Life-Cycle-based Solid Waste Management. I: Model Development

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Abstract: This paper describes an integrated solid waste management (ISWM) model to assist in identifying alternative SWM strategies that meet cost, energy, and environmental emissions objectives. An SWM system consisting of over 40 unit processes for collection, transfer, separation, treatment (e.g., combustion, composting), and disposal of waste as well as remanufacturing facilities for processing recycled material is defined. Waste is categorized into 48 items and their generation rates are defined for three types of sectors: single-family dwelling, multifamily dwelling, and commercial. The mass flow of each item through all possible combinations of unit processes is represented in a linear programming model using a unique modeling approach. Cost, energy consumption, and environmental emissions associated with waste processing at each unit process are computed in a set of specially implemented unit process models. A life-cycle approach is used to compute energy consumption and emissions of CO, fossil- and biomass-derived CO_2, NO_x, SO_x, particulate matter, PM_{10} and greenhouse gases. The model is flexible to allow representation of site-specific issues, including waste diversion targets, mass flow restrictions and requirements, and targets for the values of cost, energy, and each emission. A companion paper describes the application of this model to examine several SWM scenarios for a hypothetical, but realistic, case study.

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Introduction

Management of municipal solid waste (MSW) is getting increased attention at national and local levels. Many communities and regulatory agencies are responding by considering a variety of solid waste management (SWM) strategies, including voluntary and mandatory recycling programs, source reduction programs and alternative waste processing options. The specific 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 a 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 with respect to environmental issues 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 (e.g., Liebman et al. 1975; Englehardt and Lund 1990; Chang et al. 1997b); recyclable material recovery facilities (e.g., Lund et al. 1994); and landfill operations (e.g., Baetz 1989; Lund 1990; Jacobs and Everett 1992). 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 (e.g., Hasit and Warner 1981; Gottinger 1988; Movassaghi 1993; Hsieh and Ho 1993; Chang et al. 1996, 1997a; Chang and Wang 1966, 1997a,b; Anex et al. 1996; Ferrell and Hizlan 1997; Hokkanen and Salminen 1997; Huang et al. 1997; Huang and Baetz 1997; Karagiannidis and Mousiopoulos 1997).

More recently, studies of integrated MSW management options across unit processes have been reported. In these studies, the waste flows are either allocated a priori among the unit op-

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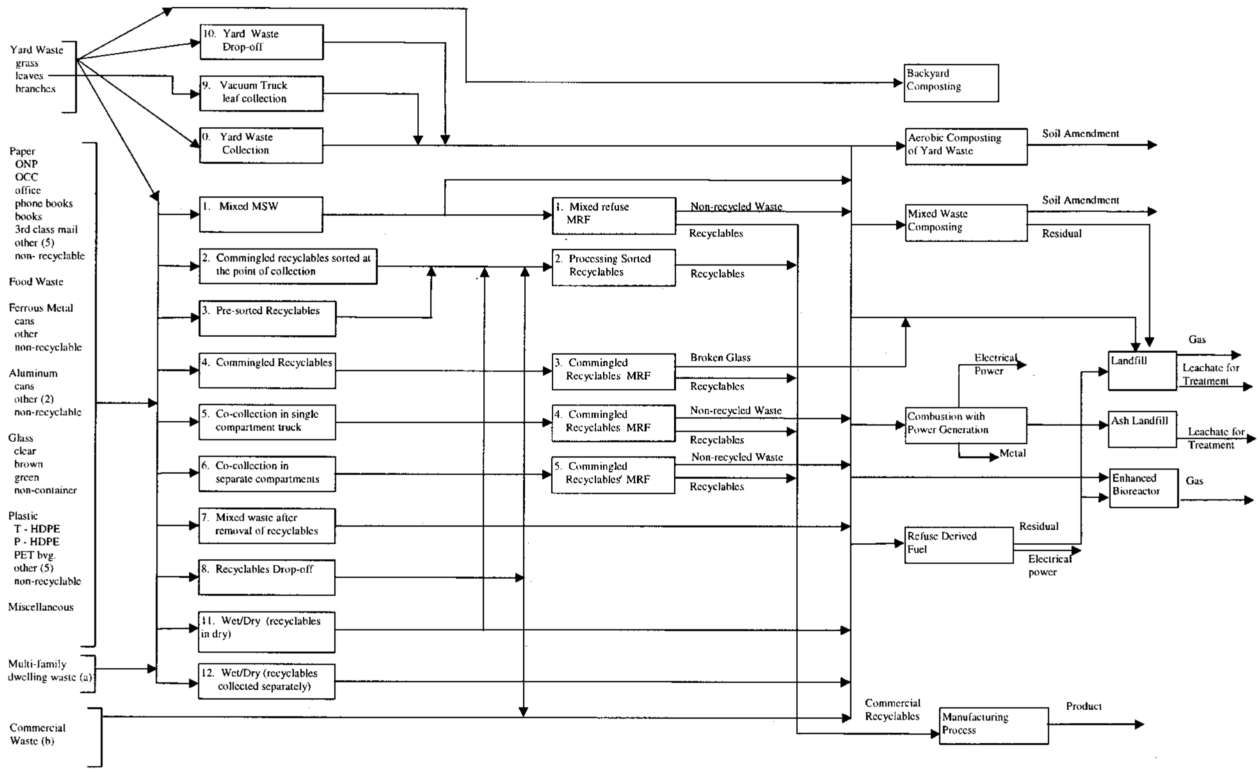

a) The components of multifamily dwelling waste are the same as those listed for residential waste (Table 1 in Solano et al., submitted).
b) The components of commercial waste are given in Table 1 in Solano et al., submitted. Collection options for commercial waste are not shown but are analogous to options 1 and 3.
*Transfer stations (truck and rail) are not shown due to space limitations. They are included in Table 1B.

Fig. 1. Mass flow diagram for integrated solid waste management system

erations or chosen based on cost considerations (e.g., Tellus 1988; Anex et al. 1996; Barlishen and Baetz 1996; Ferrell and Hizlan 1997), with limited or no explicit consideration of environmental emissions. 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. (1996) and Chang and Wang (1996, 1997a,b) 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 offsets associated with the amount of electricity replaced by that generated at a waste-to-energy facility.

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]. 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 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 processes 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 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. Since simple implementations of these equations result in a set of nonlinear equations, a special and unique modeling approach to maintain linearity has been developed for the model presented in this paper. This approach is based on defining variables that represent collection combinations and, for each of them, the waste flow alternatives that specify a feasible set of unit processes to handle the waste.

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). The mathematical modeling framework presented here can be used to represent a wide range of MSW unit processes and their interrelationships (Fig. 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 μm (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 to 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. A companion paper (Solano et al. 2002) discusses applications of the ISWM model and presents more extensive case studies.

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, various options will be used to collect MSW, including the collection of mixed waste or the separate collection of yardwaste, commingled recyclables, and the residual MSW. 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 1.

The MSW system includes three types of sectors: residential, multifamily, and commercial, and the collection unit processes are categorized by these generation sectors [Table 1(a)]. Transfer stations, central facilities 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 1(b)]. Similarly, each MRF design is dependent upon the manner in which refuse is collected and delivered to that MRF [Table 1(c)]. For instance, a MRF for processing presorted recyclables (S2) will require less sorting than a MRF for processing mixed waste (S1).

All waste treatment facilities considered have the potential to generate a product, such as energy or compost, and will reduce the mass of waste to be buried in a landfill [Table 1(d)]. Finally, three landfills were considered: a traditional landfill operated to minimize water infiltration, an ash landfill to receive combustion ash only, and a bioreactor landfill operated to enhance decomposition [Table 1(e)].

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 based on annual average values. MSW is divided into 48 components (USEPA 1997), which are listed by Solano et al. (2002) and Solano (1999). This list indicates which items are applicable in each sector. For example, residential sectors include 42 items and the commercial sectors include 24 items.

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. Fig. 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 Fig. 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.

Collection Combinations and Waste Flow Alternatives

''Collection Combinations'' are formed 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 yard waste collection and residuals mixed waste collection can collect all waste generated. Another example is the combination of yard waste collection, commingled recyclables collection, and residuals mixed waste collection. In the first instance, all waste items not collected as yard waste 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 yard waste and recyclables. A collection combination including only commingled recyclables collection and yard waste collection, however, could not collect all generated waste since there is no option available to collect nonrecyclable and nonyard waste items such as food waste. All alternative collection combinations composed of available collection unit processes are defined a priori. Example combinations and the corresponding waste flow alternatives are shown in Table 2. All collection combinations are shown in Table 3.

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 yard waste and residuals mixed waste collection must be followed by waste flow alternatives to handle yard waste (e.g., yard waste composting) and mixed waste (e.g., combustion and ash landfill, dry landfill, RDF, bioreactor landfill, mixed waste MRF, and mixed waste composting). For each available collection combination, a set of waste flow alternatives is defined (see examples in Table 2).

Conceptual Model Formulation

System Representation

The structure of the model is described using a simple example shown in Fig. 2. The collection combinations ($A1$ and $A2$) and the waste flow alternatives ($B11$, $B12$, $B21$, and $B22$) for each collection combination are defined as follows:

- A1—mixed waste collection ($C1$);

Table 1. (a) Unit Processes for Waste Management Activities: Collection; (b) Unit Processes for Waste Management Activities: Transfer; (c) Unit Processes for Waste Management Activities: Separation; (d) Unit Processes for Waste Management Activities: Treatment; and (e) Unit Processes for Waste Management Activities: Disposal.

(a)

Unit process	Code
Residential Sector	
Collection of yard trimmings for aerobic composting	$C0$
Collection of mixed waste	$C1$
Collection of commingled recyclables sorted at point of collection by collection crew	$C2$
Collection of presorted recyclables	$C3$
Collection of commingled recyclables sorted at MRF with old newsprint ONP in separate compartment	$C4$
Collection of commingled recyclables and mixed waste (bagged separately) in single compartment truck	$C5$
Collection of commingled recyclables and mixed waste (bagged separately) in two compartment truck	$C6$
Collection of mixed waste after removal of recyclables or yard waste	$C7$
Recyclables drop off by generator	$C8r$
Collection of leaves using vacuum truck	$C9$
Yard trimming drop off by 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 $C4$	$C12$
Multifamily sector	
Recyclables drop off by generator	$C8m$
Collection of mixed waste in one truck	$C13$
Collection of presorted 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 $C15$	$C18$
Commercial sector	
Collection of presorted recyclables	$C19$
Collection of mixed waste before or after recyclables removal	$C20$

(b)

Unit process	Code
Transfer of mixed waste	$TR1$
Transfer of commingled recyclables	$TR2$
Transfer of both mixed waste and sorted recyclables brought in separate bags in single-compartment truck	$TR3$
Transfer of both mixed waste and sorted recyclables brought in separate bags in two-compartment truck	$TR4$
Transfer of presorted recyclables	$TR5$
Transfer of MSW onto trains at transfer station	$RT1$
Transfer of mixed waste from trains to vehicles that transport MSW to traditional landfill	$RT2$
Transfer of mixed waste from trains to vehicles that transport MSW to bioreactor	$RT3$

Table 1. (*Continued*)

(c)

Unit process	Code
MRE 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 presorted 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 $C6$	$S5$

(d)

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

(e)

Unit process	Code
Traditional landfill	$D1$
Ash monofill	$D2$
Bioreactor landfill	$D3$

- A2—commingled recyclables collection ($C2$) and residual mixed waste collection ($C7$);
- B11—mixed waste to landfill ($C1 \to D1$);
- B12—mixed waste to combustion ($C1 \to T3 \to D2$);
- B21—commingled recyclables to presorted recyclables MRF ($C2 \to S2$) and residual mixed waste to landfill ($C7 \to D1$);
- B22—commingled recyclables to presorted recyclables MRF ($C2 \to S2$) and residual mixed waste to combustion ($C7 \to T3 \to D2$).

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 Fig. 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

$$x(A1)+x(A2)=M_{\text{waste}} \tag{1}$$

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 Fig. 4 where $x(A1)$ is allocated between waste flow alternatives $B11$ and $B12$ such that

$$x(A1)=x(A1,B11)+x(A1,B12) \tag{2}$$

where $x(A1,B11)=$mass portion of $x(A1)$ handled by waste flow alternative $B11$ and $x(A1,B12)=$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

$$x(A2)=x(A2,B21)+x(A2,B22) \tag{3}$$

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 Fig. 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

$$x(A1,B11)=x(A1,B11,\text{ONP})+x(A1,B11,\text{FW}) \tag{4}$$

where $x(A1,B11,\text{ONP})=$mass portion of waste item ONP handled by waste flow alternative $B11$ in collection combination $A1$ and $x(A1,B11,\text{FW})=$analogous mass portion of waste item FW. 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

$$x(A1,B12)=x(A1,B12,\text{ONP})+x(A1,B12,\text{FW}) \tag{5}$$

$$x(A2,B21)=x(A2,B21,\text{ONP})+x(A2,B21,\text{FW}) \tag{6}$$

$$x(A2,B22)=x(A2,B22,\text{ONP})+x(A2,B22,\text{FW}) \tag{7}$$

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

Table 2. Examples of Collection Combinations and Waste Flow Alternatives

Collection combination	Waste flow alternatives
Residential: mixed waste collection ($C1$)	• Mixed waste collection to traditional landfill ($C1 \rightarrow D1$) • Mixed waste collection to combustion ($C1 \rightarrow T3 \rightarrow D2$)
Residential: Commingled recyclables collection ($C2$), residual mixed waste collection ($C7$)	• Commingled recyclables collection to presorted recyclables MRF ($C2 \rightarrow S2$) and residual mixed waste collection to traditional landfill ($C7 \rightarrow D1$) • Commingled recyclables collection to presorted recyclables MRF ($C2 \rightarrow S2$) and residual mixed waste collection to combustion ($C7 \rightarrow T3 \rightarrow D2$)
Residential: Yard waste collection ($C0$), commingled recyclables collection ($C2$), residual mixed waste collection ($C7$)	• Yard waste collection to yard waste composting ($C0 \rightarrow T1$); commingled recyclables collection to presorted recyclables MRF ($C2 \rightarrow S2$) and residual mixed waste to traditional landfill ($C7 \rightarrow D1$) • Yard waste collection to yard waste composting ($C0 \rightarrow T1$); commingled recyclables collection to presorted recyclables MRF ($C2 \rightarrow S2$) and residual mixed waste collection to combustion ($C7 \rightarrow T3 \rightarrow D2$)
Residential: Yard waste collection ($C0$), presorted recyclables collection ($C3$), residual mixed waste collection ($C7$)	• Yard waste collection to combustion ($C0 \rightarrow T3$); presorted recyclables collection to presorted recyclables MRF ($C3 \rightarrow S2$) and residual mixed waste collection to mixed waste MRF and then MRF residuals to traditional landfill ($C7 \rightarrow S1 \rightarrow D1$) • Yard waste collection to combustion ($C0 \rightarrow T3 \rightarrow D2$); presorted recyclables collection to presorted recyclables MRF ($C3 \rightarrow S2$) and residual mixed waste collection to mixed waste transfer station and then to traditional landfill ($C7 \rightarrow TR1 \rightarrow D1$)
Multifamily: Recyclables drop-off collection ($C8m$), residual mixed waste collection ($C16$)	• Recyclables drop off collection to presorted recyclables MRF ($C8m \rightarrow S2$) and residual mixed waste collection ($C16$) to traditional landfill ($D1$) • Recyclables drop off collection to presorted recyclables MRF ($C8m \rightarrow S2$) and residual mixed waste collection ($C16$) to combustion ($T3 \rightarrow D2$)
Multifamily: Presorted recyclables collection ($C14$), residual mixed waste collection ($C16$)	• Presorted recyclables collection to presorted recyclables MRF ($C14 \rightarrow S2$) and residual mixed waste collection ($C16$) to mixed waste transfer station and then to traditional landfill ($C16 \rightarrow TR1 \rightarrow D1$) • Presorted recyclables collection to presorted recyclables MRF ($C14 \rightarrow S2$) and residual mixed waste collection ($C16$) to mixed waste transfer station and then to combustion ($C16 \rightarrow TR1 \rightarrow T3 \rightarrow D2$)
Commercial: Commingled recyclables collection ($C19$), residual mixed waste collection ($C20$)	• Commingled recyclables collection to presorted recyclables MRF ($C19 \rightarrow S2$) and residual mixed waste collection to traditional landfill ($C20 \rightarrow D1$) • Commingled recyclables collection to presorted recyclables MRF ($C19 \rightarrow S2$) and residual mixed waste collection to combustion ($C20 \rightarrow T3 \rightarrow D2$)

in each collection unit process used within that waste flow alternative. For instance, $x(A1,B11,\mathrm{ONP})$, 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 mixed waste collection ($C1$). Therefore, $x(A1,B11,\mathrm{ONP})$ will be fully allocated to this collection unit process, resulting in Eq. (8)

$$x(A1,B11,\mathrm{ONP}) = x(A1,B11,\mathrm{ONP},C1) \tag{8}$$

where $x(A1,B11,\mathrm{ONP},C1)$ = 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 Eqs. (9)–(11)

$$x(A1,B11,\mathrm{FW}) = x(A1,B11,\mathrm{FW},C1) \tag{9}$$

$$x(A1,B12,\mathrm{ONP}) = x(A1,B12,\mathrm{ONP},C1) \tag{10}$$

$$x(A1,B12,\mathrm{FW}) = x(A1,B12,\mathrm{FW},C1) \tag{11}$$

The mass balances described by these equations for collection combination $A1$ are shown in Fig. 6.

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 in that collection combination (i.e., $C2$ and $C7$). Consider the mass of ONP handled by 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 $B21$, $x(A2,B21,\mathrm{ONP},C2)$ represents the

Table 3. List of All Collection Combinations

Sector type	Collection combinations[a]		
Residential	$C1$	$C0/C7$	$C0/C2/C7$
	$C5$	$C2/C7$	$C0/C3/C7$
	$C6$	$C3/C7$	$C0/C4/C7$
	$C11$	$C4/C7$	$C0/C8r/C7$
	$C12$	$C8r/C7$	$C10/C2/C7$
		$C10/C7$	$C10/C3/C7$
			$C10/C4/C7$
			$C10/C8r/C7$
Multifamily	$C13$	$C8m/C16$	
	$C17$	$C14/C16$	
	$C18$	$C15/C16$	
Commercial	$C20$	$C19/C20$	

[a]Codes for collection unit processes are defined in Table 1(a).

mass portion of ONP collected (as commingled recyclable) by collection unit operation $C2$ and $x(A2,B21,\text{ONP},C7)$ 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 Eq. (12):

$$x(A2,B21,\text{ONP})=x(A2,B21,\text{ONP},C2)+x(A2,B21,\text{ONP},C7) \tag{12}$$

Similarly, mass balances can be written for all waste items allocated among all available collection unit processes in each waste flow alternative within collection combination A2.

$$x(A2,B21,\text{FW})=x(A2,B21,\text{FW},C2)+x(A2,B21,\text{FW},C7) \tag{13}$$

$$x(A2,B22,\text{ONP})=x(A2,B22,\text{ONP},C2)+x(A2,B22,\text{ONP},C7) \tag{14}$$

$$x(A2,B22,\text{FW})=x(A2,B22,\text{FW},C2)+x(A2,B22,\text{FW},C7) \tag{15}$$

These mass balances are subject to other model constraints that ensure that waste flow is consistent with technically feasible alternatives. For example, 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.

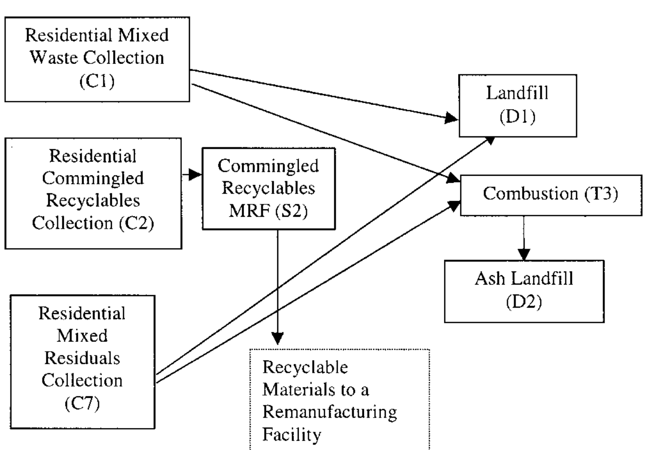

Fig. 2. Unit processes considered in illustrative example.

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 $A1$ $[x(A1,B12,\text{ONP},T3)]$ is equal to the mass of ONP collected by $C1$ corresponding to that waste flow alternative $[x(A1,B12,\text{ONP},C1)]$. Downstream of the combustion facility, the mass entering the ash landfill will be a function of the 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. The mass balances for collection combination $A1$ are illustrated in Fig. 7. Similar mass balances exist for collection combination $A2$.

Mathematical Model Formulation

The model formulation described in the previous section is represented by a set of linear equations, which form the basis for a linear programming (LP) model. These linear equations enforce feasible mass flows of waste through the MSW system. Additional equations are introduced to ensure that these feasible mass flows also meet other conditions, such as capacity restrictions at unit processes, minimum diversion requirements, and other waste management goals. All 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. The solution to the LP model then identifies the optimal solution for the selected objective function. For example, SO_x emissions could be minimized.

The approach used to construct the equations for the example problem in the section ''Conceptual Model Formulation,'' can be extended to construct the LP model for a larger SWM system. The LP model for the example includes 40 constraint equations and 40 variables, while the LP model for a system that would include typical process options and waste items would have on the order of 10,000 constraints and that many decision variables.

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:

$$\text{Net\_Cost}=\sum_{u\in U}\text{Cost}_u-\text{Revenue} \tag{16}$$

where Net_Cost = net system cost (\$/year); U = set of unit processes: $U=C\cup S\cup T\cup D$; C = set of collection unit processes; in

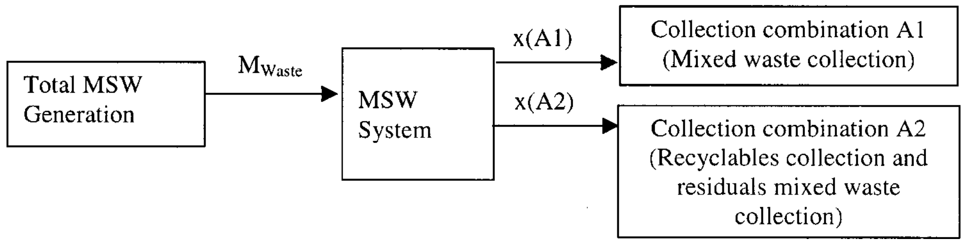

Fig. 3. Mass balance for MSW system

the example $C=\{C1,C2,C7\}$; S=set of separation unit processes; in the example $S=\{S2\}$; T=set of treatment unit processes; in the example $T=\{T3\}$; D=set of disposal unit processes; in the example $D=\{D1,D2\}$; Cost_u is the total cost of unit process u (\$/year); and Revenue is from sales of recyclables (\$/year) as described in Eq. (18).

Each unit process cost is defined as

$$\text{Cost}_u=\sum_{k\in W}\alpha_{u,k}y_{u,k}\ \forall u\in U \tag{17}$$

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

Revenue is defined as

$$\text{Revenue}=\sum_{k\in \text{WR}}\lambda_k\sum_{s\in \text{S}}\delta_{s,k}y_{s,k} \tag{18}$$

where Revenue=total revenue from the sale of recyclable materials (\$/year); λ_k=revenue coefficient for recyclable item k (\$/ton); $\delta_{s,k}$=fraction of recyclable waste item k actually separated at the separation unit process s: $1\geqslant\delta_{s,k}\geqslant 0$; $y_{s,k}$=mass of recyclable item k processed at separation unit process s (tons/year); and $S=\{S2\}$, 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 Eq. (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:

$$\text{LCI}(p)=\sum_{u\in U}\text{LCI}(p)_u \tag{19}$$

where U=set of unit processes and $\text{LCI}(p)_u$=energy consumption or the net environmental emissions of pollutant p at unit process U.

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

$$\text{LCI}(p)_u=\sum_{k\in W}\xi(p)_{u,k}y_{u,k}\ \forall u\in U \tag{20}$$

where $\xi(p)_{u,k}$=energy consumption or the emission of pollutant p per ton of waste item k processed in unit process u and $y_{u,k}$=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 multiobjective analysis.

Constraints

Mass Flow Constraints

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

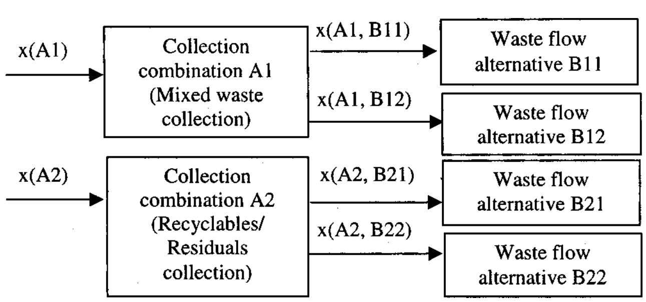

Fig. 4. Mass balances for collection combinations

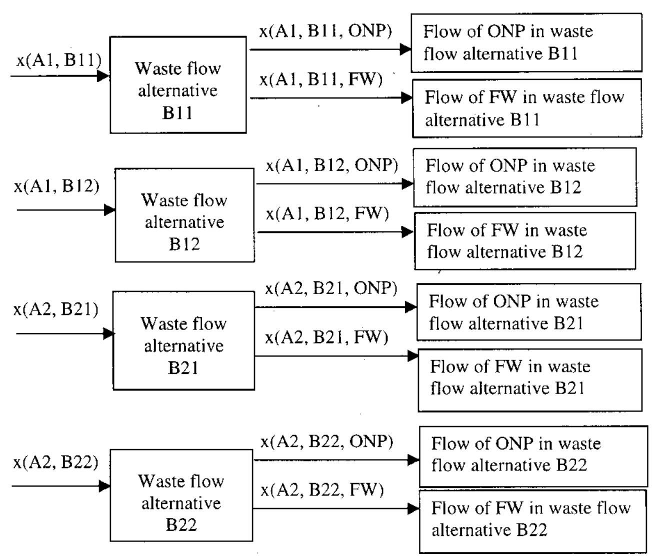

Fig. 5. Mass balances for waste flow alternatives

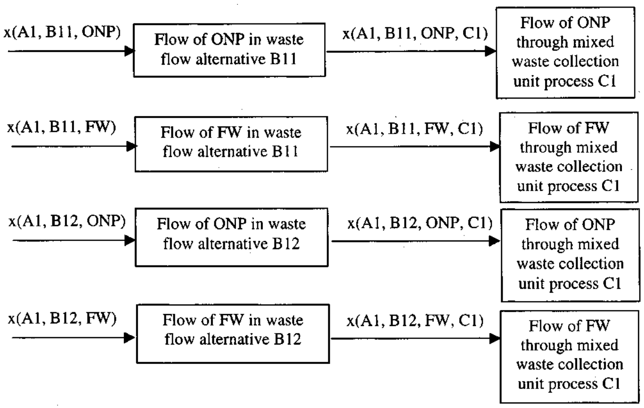

Fig. 6. Mass balances for individual waste items handled in collection combination A1

1. Mass flows in collection combinations

$$\sum_{i \in A} x_i = M_{\text{Waste}} \tag{21}$$

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

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

$$x_i = \sum_{j \in B_i} x_{i,j} \ \forall i \in A \tag{22}$$

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

$$x_{i,j,k} = \beta_k x_{i,j} \ \forall i \in A, \forall j \in B_i, \forall k \in W \tag{23}$$

where

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

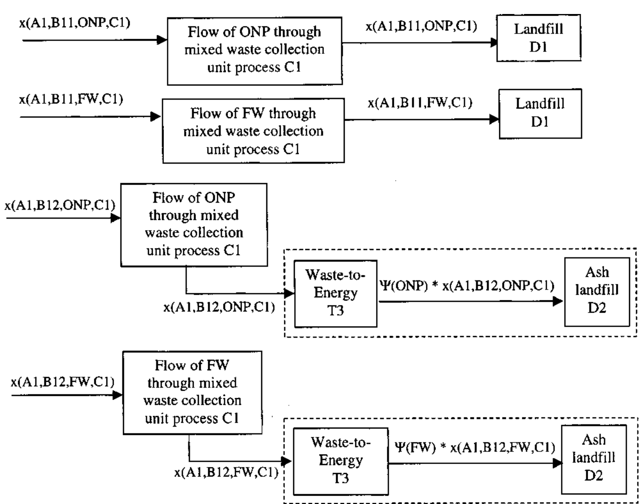

Fig. 7. Mass balances for waste handled by collection unit processes in collection combination A1

$x_{i,j,k}$ = mass of waste item k flowing in waste flow alternative j within collection combination i (tons/year) and 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
   - 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.

$$x_{i,j,k,m} = x_{i,j,k} \ \forall i \in A, \forall j \in B_i, \forall k \in W \tag{24}$$

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

   - 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:

$$x_{i,j,k,r} = \phi_{k,r} x_{i,j,k} \quad \forall i \in A, \ \forall j \in B_i, \ \forall k \in W \tag{25}$$

$$x_{i,j,k,m} = x_{i,j,k} - x_{i,j,k,r} \quad \forall i \in A, \ \forall j \in B_i, \ \forall k \in W \tag{26}$$

where r = either a recyclables collection unit process or a yardwaste collection unit process within collection combination i; m = mixed waste collection unit process (for handling the residuals) within collection combination i; $x_{i,j,k,r}$ = mass of waste item k collected by collection unit process r and flowing through waste flow alternative j within collection combination i (tons/year); $x_{i,j,k,m}$ = 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, $\phi_{k,r} = 0$ if $k \in WN$ and $0 \leqslant \phi_{k,r} \leqslant 1$ if $k \in WR$.

5. Mass flows of waste items processed by each unit process. For each mixed waste collection unit process (i.e., $u = m$)

$$y_{u,k} = \sum_{i \in A} \sum_{j \in B_i} x_{i,j,k,m} \ \forall m \in C, \ \ \forall k \in W \tag{27}$$

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

$$C = \{C1, C2, C7\}$$

For each recyclable or yard waste collection unit process (i.e., $u = r$)

$$y_{u,k} = \sum_{i \in A} \sum_{j \in B_i} x_{i,j,k,r} \quad \forall r \in C, \ \ \forall k \in W \tag{28}$$

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

$$C = \{C1, C2, C7\}$$

For each separation, treatment or disposal unit process u

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

$$\forall u \in (S \cup T \cup D), \ \ \forall k \in W \tag{29}$$

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

$$\left(\sum_{k\in \mathrm{WR}} \delta_{\mathrm{S2},k} y_{\mathrm{S2},k} + \sum_{k\in \mathrm{W}} y_{\mathrm{T3},k}\right) \geqslant \theta_{\mathrm{diversion}} \mathrm{M}_{\mathrm{Waste}} \qquad (30)$$

where $\theta_{\mathrm{diversion}}$ is the specified target diversion rate: $0 \leqslant \theta_{\mathrm{diversion}} \leqslant 1$.

Supporting Components and Parameters for Integrated Solid Waste Management 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 life-cycle methods for use in SWM (Weitz et al. 1999). 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 Eqs. (17) and (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 are not allocated to recovered glass. Process models for collection (Curtis and Dumas 1998), waste transportation (Kosmicki 1997a), transfer stations (Kosmicki 1997b), material recovery (Nishtala and Solano 1997), combustion (Harrison et al. 2000) and landfills (Sich and Barlaz 1999) have been developed and incorporated in the ISWM model.

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 costs; and revenues from the 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 methodology for calculation of the amounts of environmental releases of pollutants from the MSW unit processes is described in the aforementioned documentation for each process model.

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 recovers 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.

Summary

This paper presents a comprehensive mathematical model for ISWM that accounts for 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 complete set of unit processes and the amount of each waste item handled within those unit processes. The variable definitions and model equations are structured especially to avoid nonlinearities that would arise typically due to the types of decisions being represented by this model. 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 (Solano et al. 2002).

This model is intended for planning, or screening, purposes and there are limitations to the existing implementation. One simplification, for instance, is that economies of scale cannot be represented. The model has been implemented in an interactive decision support system (Harrison et al. 2001) 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 study and design would be required to produce the final design for field-scale implementation of an SWM system based on the model solution.

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