.6
Residuals ($C16$)	2.4	62.2	2.3	58.7	2.3	58.8	2.3	58.9	2.3	59.0
Commercial collection										
Presorted recyclables ($C19$)	2.0	45.9	2.1	46.1	2.0	45.9	2.0	45.9	2.0	45.5
Residuals ($C20$)	6.7	128.6	6.7	128.4	6.7	128.6	6.7	128.6	6.7	129.1
Separation										
Mixed waste MRF ($S1$)	—	—	3.6	128.4	3.6	128.6	3.6	128.6	10.6	351.5
Presorted recyclables MRF ($S2$)	1.0	59.3	1.1	63.2	1.1	63.1	1.1	62.8	1.2	68.9
Treatment										
Yard waste compost ($T1$)	—	—	—	—	—	—	—	—	0.3	16.5
Combustion ($T3$)	—	—	0.07	0.8	9.6	117.5	19.8	236.8	26.1	309.5
Disposal										
Landfill ($D1$)	10.0	377.5	9.2	349.2	6.1	232.6	3.0	113.6	—	—
Ash landfill ($D2$)	—	—	—	—	0.4	29.7	0.9	62.6	1.2	82.0
Transportation	0	59.3	0.3	191.8	0.3	221.7	0.4	255.4	1.0	506.9
Recyclable revenues	6.3	—	9.2	—	9.2	—	9.1	—	12.3	—
Net cost	27.9	—	29.1	—	36.1	—	43.7	—	67.8	—

[a] Diversion is defined to include recycling, combustion, and yard waste composting in three sectors.

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 13.6% diversion. In addition, diversion targets of 15, 20, 25, and 26.5% were modeled. The maximum possible diversion rate that can be achieved by recycling in this case is 26.5%, 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 5. This table lists the unit operations selected and the mass handled in each unit operation. As the diversion target begins to increase, more materials are recovered from residual waste that is processed at a mixed waste MRF. As the diversion target increases further, presorted collection from the multifamily sector is utilized. 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 ($C2$) 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 nonresidential sectors.

As expected, the cost of the SWM strategy yielding the maximum diversion rate is relatively high ($63.0 million/year)—more than twice as much as the minimum cost ($27.9 million/year) (Table 5). These results show that as the diversion target increases, more expensive unit operations that yield higher levels of recyclable recovery are incrementally selected. The rapid increase in net cost for diversion levels greater than 20% is associated with

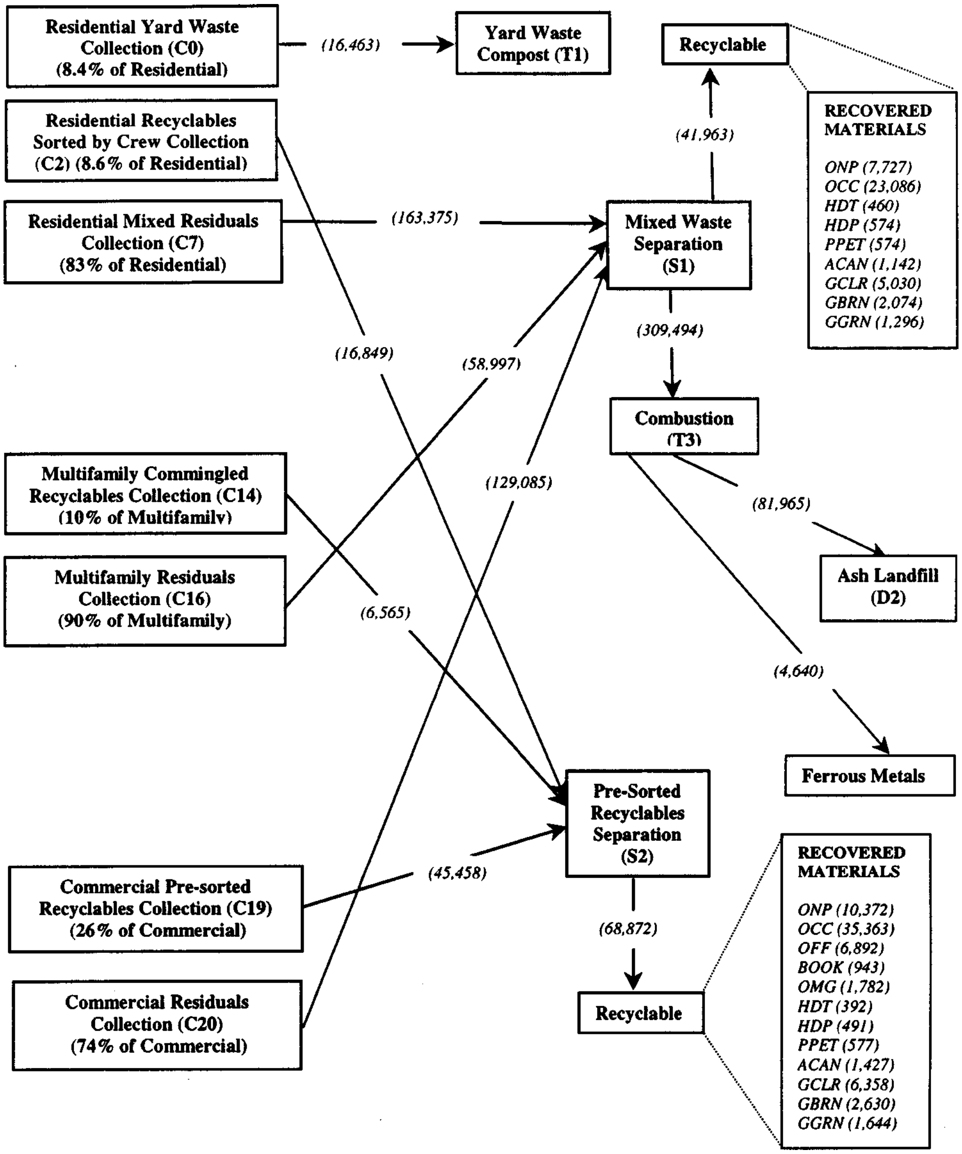

Fig. 4. Mass flows for minimum cost strategy at maximum diversion rate of 82.3% (*numbers in parentheses show mass in metric ton/year*)

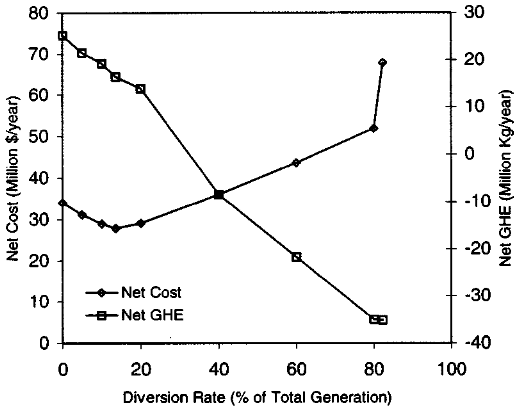

Fig. 5. Net cost and net GHE versus diversion rate (diversion includes recycling, yard waste composting, and combustion in all sectors)

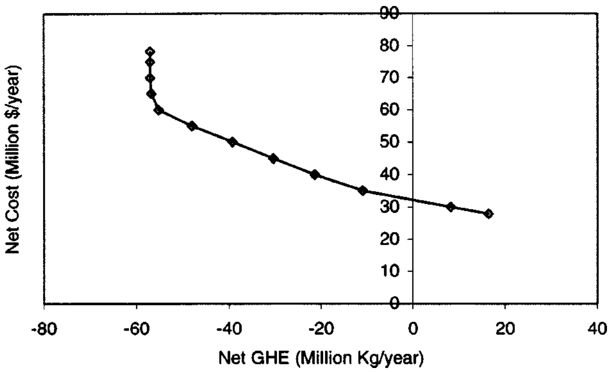

Fig. 6. Cost versus GHE tradeoff

Table 7. Alternative Cost-Effective Solid Waste Management Strategies

	SCENARIOS							
	Minimum cost		Alternative 1		Alternative 2		Alternative 3	
Unit processes	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)	Cost (10^6 \$/year)	Mass (10^3 metric ton/year)
Residential collection								
Mixed waste ($C1$)	—	—	12.0	196.7	—	—	12.0	196.7
Residuals ($C7$)	11.8	186.7	—	—	11.7	186.7	—	—
Recyclables drop off ($C8r$)	0.3	10.0	—	—	0.3	10.0	—	—
Multifamily collection								
Recyclables drop off ($C8m$)	0.1	3.3	—	—	—	—	—	—
Mixed waste ($C13$)	—	—	2.5	65.6	—	—	—	—
Presorted recyclables ($C14$)	—	—	—	—	0.9	6.7	0.9	6.8
Residuals ($C16$)	2.4	62.2	—	—	2.3	58.8	2.3	58.7
Commercial collection								
Presorted recyclables ($C19$)	2.0	45.9	0.3	6.8	2.0	45.9	0.2	4.6
Residuals ($C20$)	6.7	128.2	6.8	148.6	6.7	128.6	7.2	157.2
Mixed waste ($C20$)	—	—	1.1	19.1	—	—	0.7	12.8
Separation								
Mixed waste MRF ($S1$)	—	—	5.7	167.7	2.8	103.5	—	—
Presorted recyclables MRF ($S2$)	1.0	59.3	0.1	6.8	1.1	62.7	0.2	11.4
Treatment								
Combustion ($T3$)	—	—	—	—	5.1	58.8	—	—
Disposal								
Landfill ($D1$)	10.0	377.5	10.1	383.7	8.1	306.5	11.3	425.4
Ash landfill ($D2$)	—	—	—	—	0.2	15.9	—	—
Transportation	—	59.3	0.3	174.5	0.3	182.6	0	11.4
Recyclable Revenues	6.3	—	5.4	—	8.0	—	1.3	—
Net cost	27.9	—	33.5	—	33.5	—	33.5	—

greater use of the separate collection of recyclables in the residential and multifamily sectors and the use of combustion at 26.5% diversion.

GHE values were also calculated for each SWM strategy included in Table 5. Fig. 3 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, which results in increasing GHE reductions from offsetting emissions from manufacturing processes using virgin materials. At the maximum diversion rate, a rapid reduction in GHE and a sharp increase in cost are seen. This results from the additional GHE reductions that correspond to energy offsets achieved at the relatively expensive waste-to-energy facility, which is only used at 26.5% diversion. In contrast, a significant reduction in GHE can be realized at a relatively small increase in cost at lower levels of diversion (Fig. 3).

Diversion through Recovery of Recyclable Material, Yard Waste Composting, and Waste-to-Energy

Another set of scenarios was defined in which required target diversion rates could be achieved via recycling, yard waste 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 82.3%, 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 6).

Fig. 4 shows the mass flows for the maximum possible (82.3%) 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 5), in the maximum diversion strategy recyclables are recovered both by recyclables collection and by recovery of recyclables at a mixed waste MRF. Additional diversion is achieved through yard waste composting. 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.

Fig. 5 shows the behavior of net cost and GHE as incremental levels of diversion are imposed. As the diversion rate approaches the maximum level (82.3%), the cost increases rapidly (approximately 50% for the last increment). Again, an increase in diver-

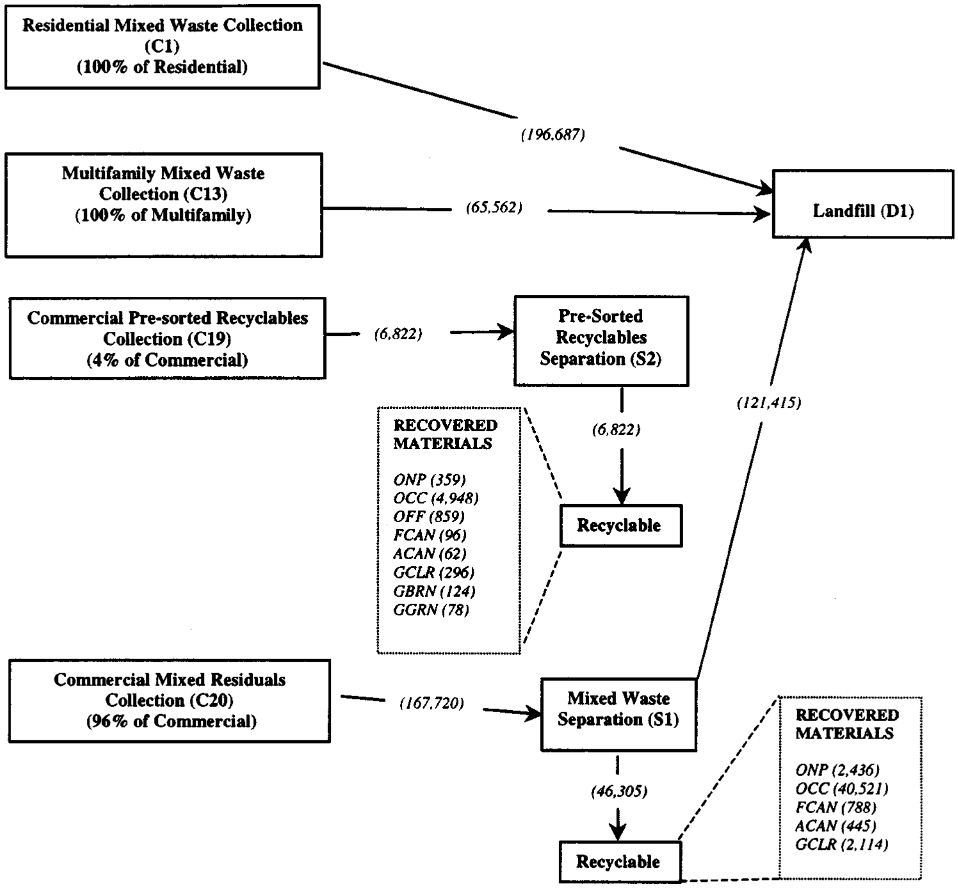

Fig. 7. Mass flows for SWM Alternative 1 (*numbers in parentheses show mass in metric ton/year*)

sion of waste from a landfill leads to increased use of separate recyclables collection, yard waste collection, and composting, and the waste-to-energy facility, all 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 13.6% 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.

Scenarios to Examine Trade Off between GHE and Cost

Another set of scenarios was defined to generate the trade off between GHE and cost. The minimum cost and the minimum GHE scenarios, which are presented in Tables 3 and 4, range in cost from \$27.9 to \$78.3 million/year, 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 trade-off curve shown in Fig. 6 was obtained. This curve indicates that GHE levels below -55 million kg/year, however, require a rapidly increasing cost. The ISWM model can be used similarly to generate tradeoff curves among other environmental parameters and cost.

Generation of Alternative Minimum Cost Solid Waste Management Strategies

Using the modeling to generate an alternative (MGA) approach (Brill et al. 1982, 1990; Chang et al. 1982), 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 considerations that are not explicitly modeled. 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 \$33.5 million/year, which is 20% greater than the minimum cost of \$27.9 million/year (Table 3). 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 objec-

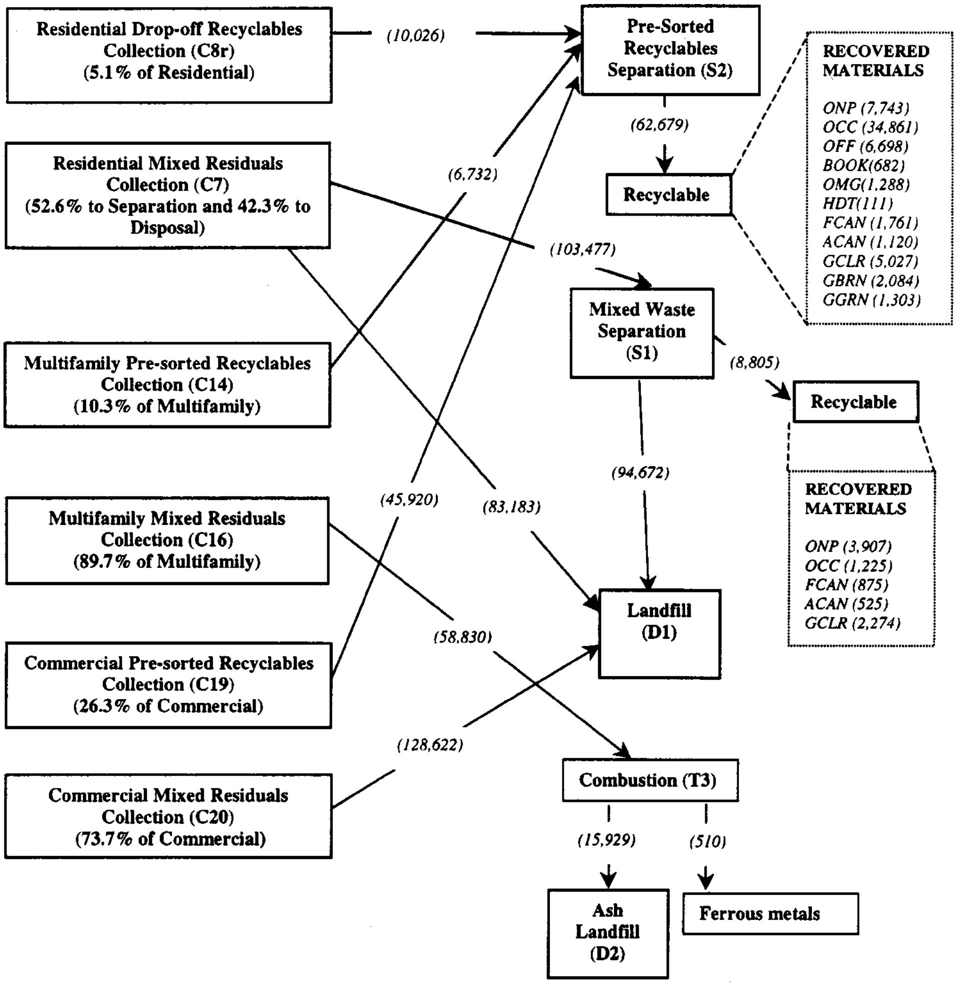

Fig. 8. Mass flows for SWM Alternative 2 (*numbers in parentheses show mass in metric ton/year*)

tive function that maximizes the differences between the decision variables used in the new alternative strategy and previously generated strategies. The resulting alternative strategies and the minimum-cost strategy are compared in Table 7. The mass flow diagrams for the three alternatives are shown in Figs. 7–9. Note that a wide range of unit operations and mass flow were selected among these 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 8). 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 3 to 26%, and NO_x emissions vary from approximately -0.07×10^6 to 0.12×10^6 kg/year. On the other hand, some emissions (e.g., CO) 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 a relatively similar cost. Also, such analyses provide a convenient way to examine alternative management choices and their performance that could

Table 8. Emissions and Diversion for Alternative Solid Waste Management Strategies

Scenario	Diversion (%)	Cost (10^6 \$/ton)	Energy (10^{12} BTU/year)	PM (10^5 kg/year)	NO_x (10^5 kg/year)	SO_x (10^5 kg/year)	CO (10^5 kg/year)	CO_2 Biomass (10^8 kg/year)	CO_2 Fossil (10^8 kg/year)	GHE (10^6 kg/year)
Minimum Cost	13.6	27.9	−0.7	−0.3	−0.7	−3.3	−2.2	4.0	−0.04	16.4
Alternative 1	12.2	33.5	−0.6	−0.6	−1.0	−3.0	−4.2	4.1	0.1	20.6
Alternative 2	26.3	33.5	−1.7	−1.0	−1.8	−6.2	−3.4	3.9	−2.7	6.8
Alternative 3	2.6	33.5	0.07	0.2	1.2	−0.5	3.7	4.6	−0.004	22.4

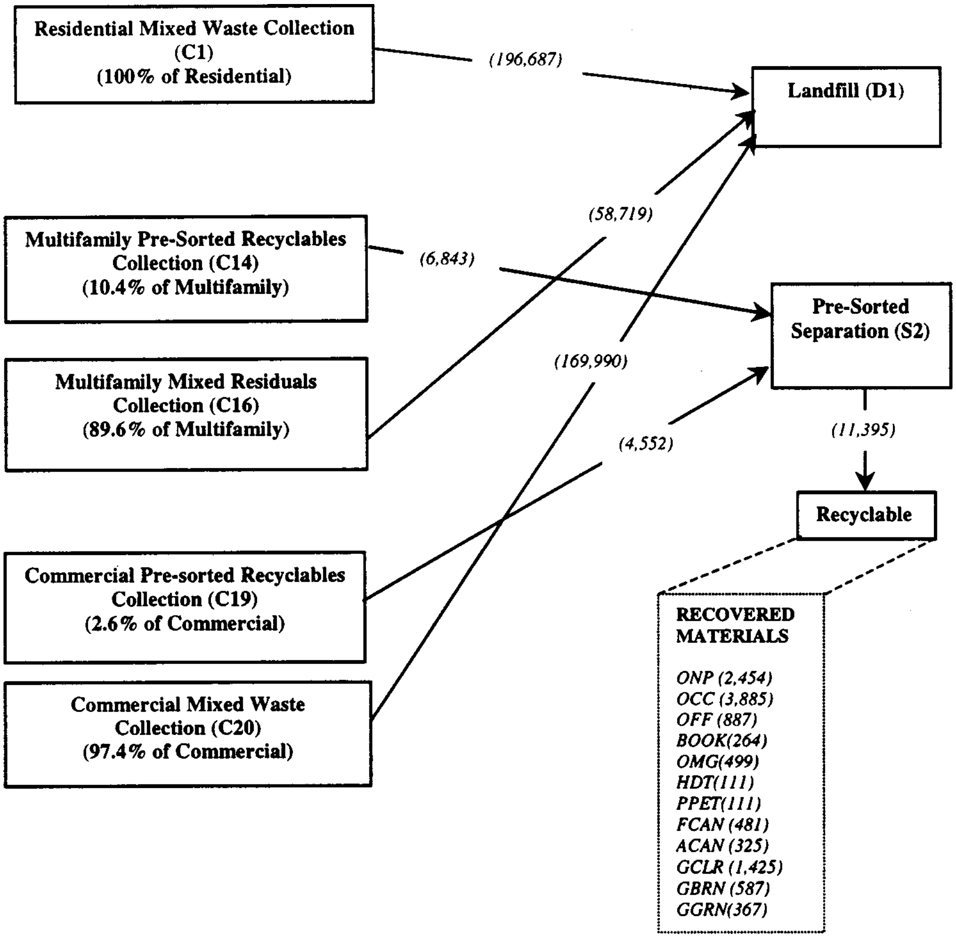

Fig. 9. Mass flows for SWM Alternative 3 (*numbers in parentheses show mass in metric ton/year*)

be realized at marginal differences in budget. These analyses also indicate the considerable degree of flexibility available to planners in developing strategies that meet given objectives.

Summary and Conclusions

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, CO_2, NO_x, SO_x, 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 trade off between cost and a diversion target as well as the trade off between cost and GHE were generated. These scenarios illustrated the large environmental (GHE) benefits associated with recycling for the specified conditions. 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. For example, only traditional landfills without energy recovery were considered. Inclusion of landfill gas to energy would influence GHE emissions. Similarly, mixed waste composting was not considered in the scenarios analyzed.

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. 2001). The extensive capabilities of the ISWM model and the decision support capabilities provide for the first time a powerful tool for representing and examining SWM policies in a systematic manner while considering cost and environmental implications. Also, this tool is useful for exploring and identifying alternative strategies to address the many challenging issues faced by municipal solid waste practitioners.

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 sec. 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.

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