LCA Concepts and Methods

Life Cycle Management of Municipal Solid Waste

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Abstract

Life-cycle assessment concepts and methods are currently being applied to evaluate integrated municipal solid waste management strategies throughout the world. The Research Triangle Institute and the U.S. Environmental Protection Agency are working to develop a computer-based decision support tool to evaluate integrated municipal solid waste management strategies in the United States. The waste management unit processes included in this tool are waste collection, transfer stations, recovery, compost, combustion, and landfill. Additional unit processes included are electrical energy production, transportation, and remanufacturing. The process models include methodologies for environmental and cost analysis. The environmental methodology calculates life cycle inventory type data for the different unit processes. The cost methodology calculates annualized construction and equipment capital costs and operating costs per ton processed at the facility. The resulting environmental and cost parameters are allocated to individual components of the waste stream by process specific allocation methodologies. All of this information is implemented into the decision support tool to provide a life-cycle management evaluation of integrated municipal solid waste management strategies.

Keywords: Combustion; compost; computer-based decision support tools; electrical energy production; landfill; life-cycle management; methodologies for environmental and cost analysis municipal solid waste; recovery; re-manufacturing; transfer stations; transportation; unit processes; waste collection; waste management strategies

1 Introduction

To date, most applications of life-cycle assessment (LCA) have generally focused on the evaluation of the environmental performance for a defined product system, while holding constant or altogether neglecting the mode of solid waste management. White et al. (1995) describe the application of LCA whereby the product system is held constant and the evaluation is done on the performance of alternatives for solid waste disposal. This concept has been implemented in programs throughout the world that are applying LCA concepts and methods to the evaluation of integrated municipal solid waste (MSW) management strategies. In evaluating such strategies, planners have a wide variety of available processes for waste collection, separation, treatment, and disposal to evaluate. Combining these processes in integrated systems forms complex interrelationships of mass flows with associated energy and resource consumptions and environmental releases. Examining these interrelationships, and identifying optimal management solutions, can be accomplished by taking a life-cycle management (LCM) approach, as illustrated in **Figure 1**. Unlike traditional product LCAs which begin with raw materials extraction, our system begins with MSW generation and considers the inputs and effects to all life cycle stages resulting from the management of MSW.

This LCM perspective encourages waste planners to consider the environmental performance of the entire system including activities that occur outside of the traditional framework

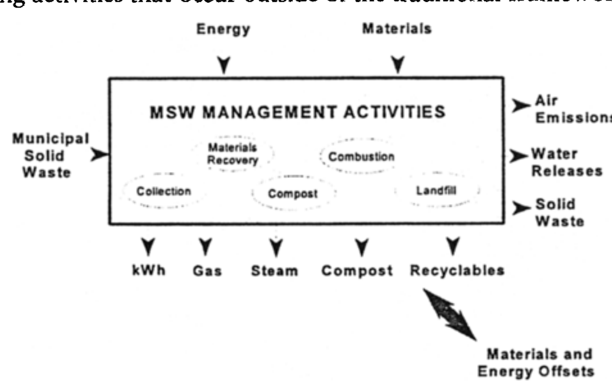

Fig. 1: Integrated municipal solid waste management.
Integrated MSW management starts with the collection of waste generated in residential, multifamily, and commercial sectors. The MSW is then transported for separation and recycling, treatment, or disposal. These activities consume energy and materials and result in environmental releases. Any materials or energy that is recovered may create offsets of virgin materials in the manufacturing and energy sectors.

of activities from the point of waste collection to final disposal. For example, when evaluating options for recycling, it is important to consider the net environmental benefits (or burdens) of those options with respect to potential offsets in raw materials extraction, manufacturing, and energy production sectors that are created. Similarly, when electricity is recovered through the combustion of waste or landfill gas, an offset some production of fuels and electricity from the utility sector is created.

The Research Triangle Institute (RTI) and the United States Environmental Protection Agency's (U.S. EPA's) Office of Research and Development are working to apply LCM to evaluate the cost and environmental performance of integrated MSW management systems in the U.S. RTI's research team for this effort includes LCA and solid waste management experts from North Carolina State University, the University of Wisconsin-Madison, Franklin Associates, and Roy F. Weston.

This research will provide information and tools that will enable local governments and solid waste planners to examine cost and environmental burdens for a large number of possible MSW management operations for 42 distinct MSW components. The primary outputs of this research will include the following:

- **Decision support tool:** is being designed to allow MSW planners to enter site-specific data (or rely on the default data) to compare alternative MSW management strategies for their communities' waste quantity and composition and other constraints. This enables users to evaluate cost, energy consumption, and environmental emissions for a large number of possible MSW management operations including MSW collection, transfer, separation (MRF and drop-off facilities), composting, combustion, and landfill disposal. A framework for the tool is shown in **Figure 2**. A full prototype version has been completed in spring 1999 and the final commercial version is planned for release by May 2000.

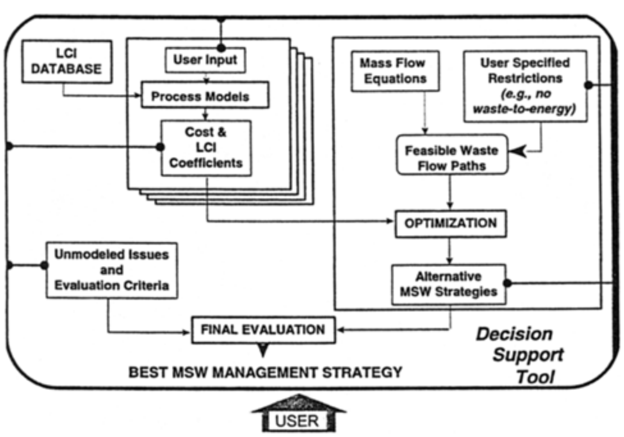

Fig. 2: Framework for decision support tool.
The decision support tool consists of several components including process models, waste flow equations, an optimization module, and a graphic user interface. The user interface integrates all model components to allow easy user manipulation of the spreadsheet models and the optimization module. It allows for additional user constraints to be specified and provides a graphical representation of the MSW management alternatives resulting from the optimization.

- **Database:** includes environmental and cost data for individual MSW management operations, materials manufacturing operations, energy (fuels and electricity) production, and various types of vehicles and equipment. Environmental data include energy consumption and emissions (air, water, solid waste). Cost data include a range of capital and operating costs borne by local governments based on the MSW management system design. The database allows users to search for data specific to a system unit operation, structure, piece of equipment and environmental or cost parameter. A beta version will be completed by September 1999, and a final version is scheduled for release by May 2000.
- **Community Case Studies:** are being conducted to test the individual models (e.g., compost model) and the overall decision support tool. Initial case studies were begun in 1998 with Lucas County, Ohio and the Great River Regional Waste Authority, Iowa. These were designed to test the methodologies developed for individual operations (e.g., waste collection, transportation, composting). Additional case studies are planned for 1999 and will reflect the issues of urban and rural settings throughout the U.S. to ensure that the decision support system is flexible enough to handle the wide range of variation among local communities.

To ensure the applicability and usefulness of the research products to local governments and other solid waste planners, we employ an inclusive review process for all research activities and documentation that includes:

- Internal project team and U.S. EPA and U.S. Department of Energy advisors.
- Project stakeholders from U.S. government, industry, academia, and environmental organizations.
- External project peer review committee.

The high level of involvement by project stakeholders and peer review committee members has contributed greatly to the success of this project.

In this paper, we provide the reader with an overview of this research effort and summarize the overall technical approach used to apply life cycle management to evaluate integrated MSW management strategies. Future papers are being prepared to present the details of methods used to estimate the cost and environmental performance for individual MSW management unit processes.

2 Goal and Scope Definition

The *overall goal* for this project is to develop information and tools to evaluate the relative cost and environmental performance of integrated MSW management strategies. For instance, how does the cost and environmental performance of a MSW management system change if a specific material (e.g., glass, metal, paper, plastic) is added to or removed from a community's recycling program? And, what are the tradeoffs in cost and environmental performance if paper is recycled versus combusted or landfilled with energy recovery?

The *primary audience* for this effort is local governments and solid waste planners. However, we anticipate that the information and tools developed through this study will also be of value to Federal agencies, environmental and solid waste consultants, industry, LCA practitioners, and environmental advocacy organizations.

The function of the system under study is to manage MSW of a given quantity and composition. Therefore, we have defined the *functional unit* as the management of 1 ton of MSW, of a specified composition. We consider all activities required to manage the MSW from the time it is sent out for collection to its ultimate disposition, whether that be disposal in a landfill, compost that is applied to the land, energy that is recovered from combustion and landfills, or materials that are recovered and remanufactured into new products.

The 42 MSW components include those defined by the U.S. EPA's Office of Solid Waste (U.S. EPA, 1997a) and are listed in **Table 1** (→ *Appendix, p. #*). This definition includes mixed MSW generated in the residential, commercial, institutional, and industrial sectors but excludes industrial process waste, sludge, construction and demolition waste, pathological waste, agricultural waste, mining waste, and hazardous waste. We have also included ash that is generated from the combustion of MSW in our system, but combustion ash is not included as part of EPA's definition of MSW. As shown in Table 1, we have divided the MSW stream into three different waste generation sectors: residential, multifamily dwelling, and commercial. The rationale for this separation is that different collection and separation alternatives may apply to each sector.

The major *unit processes* included in the overall system under study are:

Waste Management:
- Collection
- Transfer Station
- Materials Recovery Facility (MRF)
- Combustion (with or without energy recovery)
- Refuse-Derived Fuel combustion (RDF)
- Composting (yard waste and mixed MSW)
- Landfill (traditional and enhanced bioreactor, with and without energy recovery, and ash landfill)

Other Processes:
- Electrical Energy
- Inter-Unit Process Transportation
- Manufacturing of Materials from Virgin Resources and Remanufacturing of materials from Recycled Resources

For each of these unit processes, " process models" are being developed that utilize generic design and operating parameters in conjunction with resource and energy consumption and emission factors to estimate cost and environmental (life-cycle inventory type) parameters. The results are highly dependent on the quantity and composition of incoming material to each unit process. Because the composition of MSW can greatly affect the cost and environmental results for different management options, the process models also contain methodologies for allocating cost and environmental parameters to the 42 MSW components. The boundaries are consistent across all process models.

The data categories for cost and environmental performance included in the study are:

Cost Categories:
- Annual capital cost
- Annual operating cost

Environmental Categories:
- Energy consumption
- Air emissions
- Waterborne releases
- Solid waste

To compare across alternative MSW management options, we can only use parameters for which comparable data exists across all unit processes. For example, although data for dioxin/furan emissions for MSW combustion facilities are readily available, comparable data do not exist for MRF, composting, and landfill operations. Thus, we cannot directly compare these unit processes based on dioxin/furan emissions. Parameters for which comparable data are available include:

- Annual cost
- Carbon monoxide
- Carbon dioxide (fossil - resulting from the combustion of fossil fuels)
- Carbon dioxide (biomass – resulting from the biodegradation or combustion of organic material)
- Electricity consumption
- Greenhouse gas equivalents
- Nitrogen oxides
- Particulate matter
- Sulfur dioxide

These parameters can be optimized on as part of the decision support tool (DST) solution, as described in Section 5.2. Additional air and water parameters are tracked and reported in the DST, but cannot be optimized because consistent and comparable data are not yet available for the parameters across all unit processes. As data become available to enable additional comparisons across unit processes, future versions of the DST can be updated to include an expanded list of optimizable parameters.

3 System Boundaries

The system boundaries for this study have largely been defined through the description of the functional elements and unit processes and the manner in which each will be treated. These elements and processes are outlined in detail in a draft system description document and summarized in the following section. Unlike traditional LCAs, however, our study integrates cost and environmental data and the boundaries for each are slightly different as described below.

3.1 Boundaries for environmental analysis

All activities which have a bearing on the management of MSW from collection through transportation, recovery and separation of materials, treatment, and disposal are included in the environmental analysis. It is assumed that MSW enters the system boundaries when it is set out or delivered to a collection site, whether it be a residential curbside, apartment collection site, or rural drop-off site. All " upstream" life cycle activities (raw materials extraction, manufacturing, and use) are assumed to be held constant. Thus, the production of garbage bags and cans and recycling bins are NOT included in the study. Similarly, the transport of waste by residents to a collection point have NOT been included. The functional elements of MSW management include numerous pieces of capital equipment from refuse collection vehicles, to balers for recycled materials, to major equipment at combustion facilities. Resource and energy consumption and environmental releases associated with operation of equipment and facilities are included in the study. For example, energy (fuel) that will be consumed during the operation of refuse collection vehicles is included in the study. In addition, electricity consumed for operation of the office through which the vehicle routes are developed and the collection workers are supervised is also included in the study. However, activities associated with the fabrication of capital equipment are NOT included.

Where a material is recycled, the resource and energy consumption and environmental releases associated with the manufacture of a new product are calculated, assuming closed-loop recycling processes, and included in the study. These parameters are then compared against those from manufacturing the product using virgin resources to estimate net resource and energy consumption and environmental releases. This procedure also applies to energy recovery from other unit processes including combustion, RDF, and landfill gas recovery projects.

Another system boundary is set at the waste treatment and disposal. Where liquid wastes are generated and require treatment (usually in a publicly owned treatment works), the resource and energy consumption and environmental releases associated with the treatment process is considered. For example, if biological oxidation demand (BOD) is treated in an aerobic biological wastewater treatment facility, then energy is consumed to supply adequate oxygen for waste treatment. If a solid waste is produced which requires burial, energy will be consumed in the transport of that waste to a landfill, during its burial (e.g., bulldozer) and after its burial (e.g., gas collection and leachate treatment systems) in the landfill. Also, if compost is applied to the land, volatile and leachate emissions are considered.

3.2 Boundaries for cost analysis

Costs have also included in this study because they play such a crucial role in making decisions about integrated MSW management strategies. Note that the system boundaries for cost analysis differ from that of the environmental analysis because they are designed to provide a relative comparison of annual cost among alternative MSW management strategies as incurred by the public sector. These costs are intended to provide a relative ranking of the different alternatives as part of a screening tool to narrow the range of options associated with integrated MSW management. No distinction is made between public and private sector costs. All MSW management activities are assumed to occur in the public sector and therefore costs are calculated as though they are accruing to the public sector. The cost analysis is intended to reflect the full costs associated with waste management alternatives based on U.S. EPA guidance from *Full Cost Accounting for Municipal Solid Waste Management: A Handbook* (U.S. EPA, 1997b).

In focusing the cost analysis on publicly accrued costs, the costs associated with electricity production, for instance, are not included in the study because the public sector only pays the price for electricity consumed. In cases where recyclables are shipped from a MRF, the cost analysis ends where the public sector receives revenue (or incurs a cost) in exchange for the recyclables. The cost analysis does not include the costs associated with the re-manufacturing processes for different materials (e.g., recycled office paper). These costs occur in the manufacturing are borne by the manufacturing sector and not to municipal or county governments. The same procedure is applied to the generation and sale of electricity derived from combustion facilities or landfills. Where waste is produced as part of a waste management facility, the cost of waste disposal or treatment is included in the cost analysis of that facility. For example, we include the cost of leachate treatment in our cost analysis of landfills. We also include the cost of training, educational, or other materials associated with source reduction or other aspects of MSW management.

Similar to environmental parameters, cost parameters are also allocated to individual MSW components. Thus, the result of the cost analysis can illustrate, for example, the additional capital and operating costs to a MRF for processing and storing glass. Similarly, the cost associated with the separate collection of residential yard waste can be analyzed.

4 Technical Approach for Unit Processes

As discussed in the previous section, the methodologies for cost and environmental analysis for each unit process are implemented in process models. Process models include sets of equations that utilize the default (or user input) facility design information to calculate all environmental and cost parameters based on the quantity and composition of waste entering each MSW management unit process. A summary of key assumptions and issues, and the status for each process model are provided in Table 2 (→ *Appendix, p. 200*).

The process models are linked in the DST through a set of mass flow equations. The cost and environmental results from process models are used in the DST to calculate the total system cost and environmental performance for alternative MSW management strategies. Summaries of the design and operating parameters and methods for cost and environmental analysis for each process model will be published individually and thus have not been provided as part of this paper.

5 Primary Research Products

Through this project we are developing information and tools that provide support to solid waste planners in evaluating the relative cost and environmental performance of integrated MSW management strategies. The project is providing this information and tools through three main research products: a decision support tool, database, and community case studies (see THORNELOE et al., 1998 for further information about these products). Each of these products is summarized in the following section.

5.1 Decision support tool (DST)

The DST provides a user-friendly interface that allows users to evaluate the cost and environmental burdens of existing solid waste management systems, entirely new systems, or some combination of both based on user-specified data on MSW generation, constraints, etc. The processes that can be modeled include waste generation, collection, transfer, separation (MRF and drop-off facilities), composting, combustion, RDF, and disposal in a landfill. Existing facilities and/or equipment can be incorporated as model constraints to ensure that previous capital expenditures are not negated by the model solution.

As illustrated in Fig. 2 (*see p. #*), the DST consists of several components including process models, waste flow equations, an optimization module, and a graphic user interface. The process models consist of a set of spreadsheets developed in Microsoft Excel. These spreadsheets use a combination of default and user supplied data to calculate the cost and environmental coefficients on a per unit mass (ton) basis for each of the MSW components being modeled (→ *Table 1, see Appendix*) for each MSW management unit process (collection, transfer, etc.). For example, in the electric energy process model, the user may specify the fuel mix used to generate electricity in the geographic region of interest, or select a default grid. Based on this information, and the emissions associated with generating electricity from each fuel type, the model calculates coefficients for emissions related to the use of 1 kWh of electricity. These emissions are then assigned to MSW components for each unit process that uses electricity and through which the mass flows. MRFs, for instance, use electricity for running conveyor belts. The emissions associated with electricity generation would be assigned to the mass of materials that flowed through that facility. The user will also have the ability to override the default data if more site-specific data are available.

Optimization modeling is relatively new in life cycle studies and in this case allows DST users to search for MSW management strategies that minimize an objective function. For example, the DST currently enables users to optimize on annual cost, electricity consumption, greenhouse gas equivalents, or emissions of carbon monoxide, carbon dioxide (fossil or biomass), nitrogen oxides, particulate matter, and sulfur dioxide. The optimization module is implemented using a commercial linear programming solver called CPLEX and is governed by mass flow equations that are based on the quantity and composition of waste entering each unit process, and that intricately link the different unit processes in the MSW management system. Constraints in the mass flow equations preclude impossible or nonsensical model solutions. For example, the mass flow constraints will exclude the possibility of removing aluminum from the waste stream via a mixed waste MRF and then sending the aluminum to a landfill. Users may also specify constraints. Examples of user-specified constraints are the use of existing equipment/facilities and a minimum recycling percentage requirement.

The graphic user interface consists of a Microsoft Visual Basic routine that integrates the different components of the tool together to allow easy user manipulation of the spreadsheet models and the optimization module. It allows additional user constraints to be specified and provides a graphical representation of the solid waste management alternatives resulting from the optimization. Currently, results are presented on a dollar cost per ton or pounds of emission per ton basis and can be viewed at the system level, process model level, or MSW component level.

5.2 Database

The database is being developed to provide cost and life-cycle inventory type information for all unit processes included in the system (see THORNELOE et al., 1998 for a summary of data being collected). The approach used to build this database is as follows. First, data from publicly available and private MSW and LCA studies, and other relevant sources, were collected and reviewed against the data quality goals and data quality indicators established for this project. The data quality assessment is based on EPA guidance from *Guidelines for Assessing the Quality of Life Cycle Inventory Data* (BAKST et al., 1995). These existing data are being compiled into a database management system using commonly available software (Microsoft Access™). The format of the database is made as consistent as possible with other LCA data efforts and format guides such as SPOLD and SPINE in Europe and LCAD in the U.S.

The database management system was established to enable users to view and manipulate information through predefined forms. In these forms, the main categories of data are predefined, and the user's options are limited to narrowing the focus of the predefined search criteria. For example, the predefined PROCESS-ENERGY form displays information about energy consumption in a waste management operation. Similarly, to see air emissions data for a waste management operation, the PROCESS-AIR RELEASES form would be used. Many such predefined forms will be made available for "common" searches. In addition, forms will be provided to allow for maintaining and updating information in the database.

The database will be used to support the DST, but it is not linked to the tool. Rather, the database will be made available as a stand-alone application that may be used as input data to other studies or models. If solid waste practitioners possess higher quality or more site-specific data than those provided in the database, users may add data to the database.

5.3 Community case studies

Preliminary case studies are currently taking place with Lucas County, Ohio, and the Great River Regional Waste Authority in Iowa. The purpose of these initial case studies is to test and obtain feedback for individual process models, including waste collection, transportation, transfer station, and MRF process models. In Ohio, preliminary scenarios focusing on meeting recycling targets of 20,000 and 40,000 tons per year in the commercial sector are being analyzed. Primary target materials for commercial recycling include cardboard, office paper, wood waste, and newspaper. Secondary targeted materials include containers, plastic, and textiles. In Iowa, we are still in the process of collecting baseline data and defining case study scenarios for analysis. The type of baseline information that is being collected includes waste characterization, facility designs, distances between facilities, residential and commercial sector characteristics, wage rates for workers in different facilities, and collection systems. It is anticipated that these initial case studies will be completed during 1999.

As a fully functional prototype of the DST is completed, "full-blown" case studies will be initiated with a variety of urban and rural communities to gain an appreciation for the variability among communities and to help us learn how to tailor the decision support tool to meet the needs of different users. Through these and additional case studies, the format for presenting results of the tool will be refined.

6 Summary

This is a large, complex project in which a number of different research activities are taking place concurrently to collect data, develop methodologies for cost and environmental analysis, construct a database and DST, and conduct case studies with communities to support the life cycle management of MSW. The products and results of this project will advance the planning of MSW management by making available information and tools to evaluate the relative cost and environmental burdens of integrated MSW management strategies.

Further information about this project and documentation for completed process models is available from Internet sites at U.S. EPA (http://www.epa.gov/docs/crb/apb/apb.htm) and the Research Triangle Institute (http://www.rti.org/units/ese/pp_proj.html).

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Appendix

Table 1: Components of MSW considered in this study[a]

Residential Waste	Multifamily Dwelling Waste	Commercial Waste
Yard Waste	**Yard Waste**	1. office paper
1. grass	1. grass	2. old corrugated containers
2. leaves	2. leaves	3. phone books
3. branches	3. branches	4. third class mail
4. food waste	4. food waste	5. aluminum cans
Ferrous Metal	**Ferrous Metal**	6. clear glass
5. cans	5. cans	7. brown glass
6. other ferrous metal	6. other ferrous metal	8. green glass
7. non-recyclables	7. non-recyclables	9. PET beverage bottles[c]
Aluminum	**Aluminum**	10. newspaper
8. cans	8. cans	11-12. other recyclables
9-10. other - aluminum	9-10. other - aluminum	13-15. other non-recyclables
11. non-recyclables	11. non-recyclables	
Glass	**Glass**	
12. clear	12. clear	
13. brown	13. brown	
14. green	14. green	
15. non-recyclable glass	15. non-recyclable	
Plastic	**Plastic**	
16. translucent-HDPE[b]	16. translucent-HDPE[b]	
17. pigmented-HDPE[b]	17. pigmented-HDPE[b]	
18. PET beverage bottles[c]	18. PET beverage bottles[c]	
19-24. other plastic	19-24. other plastic	
25. non-recyclable plastic	25. non-recyclable plastic	

Residential Waste	Multifamily Dwelling Waste	Commercial Waste
Paper	**Paper**	
26. newspaper	26. newspaper	
27. office paper	27. office paper	
28. corrugated containers	28. corrugated containers	
29. phone books	29. phone books	
30. books	30. books	
31. magazines	31. magazines	
32. third class mail	32. third class mail	
33-37. other paper	33-37. other paper	
38. non-recyclable paper	38. non-recyclable paper	
39. miscellaneous	39. miscellaneous	

[a] Numbers represent the number of individual MSW components that can be included in the decision support tool.
[b] HDPE = high density polyethylene
[c] PET = polyethylene terephthalate

Table 2: Process model assumptions and allocation procedures

	Key Assumptions/Design Properties	Allocation Procedures*
Waste Management Unit Processes		
Collection	Location specific information (e.g., population, generation rate, capture rate) is provided by the user of the tool.	Environmental is based on mass. Cost is based on volume and mass.
Transfer Station	User selects between several default design options based on how the MSW is collected.	Environmental is based on mass. Cost is based on volume and mass.
Materials Recovery Facility	Design of the MRF depends on the collection type (mixed waste, commingled recyclables, etc.) and the recyclables mix. Eight different default designs are available.	Environmental is based on mass. Cost is based on volume and mass and includes revenue from the sale of recycables.
Combustion	The default design is a new facility assumed to meet the most recent U.S. regulations governing combustion of MSW. Designs to model older facilities are also available.	Environmental is based on mass and stoichiometry. Cost is based on mass and includes revenue from sale of metal scrap and electricity (based on Btu value of the waste and the heat rate of the facility).
RDF	Pelletized and "fluff" RDF design options are available. The facilities, including the combustion of RDF, are assumed to meet the most recent U.S. regulations governing combustion of MSW.	Under Development
Composting	A low and high quality mixed MSW and yard waste compost facilities are included. All use the aerated windrow composting process as the default design.	Environmental is based on mass. Cost is based on volume and mass and includes revenue from the sale of recycables.
Landfill	The default design is a new facility that meets U.S. Subtitle D and Clean Air Act requirements. Enhanced bioreactor and ash designs are also available.	Under Development
Additional Unit Processes		
Electrical Energy	Regional electrical energy grids are used for waste management processes; national grid for upstream processes.	Environmental is based on the fuel source used by regional or national electricity grids. Regional grids are used for waste management operations; National for manufacturing operations. Cost is not considered.
Inter-Unit Transportation	Distances between different unit operations are key input variables.	Environmental is based on mass. Cost is based on volume and mass, and is considered only for transportation necessary for waste management.
Manufacturing	Virgin and recycled (closed loop) processes are included. Electricity savings resulting from reprocessing displace regional base-loaded generation (mainly coal).	Environmental is based on mass. Cost is not considered.

* Allocation of costs, resource and energy consumption, and environmental releases to individual MSW components.