System Description for a Life-Cycle Inventory of Municipal Solid Waste Management Alternatives

Morton A. Barlaz and Ranji Ranjithan
North Carolina State University
(7/22/95)

Executive Summary

The objective of this document is to define the boundaries of the solid waste management system to be included in the life-cycle assessment (LCA) of solid waste management alternatives. This system definition will serve as a guide for collection of the relevant data required for a life-cycle inventory. The boundaries are specified in terms of waste composition and generation rates, unit operations involved in solid waste management (collection, separation, composting, combustion, anaerobic digestion, refuse derived fuel and landfill), remanufacturing of products from recycled waste components, and the interrelationships between these unit operations. Figure 1 illustrates the functional elements which comprise the solid waste management system. The key unit operations in the system and the manner in which waste can flow between these processes are illustrated in Figure 2. The system boundary is specified with the objective of being as flexible as possible. However, given the large diversity of settings in which municipal solid waste (MSW) is generated in the U.S., development of a single system definition to address all situations would be unnecessarily complicated.

The components of MSW to be included in the life-cycle inventory (LCI) will be consistent with EPA's characterization of MSW. This definition includes waste 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. Ash generated from the combustion of MSW will be included in the system. The MSW to be included in this system is divided into three categories: residential waste, waste generated in multifamily dwellings and commercial waste. In analyzing a specific solid waste management system, it will be possible to consider different compositions for each type of waste. Lists of the components included within each category are presented in Table 1 of the main document. In addition to individual components, the system will allow for the recovery of combinations of components such as the recovery of mixed paper for use as either pulp or fuel.

The unit operations to be included in the system include collection and transfer, separation (in material recovery facilities and drop-off centers), treatment (composting, combustion, RDF, anaerobic digestion), and burial. Data on the cost, energy and resource consumption, and pollutant emissions corresponding to individual processes within each unit operation will be collected as part of this project.

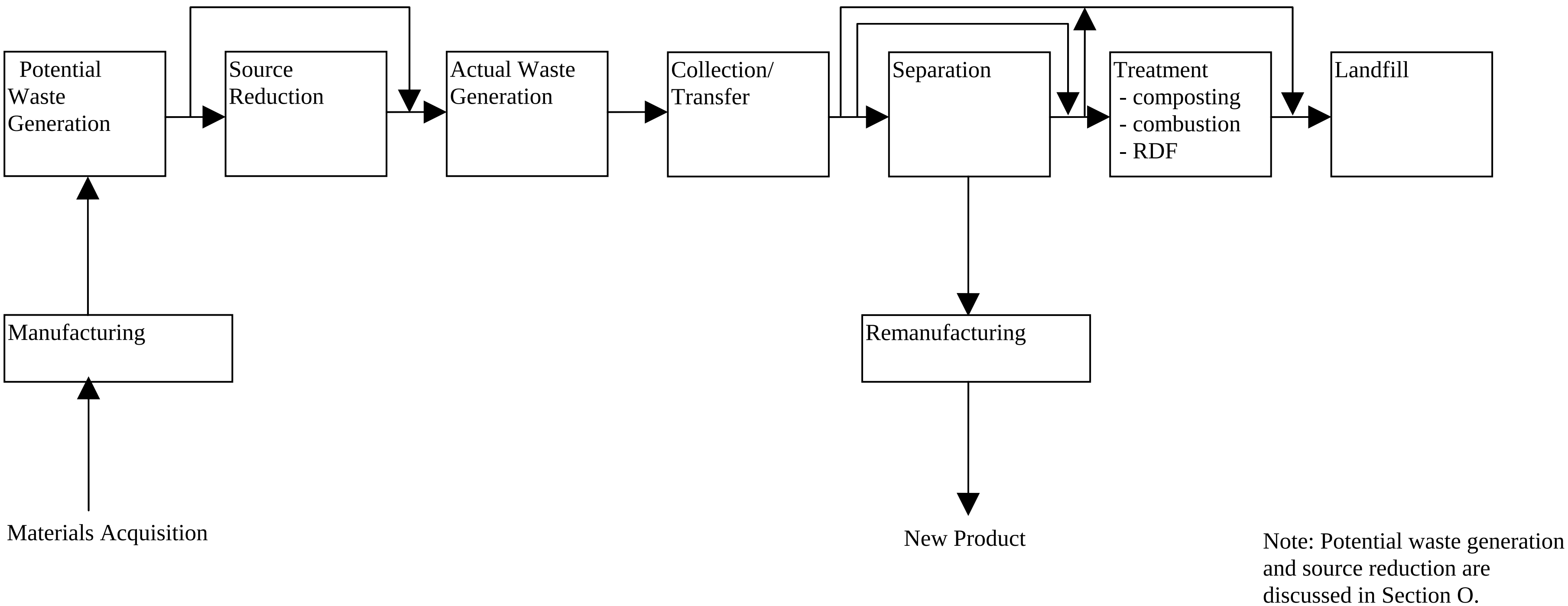
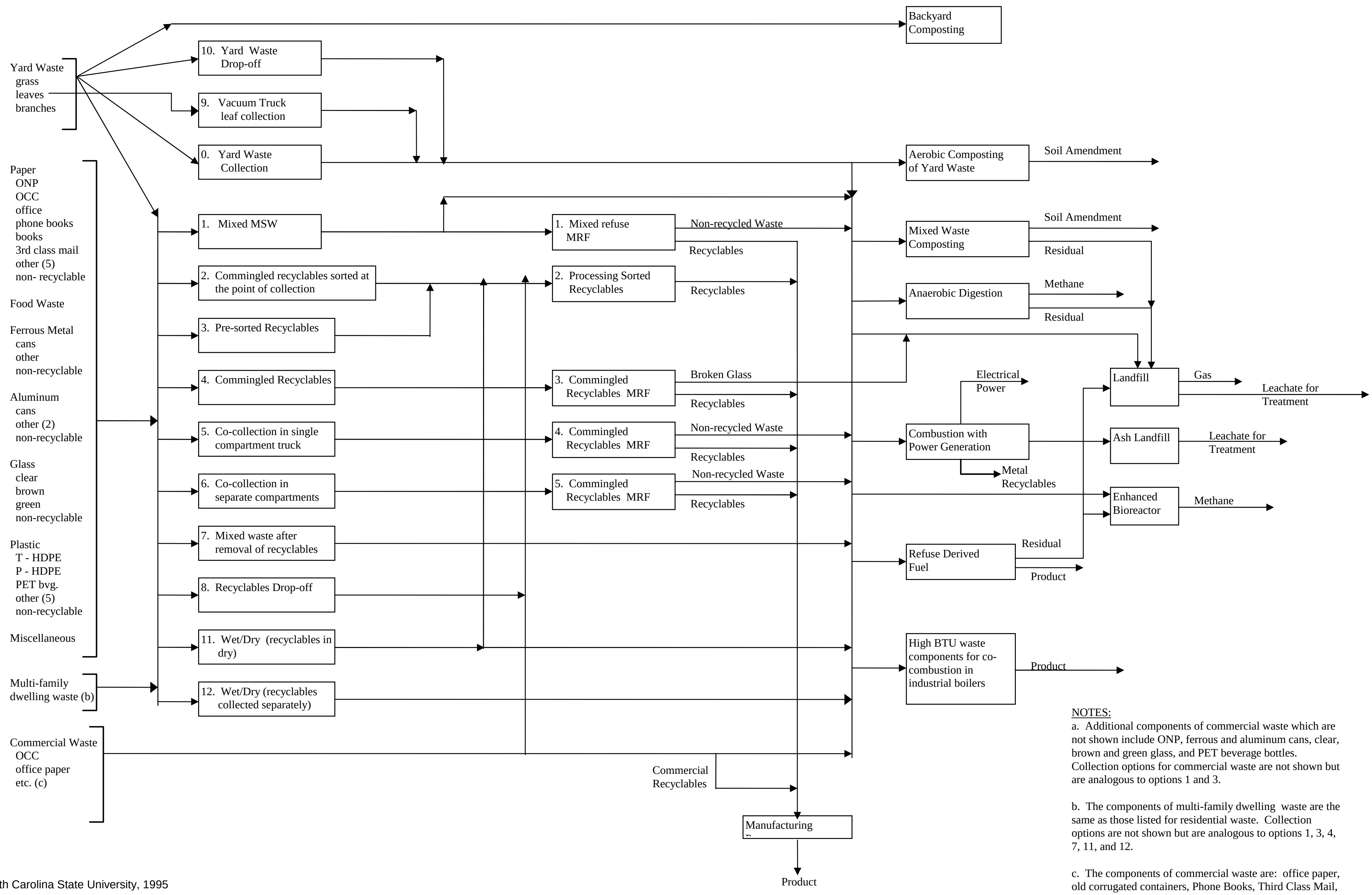


Figure -1 Functional Elements of the Life Cycle Analysis of Municipal Solid Waste Management Alternatives.



North Carolina State University, 1995

Figure 2 - Alternatives for Solid Waste Management

NOTES:

a. Additional components of commercial waste which are not shown include ONP, ferrous and aluminum cans, clear, brown and green glass, and PET beverage bottles. Collection options for commercial waste are not shown but are analogous to options 1 and 3.

b. The components of multi-family dwelling waste are the same as those listed for residential waste. Collection options are not shown but are analogous to options 1, 3, 4, 7, 11, and 12.

c. The components of commercial waste are: office paper, old corrugated containers, Phone Books, Third Class Mail, ferrous cans, aluminum cans, clear glass, brown glass, green glass, PET beverage bottles, newspaper, other recyclable (3), non-recyclables (3).

d. Transfer stations (truck and rail) are not shown due to space limitations. They are included in the system of alternatives.

Several refuse collection options are defined for each waste generation sector. In the residential sector, options include the collection of mixed refuse, the collection of recyclables as either commingled recyclables or recyclables sorted by the collection crew or the waste generator, co-collection of refuse and recyclables in the same vehicle and wet/dry collection with recyclables either included with the dry components or collected in a separate truck. Collection alternatives for refuse generated in multifamily dwellings include the collection of mixed refuse, the collection of either commingled or presorted recyclables and wet/dry collection with recyclables either included with the dry components or collected separately. Collection options for the commercial sector include collection of both mixed refuse and presorted recyclables. Drop-off of recyclables at centralized facilities and dedicated yard waste collection are also considered.

Transfer stations serve as a central facility at which the collected waste is consolidated before shipment to a separation, treatment or disposal facility. Several types of transfer stations will be included in the system in order to receive waste from any of the aforementioned refuse and recyclable collection alternatives. In addition, rail transport is included for mixed refuse generated in the residential, multi-family or commercial sectors.

In MSW management strategies where materials recycling is utilized, recyclables will require processing in a materials recovery facility (MRF). The design of a MRF is dependent upon the manner in which refuse is collected and subsequently delivered to the MRF. Thus, the collection and recycling of MSW are interrelated and this interrelationship is captured in the system. Eight different MRFs, each capable of recovering a set of recyclables from the applicable collection alternative, are considered in this system.

The recyclable material recovered from a MRF will ultimately be delivered to a remanufacturing process. The energy and resource consumption, and emissions corresponding to manufacturing a product from recyclable material (remanufacturing) will be considered in the system. In order to compare a remanufacturing process with manufacturing the same product from virgin material, the energy and resource consumption, and releases which apply to a virgin manufacturing process will also be considered.

Waste treatment options to be considered include combustion with energy recovery and conversion to electricity, composting of either mixed waste or yard waste, and anaerobic digestion. The combustion process will be assumed to have air pollution control devices which meet current regulations. In addition, two types of RDF will be considered. The first type of RDF facility will separate the refuse stream to recover a relatively high BTU fraction for use as a fuel. A second variation on the RDF theme will be referred to as co-combustion. Within this option, particular components of MSW are recovered for combustion in industrial boilers such as utility boilers and hog fuel boilers in the paper industry.

Three types of landfills will be considered in the system; one designed for the receipt of mixed refuse and operated to minimize water infiltration, a second designed for the receipt of combustion ash and a third designed for the receipt of mixed refuse and operated to enhance decomposition. All facilities will be designed in accordance with relevant federal regulations with respect to liner design, leachate and gas collection, etc. A user will be able to specify the liner design to be considered.

Finally, source reduction will be considered in the system. This represents a reduction in mass or toxicity of the waste stream. The effects of source reduction are unique to very specific components of the waste stream. A framework for analysis of source reduction is included in the system. However, data collection for source reduction options for industrial processes are beyond the scope of the project.

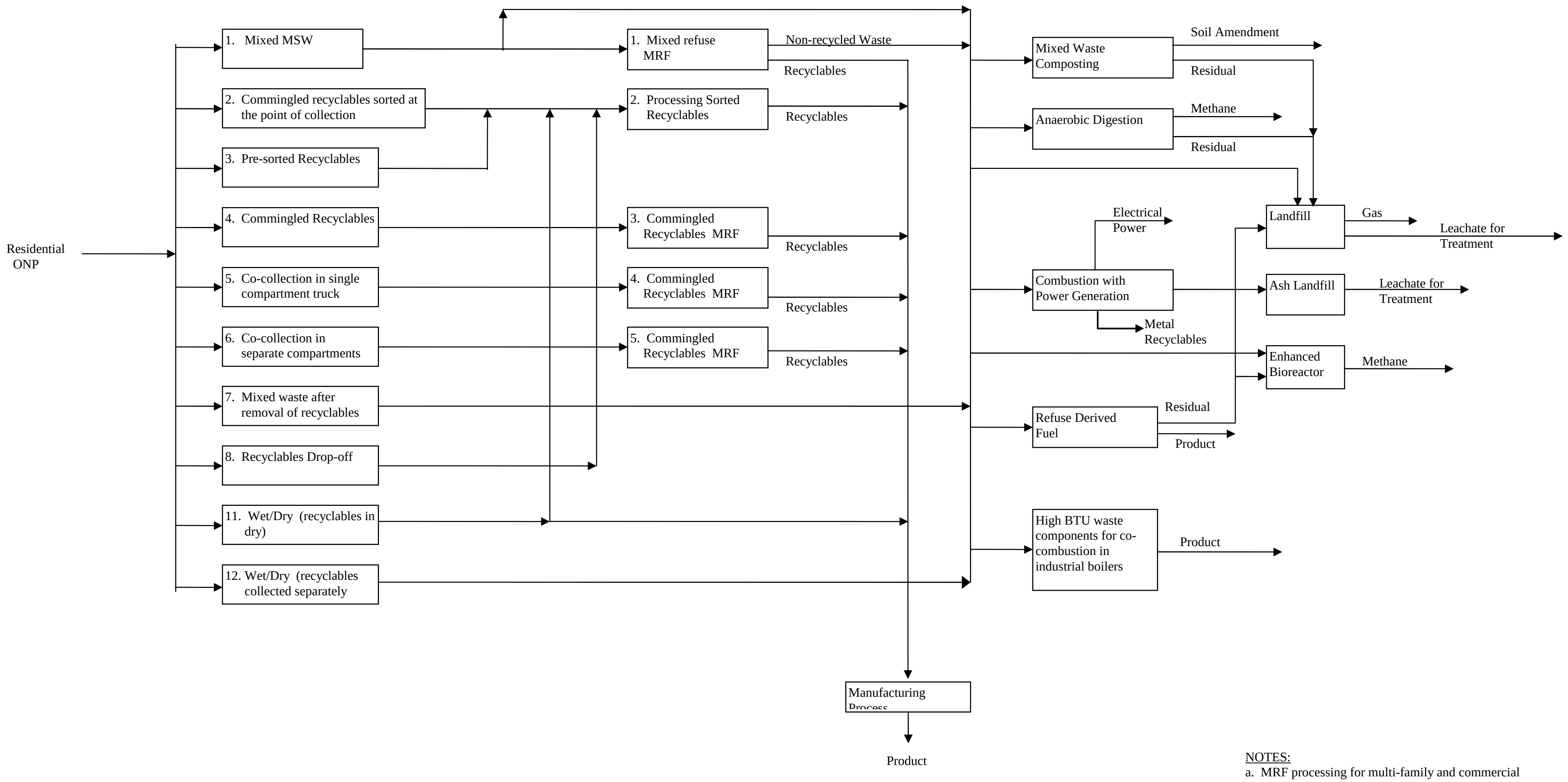
The ultimate product of this research will be a user friendly decision support tool designed to assist local solid waste management personnel to understand the economics, resource consumption and emissions associated with alternate solid waste management strategies. The decision support system will be supported by a database with data on life-cycle inventory parameters for individual SWM unit operations. Together, the decision support tool and database will allow the user to analyze their own solid waste management system and easily explore alternatives.

A. Introduction

The objective of this document is to describe the system and the system boundaries which will be used to conduct the life-cycle assessment (LCA) of municipal solid waste (MSW) management alternatives. This system description is a small but critical part of the overall project, the emphasis of which is the collection of data required for a life-cycle inventory of solid waste management (SWM) alternatives. The inventory analysis will be divided into a number of distinct SWM processes linked together as illustrated in Figure 1. These processes include waste generation, source reduction, collection and transfer, separation (MRFs and drop-off facilities), treatment (which may include composting, anaerobic digestion, combustion or RDF production) and disposal in a landfill or enhanced bioreactor. Remanufacturing is considered to the extent that a specific component of the waste stream is recycled. In this case, the inventory analysis will include both resource consumption and the emissions involved in the remanufacturing process, as well as the resource and emissions offset by virtue of using recycled versus virgin materials. While Figure 1 illustrates the functional elements which comprise the MSW system, the key unit operations in the system and the manner in which waste can flow between these unit operations are illustrated in Figure 2. As presented in Figure 2, there are many interrelationships between the separate unit operations. For example, decisions made with respect to waste separation influence downstream processes such as combustion. An example of waste management alternatives for one waste component is presented in Figure 2a. This figure illustrates the possible paths for old newsprint (ONP) through the system.

In defining the SWM system, our objective is to be as flexible as possible. However, given the large diversity of settings in which MSW is generated in the U.S., development of a single system definition to address all situations will be unnecessarily complicated. Thus, there are likely to be situations where this system definition cannot be applied.

The ultimate product of this research is an easy to use decision makers tool. This tool is a decision support system that will allow a user to perform a life-cycle inventory (LCI) based on locality specific data on MSW generation and management. The decision support system will be supported by a database with data on LCI parameters for individual SWM unit operations. Work will proceed concurrently to collect the data required for analysis of site specific SWM scenarios and to develop the decision support system. A brief description of the overall decision support system is presented in the following section in order to facilitate review and evaluation of the system. Following this description, this document is structured to follow the order of the functional elements as presented in Figure 1, with the exception of source reduction which is presented after landfills. The discussion of system boundaries is presented in the final section by which time the reader will have a more complete understanding of the proposed system.



NOTES:
a. MRF processing for multi-family and commercial ONP are not shown due to space limitations. They are included in the system of alternatives.

c. Transfer stations (truck and rail) are not shown due to space limitations. They are included in the system of alternatives.

Figure 2a - Waste Flow Alternatives for Residential Newsprint

North Carolina State University, 1995

B. Framework for Decision Maker's Tool

The overall decision support system includes several components as illustrated in Figure 3. The decision support system is the primary mechanism through which the data gathered are to be integrated into the analysis of alternate SWM strategies. The underlying component of the overall system is the waste flow equations. These equations are a mathematical representation of the manner in which each waste component can and cannot flow through the system. For example, these equations will exclude the composting of waste components other than grass, leaves and branches in the yard waste composting unit operation. The potential flow paths for ONP are illustrated in Figure 2a. The waste flow equations represent all possible waste stream components which may be handled in all possible processes.

The next component of the decision support system is the one that will be used to estimate the cost and life-cycle factors corresponding to each SWM unit operation. We will refer to this component as a process model. A process model will be developed for each functional element presented in Figure 1, including waste generation, composition and characteristics, source reduction, collection, transfer station, separation (MRF), composting, anaerobic digestion, combustion, refuse derived fuel (RDF) and landfill or enhanced bioreactor. The objective of each process model will be to utilize user input and default design information for the calculation of coefficients which describe the relationship between waste quantity and composition and a specific life-cycle parameter as well as cost. For example, in the collection process model, the user will be asked to specify the collection frequency desired for a community and the distance from a collection route to a downstream facility (MRF, composting, incinerator, RDF plant, landfill, etc.). Based on such design information, the process model will calculate coefficients for cost and life-cycle parameters. This would include the cost for refuse collection in $/ton. In the cases of diesel fuel and particulate emissions, the process model would calculate diesel consumption per ton of refuse collected and the pounds of particulate matter released from a collection alternative per ton of refuse collected. The process model will then assign costs, energy consumption and emissions to the individual components of the waste stream which are identified in Section D. Where the user already has these data, they will have the opportunity to input them directly and bypass the design component of a process model. Assignment of emissions to individual waste components is discussed further in section B.1. A majority of the resources associated with this research project are oriented towards the collection and manipulation of the data required for the process models.

The next major component of the decision support system is the optimization module. The user may choose to evaluate all feasible SWM strategies using the optimization module, or simply use the decision support system as an accounting tool to represent their existing SWM system. In order to identify an optimal SWM strategy with respect to a specific objective, it is necessary to (1) identify the objective and (2) systematically search all feasible SWM alternatives represented by the waste flow equations. The objective, which may be identified by the user, could be to minimize total cost, particulate matter emissions, or any other LCI parameter. The optimization module is then used to systematically search all potential waste management scenarios for the "best" SWM strategy with respect to the objective.

Site-specific information input by the user will be incorporated into the optimization module during the search for optimal SWM strategies. Thus, any strategy identified by the optimization module will meet site-specific constraints imposed by the user. For example, the optimization module can be constrained by the user to search for SWM strategies which recycle a minimum of a specified fraction of the waste stream or utilize an existing process.

The decision support system may also be used as an accounting tool. In this case the user would specify the SWM strategy under consideration and the decision support system would compute the cost and life-cycle inventory.

The final component of the decision support system is the user interface. This interface will provide the user with a friendly platform through which to interact with the different components of the decision support system. It will allow the user to view and edit process model data, provide site-specific information and constraints, and run the optimization module. The interface will also provide a graphical display of the SWM system under consideration and allow the user to conduct "what-if" type analyses for user input SWM scenarios.

B.1 Assignment of Cost and Emission Factors to Individual Waste Components

A life-cycle inventory of MSW management alternatives requires that emissions and resource utilization be assigned for each MSW component in each unit operation. There are situations in the LCI where this will be problematic. Examples include emissions associated with the combustion of individual waste components and the contribution of individual components to leachate composition and gaseous emissions from landfills. While we are aware of this issue, the manner in which it will be addressed will be developed throughout years 1 and 2 as data are collected and analyzed. The overall approach to addressing this issue is as follows. First, there has been some recent research on the contributions of individual components to overall emissions during combustion. Where such data are available they will be used. Second, such data may be a high priority for measurement in year 2. Third, sensitivity analyses will be performed to evaluate where the results of the LCI are sensitive to the manner in which overall emissions are assigned to individual components. Where it is apparent that the appropriate data are not available and cannot be measured within the resource constraints of this project, simplifying assumptions will be made and identified in the project documentation.

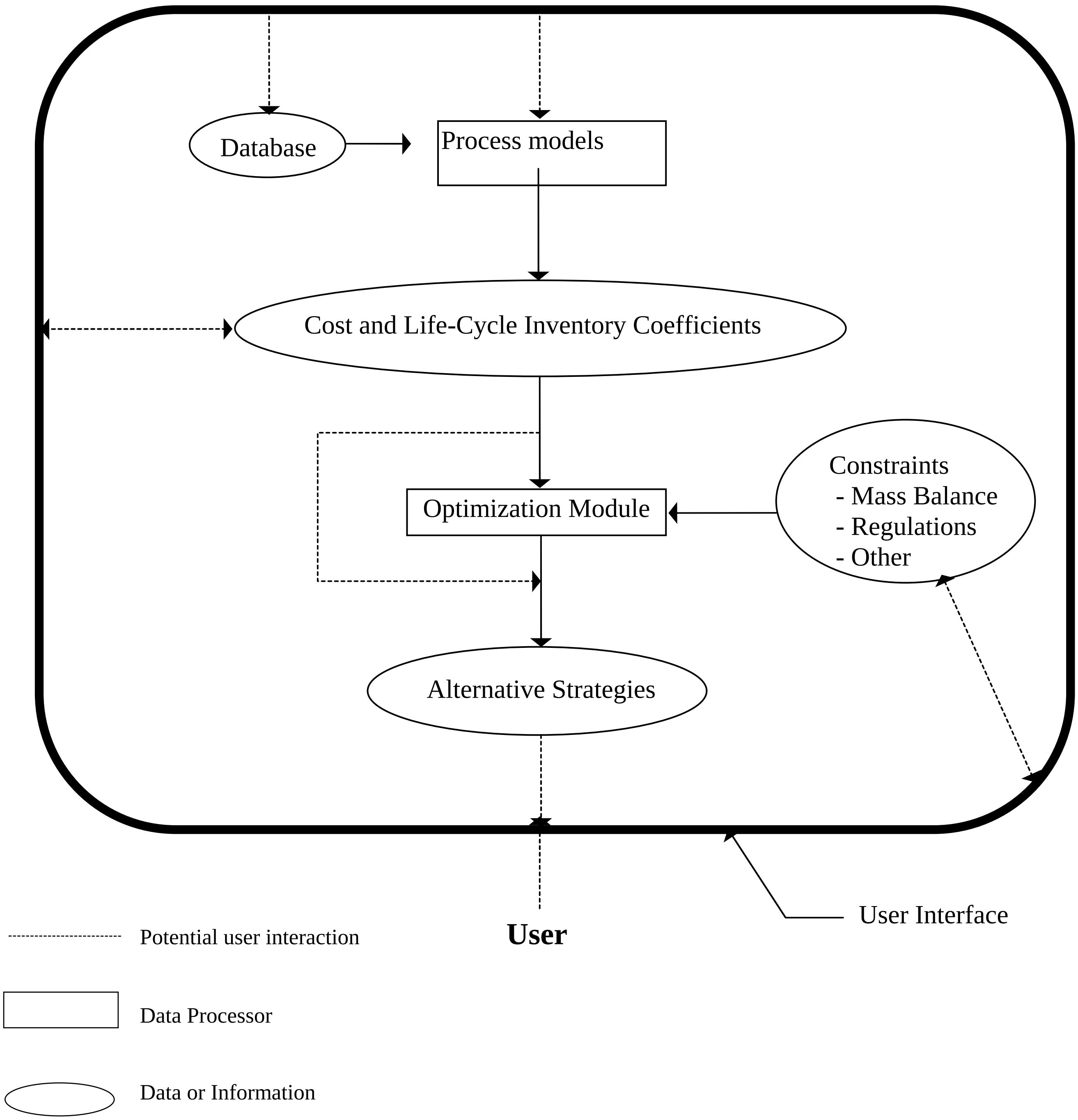


Figure 3 - Relationship between Data and Components of the Decision Support System and the User.

In the case of landfills, one potential solution for assignment of leachate COD to individual components would be to let the assignment reflect the relative biodegradability of a component. Recent research has documented the rapid anaerobic biodegradability of food and grass relative to paper. Thus, the COD contribution of the rapidly degradable components will be greater. In addition, no COD should be assigned to non-biodegradable components except plastics, which may release plasticizers.

C. Waste Generation

Our objective is to perform an LCI on management strategies applicable to wastes defined as MSW by EPA (USEPA 1994). This definition includes waste 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. Ash generated from the combustion of MSW will be included in the system.

The MSW stream has been divided into three waste categories; residential, multifamily dwelling and commercial. The logic for this separation is that different collection and recycling alternatives apply to each category. The user will be asked to specify the fraction of the population from which waste is collected using collection alternatives appropriate for residential and multifamily dwelling waste as described in Section F. The third category of waste defined here is commercial waste which includes MSW generated in offices, institutions, industries, etc. Arrangements for the collection of this waste are typically handled by the waste generator and are unlikely to overlap with the collection of residential and multifamily dwelling waste. However, these wastes typically enter the same system that handles residential and multifamily dwelling waste at some point in their management.

The composition of waste from the residential, multifamily and commercial sectors will likely differ. In developing the LCI, the user will have the opportunity to input the waste generation rate and composition for each of the waste generation sectors. Default data will be provided for each category. We recognize that such data may be difficult for the user to obtain for commercial waste. However, the composition and generation rate for commercial waste is extremely site specific and default data are not likely to be reliable. Ideally, commercial waste generation factors could be provided by SIC code. Development of such factors is beyond the scope of this project. Should such factors be developed by others, the commercial waste component of the process model could be modified to incorporate SIC codes.

D. Waste Composition

Municipal solid waste has been divided into individual components as listed in Table 1. The rationale for the selected components is described here. The residential and multifamily dwelling waste streams have been divided into 39 components. The components were selected to include those items which are most commonly recycled such as old newsprint (ONP) and HDPE milk and water containers.

In addition, the categories have been selected to allow for flexibility by the addition of "other" categories. For example, five extra categories are allowed for "other paper." If the user wishes to consider the recycling of a paper component(s) not listed in Table 1, then the composition of that waste component can be entered as a non-zero value in a "paper-other" category. Similarly, if the user does not wish to consider recycling of a component, such as office paper from residential waste, then the user simply enters its composition as 0%. Five "other" categories have been added for plastics, two for aluminum and a single "other" category was added for ferrous metal in the residential and multifamily dwelling waste streams.

The waste components listed in Table 1 are the same for residential and multifamily dwelling waste. However, the user may enter different compositions for each waste component if desired. The commercial waste stream has been divided into 18 components. These components include the major recyclables in commercial waste based on national averages (office paper and old corrugated containers (OCC)), materials which are commonly recycled (ferrous cans, aluminum cans, PET beverage bottles, container glass and newsprint), three "other" categories for recyclables and three “other” categories for non-recyclables.

While wastes are listed as individual components in Table 1, there are cases where wastes can be grouped together. The waste flow equations will be written to allow consideration of mixed color glass recycling in addition to recycling by individual color. Of course, recycling of mixed color glass would be dependent on the availability of a market. This is specified by the user who can input the revenue associated with mixed color glass in the MRF process model. The user will also have the opportunity to remove from consideration mixed color glass recycling. Similarly, the user will have the opportunity to allow consideration of mixed paper or mixed plastic recycling. In the case of mixed paper and mixed plastic, the user will be required to specify whether the recyclables are used in remanufacturing or as a fuel.

The waste generation process model will request the generation and composition data described in this and the previous section. This process model will also contain default data on physical and chemical characteristics of each waste component such as density, BTU value and moisture content. These data will be used to calculate characteristics of the waste stream, such as moisture content and BTU value, as a function of waste composition.

E. In-Home Recyclables Separation

The manner in which residential and multifamily dwelling waste are collected will influence resource consumption (e. g. water, electricity) in the home (or apartment). Several of the collection alternatives described in the following section include source separation of recyclables. Where a collection alternative involves the separate set out of recyclables, they

Table 1 - Components of MSW to be Considered in the LCA[a]

Residential Waste

Yard Waste

1. grass[b]
2. leaves[b]
3. branches[b]
4. Food Waste

Ferrous Metal

5. cans
6. other ferrous metal
7. non-recyclables

Aluminum

8. cans

9/10. other - aluminum

11. non-recyclables

Glass

12. clear
13. brown
14. green
15. non-recyclable

Plastic

16. translucent-HDPE (milk/water containers)
17. pigmented-HDPE bottles
18. PET beverage bottles

19-24. other plastic

25. non-recyclable plastic

Paper

26. newspaper
27. office paper
28. old corrugated containers
29. Phone Books
30. Books
31. Old Magazines
32. Third Class Mail

33-37. other - paper

38. paper - non-recyclable

39. Miscellaneous

Multifamily Dwelling Waste

Yard Waste

1. grass[b]
2. leaves[b]
3. branches[b]
4. Food Waste

Ferrous Metal

5. cans
6. other ferrous metal
7. non-recyclables

Aluminum

8. cans

9/10. other - aluminum

11. non-recyclables

Glass

12. clear
13. brown
14. green
15. non-recyclable

Plastic

16. translucent-HDPE (milk/water containers)
17. pigmented-HDPE bottles
18. PET beverage bottles

19-24. other plastic

25. non-recyclable plastic

Paper

26. newspaper
27. office paper
28. old corrugated containers
29. Phone Books
30. Books
31. Old Magazines
32. Third Class Mail

33-37. other - paper

38. paper - non-recyclable

39. Miscellaneous

Commercial Waste

1. office paper
2. old corrugated containers
3. Phone Books
4. Third Class Mail

5. ferrous cans
6. aluminum cans
7. clear glass
8. brown glass
9. green glass
10. PET beverage bottles
11. newspaper

12-14 other recyclable

15-17 non-recyclables

Notes

a. Items without numbers represent broad waste categories. Items with numbers represent the proposed breakdown of MSW.

b. Yearly average compositions are required.

may be rinsed for in-home storage prior to set out at curbside. Specifically, if recyclables are collected in options 2 through 6 described in the following section, then ferrous cans, aluminum cans, glass bottles, t-HDPE and PET beverage bottles may be rinsed

F. Waste Collection

There are a number of options for the collection of refuse generated in the residential, multifamily dwelling and commercial sectors. The manner in which refuse is collected will affect the cost, resource utilization, emissions and design of both the collection operation and potential down stream processing facilities such as a MRF. The collection options which we propose to consider are presented in this section. The numbers given for each option are used throughout this document and appear in Figure 2. Alternatives for the collection of multifamily dwelling and commercial refuse are not individually presented in Figure 2 due to space limitations. The role of transfer stations is described in the following section.

Collection of Residential Refuse

Mixed Refuse Collection

1. Collection of mixed refuse in a single compartment truck with no separation of recyclables.

Recyclables Collection

2. Set out of commingled recyclables which are sorted by the collection vehicle crew at the point of collection into a multi-compartment vehicle.

3. Collection of recyclables presorted by the generator into a multi-compartment vehicle.

4. Collection of commingled recyclables in a vehicle with two compartments; one for all paper components, and the other for non-paper recyclables.

Co-Collection

5. Collection of mixed refuse and recyclables in different colored bags for transport in a single compartment of a vehicle. Bags would then be sorted at a MRF. All paper recyclables are collected in one bag, and non-paper recyclables are collected in a separate bag.

6. Collection of mixed refuse and recyclables in different colored bags in separate compartments of the same vehicle. The refuse and recyclables would then be

delivered to a MRF and the mixed refuse would be delivered to a combustion facility, composting facility, RDF plant or landfill. Commingled recyclables and mixed waste are collected in a three compartment truck – one compartment for mixed waste, one for paper recyclables, and the third compartment for non-paper recyclables.

Residuals Collection

7. If recyclables are collected in options 2, 3 or 4, then residual MSW is collected in a single compartment vehicle as in option 1.

Recyclables Drop-off

8. This alternative allows for the waste generator to bring recyclables to a centralized drop-off facility. This could also be a buy-back center.

Yard Waste Collection

0. Collection of yard waste in a single compartment vehicle. The user will be asked to specify whether waste is collected in bulk, in plastic bags which must be emptied prior to composting, or in biodegradable paper bags which need not be emptied. Of course, yard waste may also be collected as mixed refuse in options 1 or 7 unless a yard waste ban is specified by the user.

9. Dedicated collection of leaves in a vacuum truck.

10. This alternative allows for the waste generator to bring yard waste to a centralized composting facility.

Wet/Dry Collection

11. Wet/Dry collection with recyclables included with the dry portion. The user will be asked to specify whether various paper types are to be included in the wet or dry collection compartments.

12. Wet/Dry collection with recyclables collected in a separate vehicle. The user will be asked to specify whether various paper types are to be included in the wet or dry collection compartments.

Collection of Refuse and Recyclables from Multifamily Dwellings

Mixed Refuse Collection

13. Collection of mixed refuse from multifamily dwellings in a single compartment truck. The user will be required to specify the use of hauled or stationary containers.

Recyclables Collection

14. Collection of pre-sorted recyclables into multiple stationary or hauled containers.

15. Collection of commingled recyclables in a two compartment vehicle: one for non-paper recyclables, and one for paper recyclables.

Residuals Collection

16. If recyclables are collected in options 14 or 15, then residual MSW is collected in a single compartment vehicle as in option 13.

Wet/Dry Collection

17. Wet/Dry collection with recyclables included with the dry portion. The user will be asked to specify whether various paper types are to be included in the wet or dry collection compartments.

18. Wet/Dry collection with recyclables collected in a separate vehicle. The user will be asked to specify whether various paper types are to be included in the wet or dry collection compartments.

Collection of Commercial Waste

Recyclables Collection

19. Collection of presorted recyclables.

Mixed Refuse Collection

20. Collection of mixed refuse before or after recycling.

Multifamily dwelling waste may or may not be collected by the city in a manner similar to residential refuse collection. Whether this waste is collected by the city or a private contractor should not affect the LCI. Prior to execution of the decision support system, the user will be asked whether multifamily dwelling waste is collected by the city. If yes, then this waste will be analyzed as part of the collection process model. If no, then this waste will be collected by a private contractor and the user will be asked to specify which, if any, components of MSW are recycled. Whether multifamily dwelling waste is collected by the city or the private sector, its life-cycle implications and costs will be included in the system.

G. Transfer Stations

Once refuse has been collected, there are a number of facilities to which it may be transported including a transfer station, MRF, combustion facility, RDF plant, composting facility, anaerobic digestion facility, landfill or enhanced bioreactor. Prior to describing the manner in which each of these processes is handled, the potential role of transfer stations is described.

The potential role of transfer stations is illustrated in Figures 4a to 4g. In Figure 4a, it is assumed that refuse is collected as mixed refuse (collection option 1). The waste may be transported to a transfer station, mixed refuse MRF, combustion facility, RDF plant, composting facility, anaerobic digestion facility, landfill or enhanced bioreactor. If the waste is brought to a transfer station, then the waste could subsequently be brought to any of these facilities. Waste flow down stream of a MRF, combustion facility, RDF plant, anaerobic digestion facility or composting facility plant is not illustrated in Figures 4a through 4g for simplicity.   These flows are part of the system and are illustrated in Figure 2. A transfer station handling mixed refuse will be referred to as Transfer Station 1. Different transfer station designs will be required dependent upon the type of waste processed.

Figure 4b illustrates the collection of commingled recyclables. These recyclables may be transported to either a transfer station (Transfer Station 2) or directly to a MRF designed to process commingled recyclables (MRF 3).

Figure 4c illustrates the role of a transfer station where refuse and recyclables are co-collected in a single compartment vehicle (collection option 5). In this case, refuse and recyclables could be delivered to either a MRF or to a transfer station. If the refuse and recyclables are delivered to a MRF, then the MRF also functions as a transfer station because the refuse must be removed from the facility to either a combustion facility, RDF plant, composting facility, anaerobic digestion facility, landfill, or enhanced bioreactor. Alternately, the refuse could be delivered to a transfer station (transfer station 3) for separation of the refuse and commingled recyclables.

Figure 4d illustrates the role of a transfer station in which refuse and recyclables are co-collected in a three compartment vehicle (collection option 6). Commingled recyclables and refuse may be transported to a transfer station (transfer station 4) where the recyclables and refuse are separated and transported to regional waste management facilities. In this case, the refuse would then be transported to a combustion facility, composting facility, anaerobic digestion facility, RDF plant, landfill or enhanced bioreactor and the recyclables would be transported to a MRF designed to process commingled recyclables (MRF-3). Alternately, the commingled recyclables and refuse may be transported to MRF-5 where the recyclables are processed and the refuse is transported to a combustion facility, RDF plant, composting facility, anaerobic digestion facility, landfill or enhanced bioreactor.

Figure 4e illustrates collection of presorted recyclables in collection options 2, 3 and 8. In these cases, recyclables could be transported either directly to a MRF designed to process presorted recyclables or to a transfer station (transfer station 5) followed by a MRF.

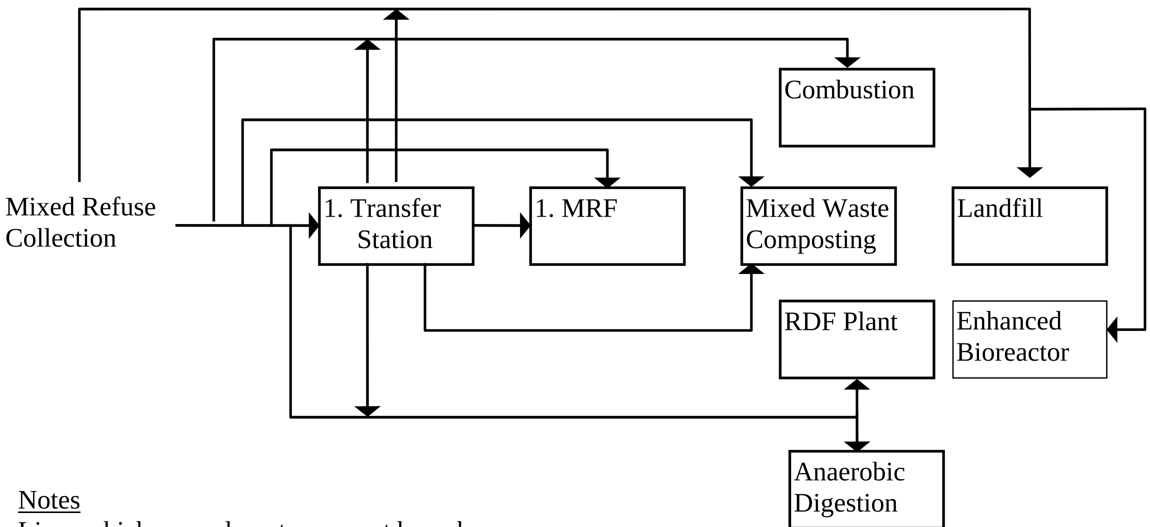
The alternate roles of transfer stations in the collection of residual MSW assuming separate collection of recyclables (collection option 7) are illustrated in Figure 4f. In this collection option, recycling has already occurred. Thus, the MSW is transported to a combustion facility, RDF plant, composting facility, anaerobic digestion facility, landfill or enhanced bioreactor either through or around a transfer station.

The transport of recyclables to and from drop-off facilities is illustrated in Figure 4g. Here, recyclables may be transported to a MRF designed to process presorted recyclables (MRF-2), either through or around a transfer station.

The final collection options involve yard waste including (a) the collection of yard waste in dedicated vehicles (option 0), (b) dedicated leaf collection in vacuum trucks (option 9) and yard waste drop-off (option 10). Transfer stations are not involved in these collection options.

Finally, the system will include transport in rail cars. Mixed refuse and wet/dry collection options (options 1, 7, 11-13, 16-18 and 20) include transport to a facility designed to place the refuse in rail cars. This is illustrated in Figure 4h. Refuse transported in rail cars is directed to one of two receiving rail transfer stations. These receiving rail transfer stations are assumed to be adjacent to either a dry or enhanced bioreactor landfill.

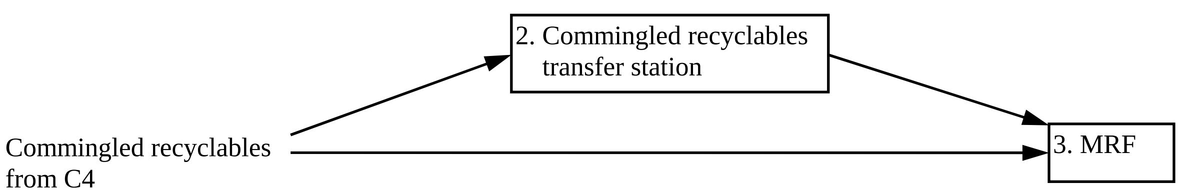
Figure 4a - Alternate Roles of a Transfer Station in Mixed Refuse Collection (Collection Option 1)



<u>Notes</u>
Lines which cross <u>do not</u> represent branches

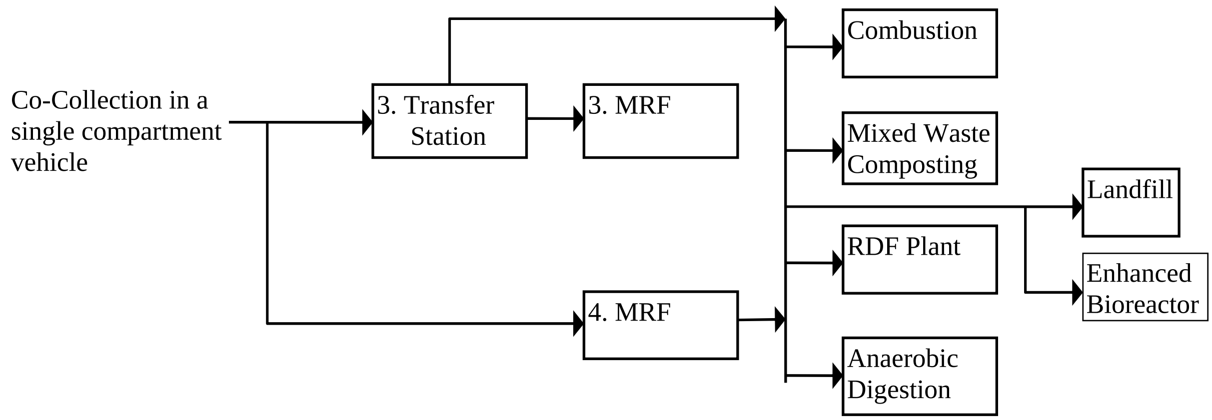
Waste transport downstream of MRF's, combustion facilities, composting and RDF plants is not shown for simplicity. These flows are considered in the system.

Figure 4b - Collection of Commingled Recyclables (Collection Option 4)



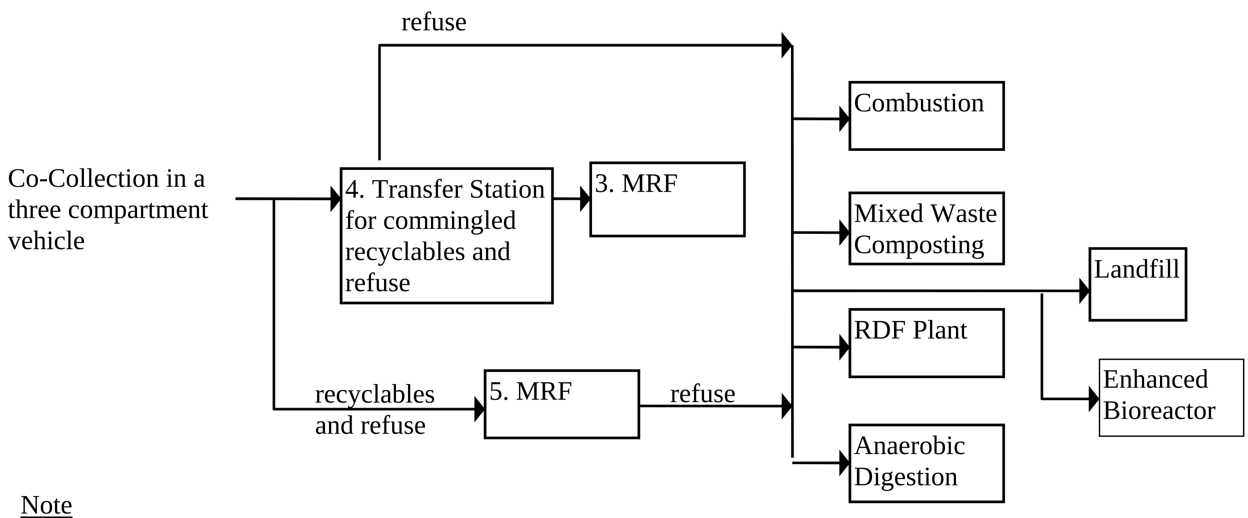
<u>Note</u>
Recyclables transport downstream of a MRF is not illustrated for simplicity. Transport of recyclables to a manufacturing facility is part of the system.

Figure 4c - Co-Collection in a Single Compartment Vehicle (Collection Option 5)



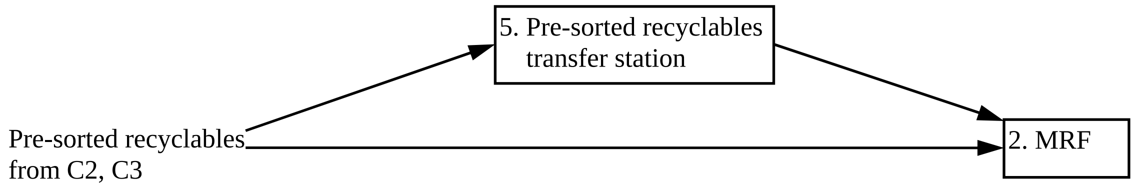
<u>Note</u>
Waste transport downstream of MRF's, combustion facilities, composting and RDF plants is not shown for simplicity. These flows are considered in the system.

Figure 4d - Co-Collection in a Three Compartment Vehicle (Collection Option 6)



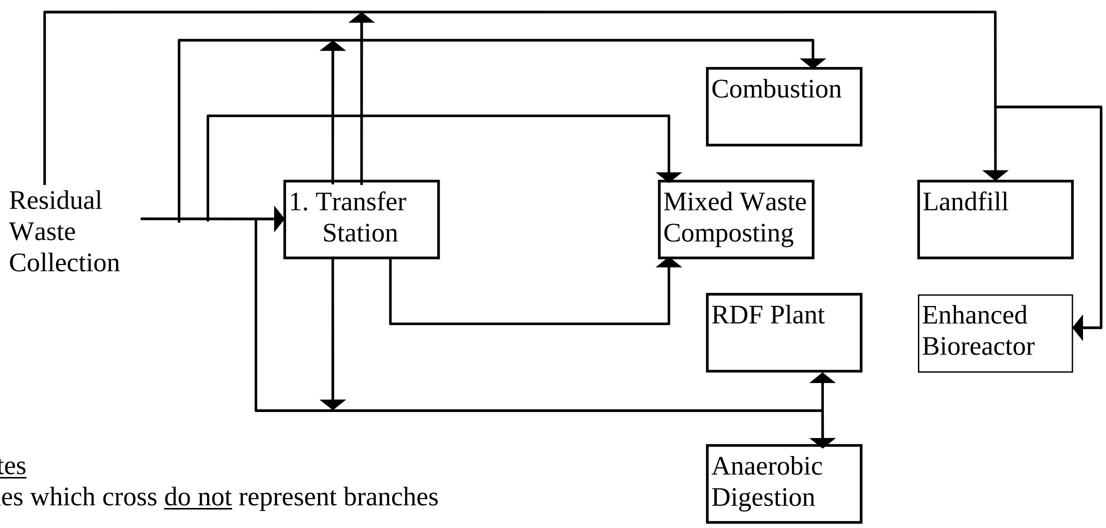
<u>Note</u>
Recyclables transport downstream of a MRF is not illustrated for simplicity. Transport of recyclables to a manufacturing facility is part of the system.

Figure 4e - Collection of Pre-sorted recyclables (Collection Options 2 and 3)



Note
Recyclables transport downstream of a MRF is not illustrated for simplicity. Transport of recyclables to a manufacturing facility is part of the system.

Figure 4f - Collection of Residential mixed waste (Collection Option 7)



Notes
Lines which cross <u>do not</u> represent branches

Waste transport downstream of MRF's, combustion facilities, composting and RDF plants is not shown for simplicity. These flows are considered in the system.

Figure 4g - Transport of Recyclables from a Drop-off Station (Collection Option 8)

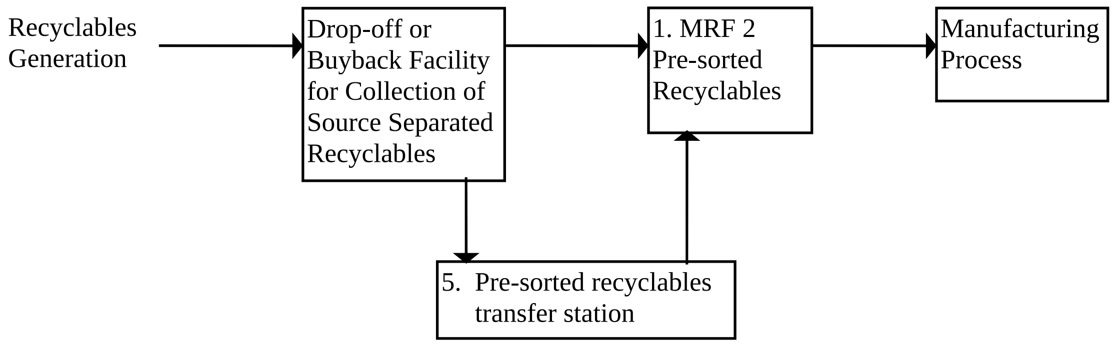
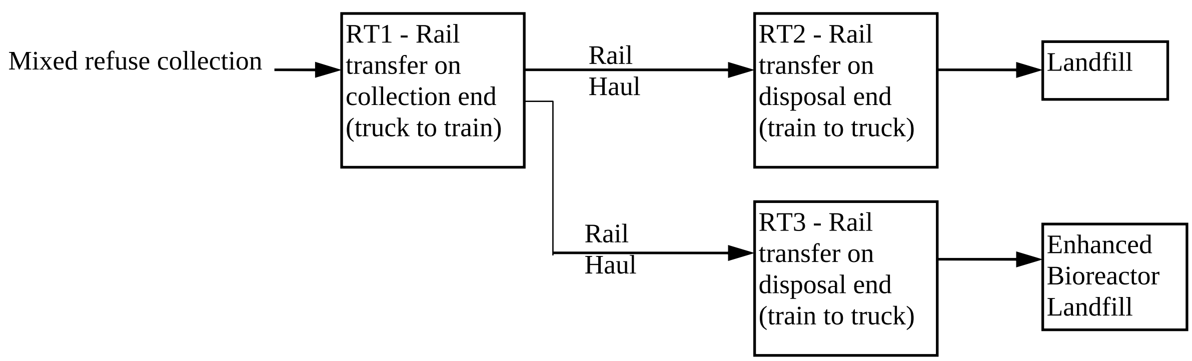


Figure 4h - Role of Rail Transfer Stations (Collection Options 1, 7, 11-13, 16-18 and 20)



H. Material Recovery Facilities (MRFs)

In MSW management strategies where materials recycling is utilized, recyclables will require processing in a MRF. The design of a MRF is dependent upon the manner in which refuse is collected and subsequently delivered to the MRF. Thus, the collection and recycling of MSW are interrelated. These interrelationships are captured in the system.

The unique design features of each MRF will have an impact on their cost as well as parameters included in the LCI. Eight distinct MRFs are considered in the system as described below. The components of MSW which can be recovered in each of the different MRFs are listed in Table 2. Table 2 also lists the components which can be accepted at a drop-off facility (collection option 8).

1. MRF 1 receives mixed refuse as collected in collection option 1 or 13.

2. MRF 2 receives presorted recyclables. Such recyclables could be generated in collection option 2, 3, 8, 14, or 19.

3. MRF 3 receives commingled recyclables as generated in collection option 4, 5, 6, 11, 15 or 17.

4. MRF 4 receives mixed refuse, commingled non-paper recyclables, and paper recyclables as delivered in a vehicle with one compartment (collection option 5). We will refer to black bags as the color bag containing refuse and blue bags as the color bag containing commingled recyclables.

5. MRF 5 receives non-paper recyclables and paper recyclables in separate blue bags (collection option 6). The commingled recyclables are handled as in MRF 3. MRF 5 also serves as a transfer station for the mixed refuse present in a separate compartment of the vehicle.

6. A front end MRF to a mixed waste composting facility. This MRF is at the front-end of a mixed waste composting facility, i.e., the material recovery operations precede composting operations. The MRF is similar to a mixed waste MRF, but includes provisions for additional sorting to remove contaminants from mixed waste that affect the composting product.

7. A front end MRF to an anaerobic digestion facility: This MRF is at the front end of an anaerobic digestion facility, i.e., material recovery operations precede anaerobic digestion operations. The MRF is similar to a mixed waste MRF, but includes additional sorting to remove contaminants that could adversely affect the anaerobic digestion process, or the quality of the digested solids.

8. A front-end MRF to a refuse derived fuel (RDF) facility. This MRF is at the front end of an RDF facility, i.e., material recovery operations precede RDF operations. The MRF is similar to a mixed waste MRF, but does not include a magnet and eddy current separator for recovery of ferrous cans and aluminum. These waste components are recovered in the RDF facility.

Table 2 - List of Materials Which Can be Recycled at Each MRF Type

Recyclable Component	MRF 1 Mixed Refuse	MRF 2 Presorted Recyclables	MRF 3 Commingled Recyclables	MRF 4 Co-collection Single Comp.	MRF 5 Co-collection Double Comp.	Drop-off or Buyback Center
Fe-cans	x	x	x	x	x	x
Al-cans	x	x	x	x	x	x
clear glass	x	x	x	x	x	x
brown glass	x	x	x	x	x	x
green glass	x	x	x	x	x	x
mixed color	x	x	x	x	x	x
glass	x	x	x	x	x	x
t-HDPE	x	x	x	x	x	x
p-HDPE	x	x	x	x	x	x
PET-bvg.	x	x	x	x	x	x
plastic-other	x	x	x	x	x	x
mixed plastics[a]	x	x	x	x	x	x
ONP	x	x	x	x	x	x
OCC	x	x				x
Phone Books		x	x	x	x	x
Books		x	x	x	x	x
Old Magazines		x	x	x	x	x
Third Class Mail		x	x	x	x	x
office paper		x	x	x	x	x
paper-other		x	x	x	x	x
mixed paper[a]	x	x	x	x	x	x

a. Includes "non-recyclable" plastics or paper.

Based on previous work, we have concluded that the MRFs described above are most cost effective when they include an automatic bag opener, a magnet for ferrous metal removal and an eddy current separator for aluminum can removal. All other sorting is performed manually. We propose to adopt these assumptions here, for purposes of developing MRF designs from which to estimate cost and LCI parameters. However, the user will have the opportunity to specify automated or manual equipment in certain cases.

The technology associated with MSW sorting in MRFs is evolving. This can be accommodated by allowing the user to bypass the design component of a process model and input costs and LCI parameters directly. Eight distinct MRFs are required as described above. However, they have many overlapping design features which will remain consistent between MRFs. The design for each MRF will be presented in year 2 as the process models are developed.

I. Remanufacturing and Energy Recovery

The LCI analysis must account for all resources, energy and emissions associated with the recycling and reprocessing of a waste component. This section presents the conceptual framework to be used to account for resource expenditures and potential savings due to the use of recycled materials. In management strategies where some portion of the MSW is recycled, the recyclables will ultimately be delivered to a facility for remanufacturing. Separation will occur during collection, or at a MRF or other waste management facility. Energy and resources will be expended to deliver recyclables to a remanufacturing facility. At the facility, additional energy and resources will be expended to convert the recyclables to a new product. The total amount of energy required to recover the recyclable from the waste stream and convert it to a new product will be included in the inventory analysis. This energy is termed E_r. In addition, the amount of energy required to produce a similar amount of product from virgin material will be calculated. This energy is termed E_v. The net amount of energy (E_n) expended (or saved) to recycle a material will then be calculated as the difference between E_r and E_v ($E_n = E_r - E_v$.)

While energy has been used here as an example, a similar calculation will be performed for all life-cycle parameters involved in the remanufacturing process such as carbon dioxide and other air emissions, wastewater pollutants, and solid waste, etc. This calculation assumes that a product manufactured using recycled materials is indistinguishable from the same product manufactured with virgin materials. Although not shown in Figure 5, ONP which is not recycled would be disposed by combustion, conversion to RDF, composting or a landfill as illustrated in Figure 2.

The calculation described above is illustrated conceptually for ONP in Figure 5. Figure 5 shows the flow diagram which accounts for the total energy required to produce and deliver to consumers 1000 tons of newsprint (as newspapers). As can be seen in Figure 5, newsprint is not produced from 100% recycled material; some virgin material is mixed with the recycled fiber.

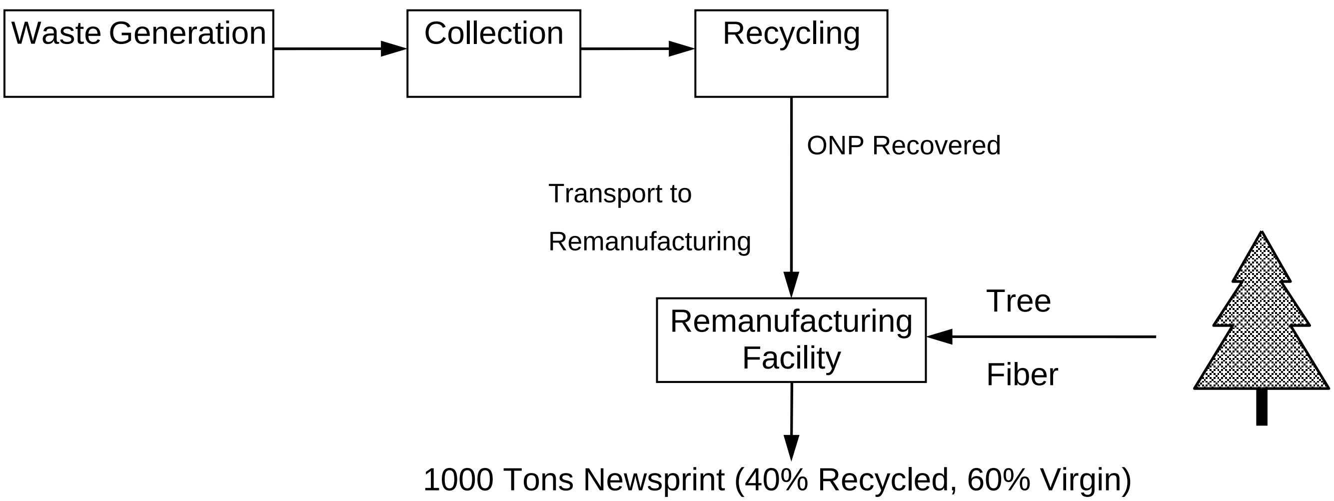
In order to develop the life-cycle inventory, an assumption must be made with respect to which remanufacturing process is utilized for a recyclable. In the case of ONP, the major use is the production of new newsprint. However, some ONP is used in other applications (container board, cellulose insulation, animal bedding, etc.). For each recyclable, it will be necessary to collect data on remanufacturing processes in order to complete the LCI. Data collection efforts will focus on the major remanufacturing process for each recyclable.

Additional remanufacturing processes will be included in the decision support system so that if resources are available to collect data on more than one remanufacturing process, the system will have the capacity to incorporate it into the analysis.

In addition to recycled materials, an offset will also be required in management strategies where energy is recovered from the direct combustion of MSW, the combustion of RDF or landfill gas. The conceptual framework described above may be applied here as well. Energy recovered from the MSW will be credited to that management strategy. In calculating emissions reductions associated with energy recovery, we will assume the 'saved' energy resulted from fossil fuel (coal, oil or natural gas) and not from hydro or nuclear power.

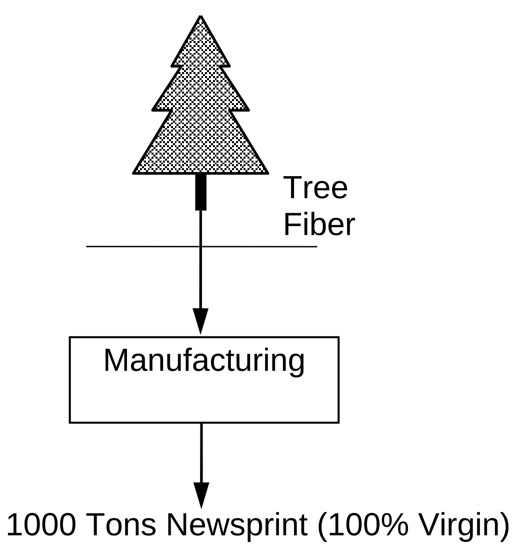
Figure 5
Illustration of Framework for Calculation of Life Cycle Effects Including Remanufacturing for Recycled Newsprint

A. Calculation of E_r



E_r = Total energy required to produce 1000 Tons of newsprint using recycled material, from collection through new product production.

B. Calculation of E_v



E_v = Total energy required to produce 1000 Tons of newsprint from virgin material. Includes energy from growth of trees through final product.

J. Composting

Composting is the aerobic biodegradation of organic matter and is considered as a treatment alternative. We propose to consider composting of either yard waste or mixed waste. Yard waste composting may occur in either a centralized municipal facility or in a generator's backyard. Here, we consider a centralized composting facility. Backyard composting will be considered in Section O on source reduction.

We propose to consider two alternatives for yard waste composting; a low and medium technology facility. The major difference between these two facilities is the degradation rate of the yard waste as influenced by the turning frequency. The detention times are assumed to be 540 and 270 days for the low and medium technology facilities, respectively and can be modified by the user. Turning is accomplished with either a front end loader once per year (low) or a windrow turner 25 times per year (medium). Again, these parameters can be modified by the user. Other major differences between the low and medium technology facilities include water addition, post process screening and the potential to treat leachate. The type of facility to be considered will be a user input parameter. Branches will be shredded prior to composting in both the low and medium technology facilities. Neither facility includes an automated air supply system.

Yard waste may be delivered in collection vehicles or dropped off by the waste generator. In addition, leaves may be delivered in vacuum trucks. If yard waste is delivered in bags, then the user will be asked to specify whether the bags are biodegradable, in which case they will not require emptying, or non-biodegradable, in which case they will need to be emptied and the bags will represent a residual. Yard waste may also be delivered in bulk.

The design of the mixed waste composting facility will be based on mechanical aeration. This facility will include preprocessing of the inlet waste stream to remove non-compostable recyclables such as metal, plastic and glass as well as non-compostable non-recyclables. The waste flow equations will be written so that paper may or may not be removed in the preprocessing step.

K. Combustion

Combustion represents a treatment alternative in which the volume of MSW requiring burial is significantly reduced. We will consider a facility in which MSW is burned with subsequent energy recovery in the form of electricity. Facilities in which energy is not recovered as well as facilities in which energy is recovered as steam are excluded from the system. The logic for this selection is that the majority of combustion facilities constructed today include energy recovery as electricity.

The cost, energy production and emission functions for a combustion facility will be developed on the basis of BTU of input waste per day as opposed to tons per day which is more standard. In so doing, we are able to link the cost and energy yield of combustion to waste composition. The BTU value of the waste input to a combustion facility will be calculated from default data on the BTU value of individual waste components and the composition of waste entering the facility. Thus, if the BTU value of MSW changes, the effect will be incorporated into estimates of potential energy recovery. This will allow comparison of the relative net benefits of recycling and combustion with energy recovery in the optimization module.

In order for a combustion facility to be feasible, a critical mass of refuse is required. The critical mass will be set up as an input parameter so that (1) a SWM alternative with an unacceptably small combustion facility is not proposed and (2) future changes in technology resulting in a change in the critical mass can be incorporated in the system. The combustion facility will include appropriate air pollution control equipment to meet current regulations.

L. Refuse Derived Fuel (RDF) and Co-Combustion

In addition to combustion as discussed in the previous section, two alternatives for recovery of the energy value of MSW will be considered in the SWM system, RDF and co-combustion. In the system described here, RDF production refers to the separation of MSW into a product stream with a relatively high BTU value and a residual stream with a relatively low BTU value. Of course, the efficiency of the separation of MSW into these streams will be less than 100%. There are many variations on the RDF theme including the production of shredded refuse for direct combustion, and the production of pellets for shipment over longer distances. The most common RDF processes will be identified in future work so that one or more generic RDF plant designs can be developed. These designs will be used as the basis for a preprocessor in which cost, energy and emission factors are developed.

The division between an RDF plant and a MRF is not entirely distinct as metals separation typically occurs in an RDF plant. Thus, if RDF is part of an MSW management strategy, then it would probably not be necessary to remove tin cans separately. Similarly, an eddy current separator at an RDF plant would eliminate its need at a MRF. As more information is developed on RDF plants, we will propose the manner in which the interrelationship between an RDF plant and a MRF will be handled.

Another manner in which energy can be recovered from MSW is by the combustion of particular components of the stream in industrial boilers. This could include utility boilers, hog fuel boilers in the paper industry and the like. The system allows for the recovery of a mixed waste paper stream and a mixed waste plastics stream during recycling. One or both of these streams could be used as fuel for an industrial boiler. This will be referred to as RDF although it will not necessarily include a separate facility.

M. Anaerobic Digestion

Anaerobic digestion of MSW could occur in either a reactor or by operation of a landfill with leachate recycle for enhanced refuse decomposition and methane production. Here we refer to digestion in a reactor. The facility will include preprocessing of the inlet waste stream to remove non-degradable recyclables such as metal, plastic and glass as well as non-degradable non-recyclables. The waste flow equations will be written so that paper may or may not be removed in the preprocessing step.

N. Landfills

Three types of landfills will be considered in the system; one designed for the receipt of mixed refuse and operated to minimize water infiltration, a second designed for the receipt of combustion ash and a third designed for the receipt of mixed refuse and operated to enhance decomposition. All landfills will be designed according to RCRA Subtitle D and Clean Air Act standards. However, through the process model, the user will have the opportunity to specify either a more lenient or stricter design with respect to the liner and cover systems. The first landfill will be operated as a dry landfill. The system will include both gaseous and liquid emissions from the landfill. The user will be required to specify whether gas is flared, recovered for energy, vented to the atmosphere or allowed to diffuse out of the landfill. This information, coupled with data on landfill gas production, will be used to estimate atmospheric emissions. Estimates will also be developed for the amount of leachate requiring treatment. This leachate will be treated in an off-site treatment facility. Energy and emissions associated with leachate treatment will be considered in our inventory analysis.

Municipal waste combustion ash will be directed to a landfill designed to accept ash. Even when a community utilizes combustion, there will be some material which should not be routed to a combustion facility and also times when it is out of service. Thus, we expect that the design for an ash landfill will include a relatively small section designed for the receipt of mixed refuse. A third landfill will be designed with leachate recycle to enhance refuse decomposition, methane production and leachate treatment. As above, the system will include both gaseous and liquid emissions. The user will be required to specify whether gas is flared or recovered for energy. This information, coupled with data on landfill gas production, will be used to estimate atmospheric emissions.

O. Source Reduction

As illustrated in Figure 1, source reduction represents the difference between potential and actual waste generation. Source reduction represents a reduction in mass or toxicity. Source reduction may lead to reductions in other LCI parameters such as COD production or particulate emissions. The effects of source reduction are unique to very specific components of the waste stream. The conceptual framework for modeling source reduction is described first, followed by examples of how it could be applied.

With reference to Figure 1, the box entitled source reduction represents a series of multipliers that adjust the waste generation rate resulting from a source reduction program. These numbers are multiplied by the waste quantities in the potential waste generation box to calculate actual waste generation. Source reduction will include a series of multipliers, with unique values for changes in waste mass and each life-cycle parameter. These multipliers will be set up as individual input parameters in a process model so that where the user has data on a specific process, it can be used. Collection of data on specific industrial processes for evaluation of source reduction is beyond the scope of this project.

Source reduction is generally applied to very specific components of the waste stream. Examples might include a lighter napkin with equivalent absorbency, or a napkin produced by an alternative manufacturing process which reduces waste production. Napkins are not one of the waste components listed in Table 1. Rather than divide the waste stream into the individual components which make up MSW in order to specifically include napkins, we have provided additional "dummy waste components" in the waste composition data input section.

These dummy variables could be used in the same way as the "paper-other" category. That is, if a user wishes to focus on napkins, then the user would consider one of the dummy variables to be napkins. The user could then enter the appropriate multipliers in the source reduction process model to account for mass and other life-cycle parameter reductions (or increases) associated with the production of a different napkin. If a waste were to be converted from a non-recyclable to a recyclable form, then its composition would have to be considered as part of one of the recyclable components identified in Table 2. If this is inappropriate, then the process model would require modification.

A simple example of the source reduction process model is its application to backyard composting. Here, yard waste which is composted by the waste generator does not enter the MSW collection system. A multiplier in the source reduction process model would be used to reflect the decreased mass of yard waste in MSW. Yard waste not collected would not require energy for collection or further processing in a centralized composting facility. However, there are life-cycle implications associated with backyard composting and these will be accounted for in a dedicated process model. The backyard composting process model would account for emissions associated with biodegradation as well as emissions associated with the use of a chipper for size reduction of branches. In the process model, the user will have to specify the fraction of backyard compost systems where a chipper is utilized.

P. Summary of System Boundaries

The system has largely been defined through the description of the functional elements and unit operations as discussed in this document and the manner in which each will be treated. In general, we will evaluate all data which have a bearing on the inventory analysis from materials acquisition through waste disposal or remanufacturing. Where a material is recycled and a new product is produced, the resources, energy and emissions associated with production of the new product as well as those saved by using a recycled material instead of a virgin material will be considered. This concept also applies to energy recovery from combustion as described in more detail in Section I and in Figure 5.

In considering remanufacturing, we will evaluate life-cycle parameters from the recovery of a raw material through its conversion to a product. Where petroleum is a raw material, the analysis would include all activity beginning with recovery of petroleum from the earth. Where energy is required in a process, the energy associated with production of the energy (precombustion energy) and the wastes associated with energy production will be considered. Where trees are utilized, resources associated with growing and harvesting the tree will be considered.

The functional elements of MSW management include numerous pieces of capital equipment from refuse collection vehicles to balers to major equipment at paper mills. Resources are associated with the fabrication of capital equipment as well as the construction of a new facility. In theory, these resources should be considered in the inventory analysis. This may be particularly relevant in evaluation of waste management strategies which suggest the construction of a new facility, such as a MRF, or the purchase of new refuse collection vehicles. While inclusion of capital equipment appears to be theoretically correct, it introduces additional complexity which may not be necessary. The amortized purchase price of a facility or a piece of equipment will be used as a screen to evaluate the importance of its inclusion in the inventory analysis. Where the amortized capital cost of a piece of equipment is low relative to the non-labor cost to operate it, we will assume that the resources involved in fabrication of the equipment are insignificant. It is difficult to identify cases where capital equipment and facility construction can or cannot be neglected ahead of time and issues such as this will be brought out for discussion by the internal advisory board as they arise.

A second type of resource that may be neglected is the energy associated with the operation of a facility's infrastructure, or "overhead" energy. For example, energy will be expended for the operation of refuse collection vehicles. We expect that a much smaller amount of energy will be expended for operation of the office through which the vehicle routes are developed and the collection workers are supervised. Our hope is to obtain estimates of this "overhead" energy based on utility bills. If this energy is less than 5% of the energy utilized by the collection vehicles, then it will be neglected unless standard overhead energy consumption factors are available. This will save the project the resources required to estimate such energy more precisely and will not affect the quality of the project output.

Another system boundary is that at the waste treatment and disposal end of the system. Where wastes are generated which require treatment, the energy associated with their treatment will be considered. If a solid waste is produced which requires burial, energy will be consumed in the transport of that waste to a landfill and its burial in the landfill.

P.1 System Boundary for Economic Analysis

In this section we propose that the system boundary for the economic analysis differs from that used for the inventory analysis. We propose that our economic analysis focus on the cost of waste management as experienced by the public sector. Thus, the economic analysis will include the cost of waste collection, transfer stations, MRFs, composting facilities, combustion, RDF plants and landfills. In addition, where a waste is produced as part of a waste management facility, the cost of waste treatment will be included in the economic analysis of that facility. For example, we will include the cost of leachate treatment in our economic analysis of landfills. The economic system boundary will also include the cost of educational or other materials associated with source reduction or other aspects of solid waste management. The boundary will be drawn at the points where waste is buried and recyclables are shipped to a downstream processor. For example, if recyclables were shipped from a MRF, the economic analysis would end where the public sector received revenue (or incurred a cost) in exchange for recyclables. The same analysis would apply to the sale of RDF or electricity. The user must be cautioned that there are situations where the revenue realized from the sale of a recyclable is artificially high. This has occurred in the past where a manufacturer has taken steps to encourage the recycling of a material by offering an artificially high price. Such situations may arise when recycling of a waste component not typically recycled begins. This situation would not be expected to persist for a period of several years.

One cost to be excluded from the economic analysis is the cost of remanufacturing. However, we feel that this cost is reflected in the price paid to a community for recyclables or electricity.

The user will have the option to enter costs directly into the process model or provide sufficient design information for the process model to estimate costs. Where costs are estimated by the process model, we propose to estimate costs in the absence of an allowance for profit. The user will then be given the opportunity to specify a profit margin if the user expects that a waste management unit operation will not be operated in the public sector. The calculated cost will then be adjusted upwards prior to its use in the optimization module.

In summary, by focusing on costs incurred in the public sector, the analysis will be of most use to local officials responsible for development of strategies for solid waste management.

Q. References

USEPA, 1994, "Characterization of Municipal Solid Waste in the United States: 1992 Update, EPA/530-R-94-042.