LIFE-CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTES: DEVELOPMENT OF WASTED SOFTWARE

by

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ABSTRACT

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A thesis, authored by Rodrigo Diaz, presented to Ryerson University in partial fulfillment of the requirements for the degree of Master of Applied Science in the Program of Environmental Applied Science and Management.

This thesis introduces WASTED (Waste Analysis Software Tool for Environmental Decisions). It is a computer-based model that uses life-cycle assessment (LCA) methodology to estimate material flows and environmental impacts of municipal solid waste management.

The model consists of a number of separate submodels that describe a typical waste management process. These models are combined to represent a complete waste management system. Based on LCA methodologies, WASTED uses compensatory systems in order to account for the avoided impacts derived from energy recovery and material recycling. In this manner, a comprehensive "cradle-to-grave" analysis of waste management is possible.

The purpose of this project is provide waste managers, environmental researchers and decision makers with a tool that helps them to evaluate waste management plans and to improve the environmental performance of waste management strategies.

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Finally, I would like to say thanks to Steph (especially!) and all my friends in Toronto that have made the pursuit of a graduate degree much more enjoyable. It is hard to move 3000 km to a different country - you guys made the adjusting process easy!

DEDICATION

This thesis is dedicated to my parents for their love and support.

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INTRODUCTION

Solid waste management deals with the way resources are used to deal with the end-of-life materials in the waste stream. Waste management is an important environmental challenge that must be addressed by every community. The management of waste streams often involves complex decisions regarding the collection, recovery, transport and disposal of municipal solid waste (MSW).

The treatment of MSW has evolved: prior to 1970, sanitary landfills in North America were rare - wastes were dumped in low-technology sites. Today, solid waste management involves advanced technologies that are more efficient and protective of the environment and human health. The need for "better" waste management solutions has been heightened by increased environmental awareness and breakthroughs both in science and environmental regulation.

Additionally, waste management has implications for all jurisdictional levels – municipalities, for example, are normally in charge of determining the optimum system for waste collection, truck routes, and especially the cost-optimization of waste collection services to households and commercial locations. On the other hand, waste management also has global significance: decisions made by cities and countries affect the release of greenhouse gases (GHG) that contribute to global climate change; for instance, landfills were the largest contributors of methane emissions in the US in 1999 (EPA, 2001). It is clear that waste management has profound effects, ranging from local to worldwide.

Given the complexity of wastes and their management, it is difficult to compare the different waste management alternatives. Should one maximize the recovery of reusable materials or incinerate wastes to generate energy? Is it better to landfill wastes in a bioreactor or in a typical landfill? Answering these questions accurately is impossible without evaluating all the implications of MSW management. The objective of the Waste Analysis Support Tool for Environmental Decisions (WASTED) model is to assist in calculating the environmental effects of waste management alternatives in order to improve the overall performance of a waste management system.

To analyze the different waste management alternatives, the WASTED model relies on environmental life-cycle assessment (LCA). This is an analytic tool that studies the potential environmental effects associated with a product or process. Life-cycle analyses are relatively recent. They started with studies that attempted to determine optimal solutions that take into account not only energy and raw material consumption environmental burdens, but also the impacts related to the final disposal of a product or service. One of the first reported LCAs was performed in 1969 by the Coca-Cola Company, to determine whether plastic or glass bottles presented fewer environmental burdens (ECOBILAN). However, it was really until the 199s that this type of analysis became commonplace. In 1997 the International Organization for Standardization issued the ISO 14040 standard, in which the different stages of the Life-cycle analysis are defined. (Ibid).

A LCA studies the environmental aspects through a product's life (a "cradle-to-grave" approach), starting with raw material acquisition and ending with final disposal. This analysis is performed by compiling an inventory of relevant inputs and outputs to the system, and evaluating the potential impacts of these inputs and outputs. In this case, the objective is to perform a "cradle-to-grave" analysis of <u>municipal wastes</u>. Therefore, this life-cycle analysis starts when materials are discarded into the waste stream and ends at the point where the waste material has been finally disposed (e.g. through incineration) or transformed into a resource (e.g. by composting).

Historically, the "default" option for managing municipal wastes has been landfilling (Tammemagi, 1999). However, environmental research has demonstrated that the optimization of MSW management has to take into account several factors. Amongst these are:

- Composition and quantity of waste generated
- Efficiency of waste collection systems
- Availability of technologies for waste management
- Market availability for recycled materials
- Emission standards to which the MSW are subject
- Socio-political factors

As can be inferred from the list above, waste management is a very complex process that has numerous economic, environmental, social and political implications.

Several Life-cycle assessment models have been developed by different institutions: government environmental agencies, universities, and waste management consultants. Although all these models have similar objectives (to evaluate environmental effects of waste management from a systematic perspective), all of them have shortcomings in one form or another. In particular, models have been developed for different regions and are difficult to "translate" from one site to another, especially with regard to their applications in sites with limited access to technology (such as developing countries). To maximize flexibility, the WASTED model includes a database of "typical" waste management parameters, but allows the input of site-specific values in order to provide optimum accuracy.

This thesis is divided in 3 parts: the first one discusses the generalities of MSW life-cycle assessment models, and presents a brief review of other models currently available and have been used as a starting point for this model. The second chapter will explain the subsystems of solid waste management: characterization, collection, recycling and other processes. The third chapter will compare the WASTED model with other models by means of different case studies. Finally, an appendix will be included to provide a user's manual for the WASTED model.

1. LIFE-CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTES

1.1 Environmental Life-Cycle Assessment

Environmental life-cycle assessment (LCA) is a systematic evaluation of the environmental consequences of a determined process, product or activity . LCA takes a "cradle-to-grave" approach, starting with the acquisition of raw materials required to manufacture a product, and ending with the disposal of all the materials back in the environment. In this context, the term "product" includes also service systems – in this case, for example, waste management systems.

A LCA evaluates all the stages of a product's life sequentially, and estimates the cumulative impacts resulting from a product's life cycle, including impacts that are often overlooked in other types of analyses like raw material extraction, disposal costs and transportation impacts. In this way, LCA provides a comprehensive picture of the environmental burdens attributed to a specific process.

Life-Cycle Assessment Methodology

The general framework for the LCA has been established by the International Organization for Standardization in the ISO 14040 Standard. The procedure to perform a LCA consists of 4 steps:

1. Goal description / application: In this first step, the ultimate goal and application of the results are to be defined. It is also in this step that system

boundaries are established, since they determine to a great extent the results of the life-cycle assessment.

2. Input / Output Analysis: This step enumerates the exchange of materials and energy at the system boundaries. In essence, this is an inventory of mass and energy entering or leaving the system.

3. Impact assessment: The third stage of a LCA consists of assessing the contributions of input/output data to generate an impact profile. In many cases, this is achieved by using a model to gauge the environmental effects of a process or product.

4. Interpretation: The environmental impacts of the analyzed process are evaluated according to the goals defined in step 1.

1.1.1 Advantages of Performing a Life-Cycle Assessment

The most obvious use for a LCA is to help decision-makers and managers to evaluate objective'' and comprehensively the environmental impacts to select the product or process that results in the least adverse impacts to the environment. Although this information is seldom the sole factor to consider in making a decision, it can be tallied along with other parameters such as cost and performance to discriminate between different options.

Other advantages related to performing a LCA are (EPA, 2001):

- Systematic evaluation of the environmental consequences associated with a given product
- Improved knowledge of the environmental trade-offs related to product alternatives, and the interdependent nature of the consequences of human activities
- Quantification of emissions to different media

In general, the main advantage of performing a LCA is the generation of a comprehensive understanding of the environmental impacts of a product, and an accurate picture of the overall environmental trade-offs implicated in the selection of such products.

1.1.2 Limitations of Conducting a Life-Cycle Assessment

LCA by itself can not determine what process or product is most efficient or cost-effective. Therefore, the information generated in this analysis should be used as a decision component in combination with other tools as part of a comprehensive decision package, and not as a "stand-alone" tool. Additionally, it is important to understand that since LCA are often based on models, they provide only an approximation of reality.

1.2 Review of Life-Cycle Assessments Of Municipal Solid Wastes

Life–cycle assessment of municipal solid wastes (MSW) exhibits certain differences compared to a "typical" LCA. In general, LCA systems are modeled so that inputs and outputs are followed from cradle-to-grave – starting with raw material acquisition and ending when the materials are discarded to the environment without further human transformations (ISO 14040). As described by Finnveden (1999), in the case of waste management a LCA often starts with the input of solid waste as it appears – in the curb or waste collection bin, after been discarded by consumers. This difference does not have an effect given the general premises of a LCA, but does require modifications for different aspects of the analysis. These aspects include system boundaries, recycling, multi-input processes, and time-frame considerations. Their influence in the development of the WASTED model will be discussed in chapter 3.

With regard to municipal solid wastes, LCAs have been used only (relatively) recently; several companies and other organizations have developed models used to quantify the impacts of MSW management decisions. To create this model, the following projects were reviewed and analyzed:

1.2.1. Integrated Solid Waste Management Model (ISWM)

This computer-based model was developed by CSR and EPIC, in Canada. The University of Waterloo has been assigned to assist with the use of this tool. This project was developed with the participation of the city of London, Ontario, and London was the initial case study. The objective of this project is to "provide Canadian municipalities with tools that will enable them to evaluate the environmental and economic performance of the various elements of their existing or proposed waste management systems leading towards the goal of ISWM [integrated solid waste management]" (Corporations Supporting Recycling [CSR], 2000). Along with the environmental model, it includes a sub-model for economical estimates. This model is available free of charge from the University of Waterloo website (www.iwm-model.uwaterloo.ca), although approval must be granted by email authorization.

ISWM is a spreadsheet-based model that consists of several input screens. Each screen covers different aspects of the life cycle inventory (LCI) of municipal solid waste:

a. Quantity and Composition of waste: This screen requires the input of the total amount of waste managed, as well as its composition in different fractions and sub-fractions (for example the Plastic category includes PET, HDPE, PVC). The model provides default values for waste composition.
b. Waste Flow: The user is required to specify the mass of waste destined for recycling, composting, land application, energy-from-waste and landfill.
c. Waste collection: This screen records the parameters for the collection and transportation of waste including distance and type of fuel utilized. It also estimates the fuel consumption, based on average fuel efficiencies for both collection and transport. If a waste transfer station is present, another screen

appears allowing the user to input the energy consumed in the operation process, as well as the distance from the transfer station to the different waste treatment facilities.

d. Electric grid selection: This screen allows the user to specify the locale (by Canadian province) in which the LCA is performed, in order to estimate the fraction of power generated by different processes (such as coal, natural gas and nuclear). Alternatively, the user may input manually the breakdown of electricity-generating processes. This is used to calculate the emissions avoided due to recycling or energy recovery.

e. Recycling: In this section the user must input the recovery percentage for the different fractions of the waste stream.

f. Material recovery facility: This screen registers the input for energy consumption, residue percentage and management, and the distance required to transport the different recovered materials to their respective reprocessors.

g. Composting: The user has to provide the breakdown of the different compostable materials (paper, food waste and yard waste) in the waste stream. Also, inputs for residue generation, transport, type of composting process and energy consumption are needed.

h. Land application: This screen requires the parameters for direct land application of yard waste (leaves and yard material). It requires the average energy consumption for this operation, as well as the breakdown of the waste applied.

i. Energy from waste: In this screen, the user is required to indicate the type of energy recovery, energy recovery efficiency, energy consumption during this process, and emission parameters. These include ash generation, and emission rates for air contaminants (based on the Ontario MOE guidelines). Transport distance for the generated ash must also be provided.

j. Landfilling: This screen records the parameters for the landfill. It includes gas and energy recovery efficiencies, annual precipitation, leachate collection efficiency and energy consumption

Model outputs are in the form of Excel spreadsheets, and include a summary of the input data, a summary of the outputs which include the total life cycle burdens, an output table that breaks down the burdens from each waste management process and a table that presents the inventory results in terms of "everyday" equivalents, such as energy consumption per household and greenhouse gases produced by car use.

As part of its limitations, the authors of this model acknowledge the following:

- It does not consider all the available waste management processes
- It does not evaluate waste reduction/reuse, nor the management of all waste streams (for example white goods or tyres).
- The model does not evaluate the energy and emissions associated with the production of waste management infrastructure (such as disposal facilities).
- The model is based upon the best data available publicly, and represents the currently accepted practices for life cycle studies. Most parameters are not easily modifiable (for example`, the user cannot modify the ratio of methane content in landfill gas)

1.2.2 Organic Waste Research (ORWARE)

This is a computer-based model that estimates substance flows, environmental impacts and costs of waste management. It has been used by several municipalities and companies to compare waste management alternatives (Eriksson, 2002). There are several published case studies that use this platform as the basis for their results. One of them is the Danish EPA, which used ORWARE to determine the overall effects of an increase in household recycling (Baky and Eriksson, 2003).

Irrespective of its name, this model covers both the organic and the inorganic fractions of waste, and consists of several sub-models that describe the different processes of a complete waste management system (including composting and incineration). It relies heavily in the Matlab interface by integrating material flows in an individual variable vector, sometimes comprising up to 50 substances (Eriksson, 2002). The different sub-models were developed in cooperation with four different Swedish research institutions: KTH – Royal Institute of Technology, IVL – Swedish Environmental Research Institute, JTI – Swedish Institute of Agricultural and Environmental Engineering and SLU – Swedish University for Agricultural Science.

The process sub-models contained in the ORWARE model are the following:

a. Waste sources and waste fractions: ORWARE is not devoted to municipal solid waste, it also includes special wastes from industry and streams such as sewage. Household waste is divided in fractions such as organic, non-combustible waste, combustible waste, paper, cardboard, diapers, rubber, glass, metal and HDPE. These fractions are further described by a set of parameters that describe the chemical composition of the waste, process performance and material recovery.

b. Waste Transport: Different parameters in this model allow for the collection in different types of trucks (for example, front-loader models), as well as transport of secondary waste[1]. Outputs of this sub-model are energy and time consumption, as well as emissions, calculated from total energy consumption.

c. Incineration: This sub-model consists of three parts: pre-treatment, incinerator operation and air pollution control. To estimate emissions site-specific data, comparable facilities' data or emission assumptions are used. Outputs of this model are emissions, energy recovered (in the form of electricity, district heating or a combination of both), and economic indicators (such as $/kg or $/KWh)

d. Thermal Gasification: This process, akin to incineration, is based on a waste-to-energy (WTE) pilot plant facility. The outputs are similar to those described in the incineration sub-model.

[1] Secondary waste refers to waste that is a by-product of a waste management process, such as ash from incineration or compost residues.

e. Landfill: This sub-model allows for the selection of five different landfill types: mixed waste, bio-reactor landfill, wastewater sludge, fly ash and slag. These types represent "typical" Swedish average landfills (Eriksson, 2002). Since Landfill degradation is slow, the scope of time surveyed by this model is extended beyond the surveyed time for the other processes. To be able to compare landfill emissions, the future impact from landfilling has been separated into surveyable (sic) time and remaining time. Inputs to this model include energy consumed (diesel and power), efficiency of landfill gas recovery and time of leachate treatment used. Outputs include emissions, energy recovery from landfill gas, and landfilling costs.

f. Material Recycling: This sub-model includes the recovery of plastics and cardboard. Parameters are based on specific Swedish plants, and include electricity consumption and the fraction rejected. Outputs from this sub-model are emissions to water, energy related emissions to air, energy consumption and waste in the form of biosludge and plastic rejects.

g. Anaerobic Digestion: This sub-model allows for thermophilic or mesophilic anaerobic digestion of organic waste. It is based on a treatment plant in Uppsala, Sweden. The model calculates the energy input for the digestion of the wastes, as well as the amount of gas and sludge as well as the costs for treatment.

h. Composting: Three types of composting are integrated in this model: small-scale composting in households, and large-scale windrow or reactor composting. The model operates under the assumption of "proper management" (no anaerobic degradation of wastes or leachate spills). Essentially, emissions are the same, although reactor composting allows for effluent gas treatment. Inputs to this model are energy consumption, emission parameters and heat recovery (for reactor composting). Outputs include emissions, cost and energy consumption/recovery.

i. Compensatory System: This is the section of the model that accounts for the utilities generated from the management of waste in other systems, as well as the raw materials displaced by recycling fractions of the waste stream. Parameters included are district heating, electrical power generation and the production of mineral fertilizer from wastes. Compensatory plastic and paper production take into account the processes used to manufacture these products from raw materials, including the transportation of raw materials and energy used during manufacturing. Since the emphasis of this model is in organic waste, no metal fractions have been included for recoverable metals (for instance, aluminium or iron).

The limitations for the ORWARE model are the following:

- It calculates the impacts of waste management during one year (except landfills).
- Materials in the waste stream exclude some components that are typical to solid waste, such as metal fractions.

- Parameters for virgin material displacement, utilities[2] displaced, and emissions for some processes (landfilling) are decidedly local – either for Sweden or Denmark – attempting to simulate faithfully the conditions in those locales.
- Use of chemicals for waste treatment is calculated, but not the emissions associated from the production of these (*cradle-to-grave*).

Finally, the authors of this model acknowledge that

> "ORWARE is a research tool [...] There is always a struggle between being as site-specific and detailed as possible, and being easy (sic) understandable. To become more user friendly without losing too much of the flexibility is something to continue to work with" (Eriksson et ál, 2002. p. 205).

1.2.3 Waste Reduction Model (WARM)

This tool was developed for the EPA by ICF Consulting: This model is tailored to keep track of greenhouse gases (GHG) emissions in order to provide U.S. DOE program 1605b[3] participants with a tool to compare the climate change impact of different waste management approaches. It includes several waste management options, as well as non-energy emissions (EPA, 2002). The results of the GHG impacts of municipal solid waste (MSW) production are summarized and explained in the life-cycle assessment of emissions and sinks (Ibid).

[2] In this document, "utilities" is used in reference to
[3] This is the U. S. Department of Energy's voluntary greenhouse gas reduction program

WARM users need to provide waste composition inputs for both the "current" and "alternative" scenarios studied, in short tons. It also requires the user to input the mass of waste that is destined for different management options (EFW for example), landfill gas collection efficiency, displaced virgin raw materials (either the current US mix or 100% virgin material), and the distances to the different waste management facilities. The output consists of a report that shows the greenhouse gas emissions (in tons of carbon or CO_2 equivalents) for both the current and alternative scenarios, as well as a comparison between the two.

This is a fairly simple and friendly model, which suffers from two main limitations: its parameters are tailored for use in the US, and it only accounts for the emission of GHGs. It also allows for little user modification of the different parameters, such as emissions during the waste transport process. This tool is available free of charge from the EPA website.

1.2.4 Other models

In this study, models such as those presented by Thorneloe et (2002) al and Barlaz et al (2003) were consulted to develop WASTED. However, both these models are site-specific; they use parameters that are not necessarily typical. Therefore, the results from these simulations can hardly be extrapolated to other case studies. In contrast, ECOBILAN has developed the Tool for Environmental Analysis and Management (TEAM). This model simulates operations associated with product design, processes and activities associated with . ¦ industrial sectors (EPA, 2002). This model is very complete, and is used by many firms and government agencies. This model charges its user a licensing fee of US$3000 and an annual contract of US$3000 (Ibid). Therefore, the need for a generic an affordable LCA for municipal solid waste systems is still unfulfilled.

In general, the premise of all these models is to evaluate the environmental effects of waste management from a systematic point of view, looking beyond the threshold of local perspectives. They differ in the degree of inclusion of different waste management technologies, the degree to which the user can modify the simulation parameters, and their ultimate purpose. The "higher end" models such as TEAM are very sophisticated and allow for fine adjustment of the parameters, but unfortunately they are quite expensive and also require extensive research to estimate site-specific parameters. Therefore, there is still a niche for a generic and easy-to-use LCA model.

All the aforementioned models have provided insight and information to develop this project. Some parameters from these models have also been adopted as baselines, while trying to circumvent some of their individual shortcomings (for example, WARM's complete devotion to study greenhouse gas emissions while disregarding any other implications or ORWARE's usage of Matlab instead of less-specialized software) with the intent to create a generic model that is simple to use and generates useful indicators.

2. WASTED MODEL

2.1 General Description

The WASTED model was developed to estimate the environmental impacts of waste management alternatives. It addresses typical aspects of MSW management from the collection of wastes through ultimate disposal. It relies on process models to calculate energy consumption (or generation) as well as emissions from each waste management operation.

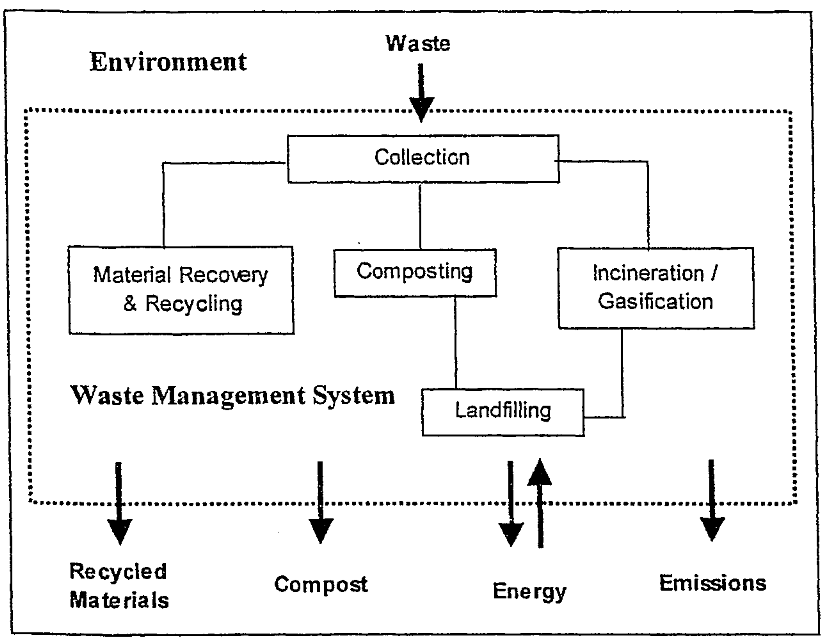
One of the crucial aspects of a LCA is a reliable “material balance” of the inputs to the system To keep track of the paths taken by the different waste streams, the WASTED model relies on a material flow analysis (MFA). A material flow analysis is an analytical tool that follows the different material inputs through the diverse processes they undergo until they exit the system boundaries (Finnveden & Moberg, 2001). This type of analysis is well suited for the analysis of MSW, since the different components of the waste stream often undergo different processes (for instance only organic materials can be composted).

Once the MFA is carried out, WASTED generates data on emissions from each of the submodels of the system. Data are sorted into different categories, to facilitate their comparison (greenhouse gases are one category, for example). The processes that are analyzed in these models are:

- Waste Collection and transfer
- Material Recovery / Recycling
- Composting
- Incineration/Gasification (energy recovery)
- Landfilling

The basis of the life-cycle analyses is the mass flow of the waste stream through these processes. A diagram of the different waste treatment processes is shown in Figure 2.1.

Figure 2.1 System Diagram



2.2 MSW Life-Cycle Assessment Methodology

Some methodological aspects require special consideration when applying LCA to municipal solid wastes. These aspects are the establishment of system boundaries, the integration of recovered materials, processes with multiple inputs and time-frame considerations.

2.2.1 System Boundaries

One of the nodal points of LCA is that the system model is created so that the inputs and outputs are followed from "cradle-to-grave". Often, this means that inputs are flows withdrawn from the environment, and outputs are flows discarded into the environment. For MSW, this approach is modified: inputs are solid wastes "as they appear" (in this case, from households), and outputs are materials or energy that are recycled, reused or discarded . This is compatible with the LCA definition, as long as the same flows appear in all systems which are to be compared (Finnveden, 1999).

Given the complexities of waste management (WM) systems, it is difficult to compare directly WM scenarios. For example, incineration generates more carbon dioxide than landfilling of wastes, but this fails to take into account the displaced emissions due to electricity generation in energy from waste (EFW) plants. Therefore, it is necessary to introduce *upstream* and *downstream* compensatory systems. Upstream compensatory systems evaluate the effects of processes that precede the waste management system; downstream compensatory systems incorporate the environmental effects of processes that take place after WM. By *expanding* the system boundaries with compensatory systems, the comparison of different systems can be made more just (Eriksson, 2002)[4]. A more detailed description of the compensatory systems will be described in section 2.4

The expanded system boundaries in WASTED are chosen within the LCA perspective. Therefore, they include the processes that are connected to the waste management system such as raw material extraction, production and use. However, they do not include the burdens associated with the generation of waste management infrastructure (such as machinery or facility siting). In practice, these burdens have been found to be relatively small compared to the emissions from waste management operations (CSR, 2000).

The LCA in WASTED is designed to account for emissions and raw material consumption regardless of the geographic location in which they occur (for example, recycled aluminium replaces virgin aluminium whether this is produced locally or imported); this consideration is important for aspects such as emissions avoidance from energy recovery. Temporal boundaries vary between the submodels; these will be discussed below.

[4] In other words, and borrowing terms from economics, compensatory systems attempt to *internalize* system *externalities*.

2.2.2 Material And Energy Recovery

In WASTED, recovered materials are considered to replace their virgin raw material equivalents. A prime example of this situation is the recovery of aluminum from beverage containers - this material can be used to manufacture new beverage containers. However, the fate of wastes is seldom that simple – the situation known as *open-loop recycling* takes place when a product is recycled into a different product (Finnveden). This is the case for recovered steel cans, since the resulting steel is not suited for milling steel sheets of the thinness required to make steel cans (EPA, 2002). A similar problem occurs with energy recovery; for example, if an extra kW/h of electricity is needed beyond the availability of the "regular" sources of power, this extra energy is likely to come from a marginal source. The LCA of this situation can prove problematic, since the system boundaries between the different products are not clearly defined.

This problem can be solved in two ways: the first is to *allocate additional environmental interactions* for the recycling of product A into product B. The second is to expand the *system boundaries* to include both products within the system.

. Allocation consists of including the environmental interdependencies of two materials into one of them, so that the two input/output analyses are merged into one – effectively integrating the environmental burdens of material B into material A. An example of this is the recycling of paper: a fraction of newspaper (material "B") is normally recovered in the form of "mixed" paper (material "A"). Therefore, the recycling of mixed paper should take into consideration the emissions derived from the manufacture of newspaper to be representative.

There are several methods for allocation, but there is no general consensus on the "correctness" of these. Rather, allocations are based on intuitive models that strive to account for the environmental impacts of open loop recycling. The following are two examples of allocation methods:

- Allocating raw materials for production of both products, and recycled material into product B only. For example, using recovered polystyrene from food packaging to manufacture housing insulation.
- Allocating a quota of recycled material to the recycled product. This is the case, for example, of paper products with a certain content of recycled paper.

Ideally, environmental allocations will result in an accurate representation of the analyzed case. Therefore, it is crucial to utilize this method only when appropriate data is available. In general, the parameters used for environmental allocation vary widely from study to study, since they tend to be very specific.

The other method to tally open-loop recycling is system boundary expansion. This consists of annexing additional functions to an existing system, in order to make it comparable to another (Finnveden, 1999). A good example of this method is the comparison between EFW options and a dry landfill with no energy recovery; since waste incineration combusts non-biogenic carbon compounds (such as plastics), the direct CO_2 emissions from incineration is higher than from landfill operation. However, waste incineration might also provide energy, which displaces power generated from other sources (fossil fuels). Therefore, the system is expanded to allow for the "avoided emissions" from energy generation by waste incineration, and so the two options can be compared more comprehensively. This is the approach recommended by the ISO 14040 standard, and it is the one used to solve open-loop recycling issues in the WASTED model. The main drawback of using the system expansion method is that the model becomes progressively larger and more complicated (Ibid).

2.2.3 Multi-Input Processes

It is the nature of MSW management processes to be complex: they include very diverse physical and chemical transformations. Models are used to predict the outcome of these transformations. These models rely on process parameters and input data to estimate the outcomes of waste management processes.

The most common type of model used in waste management relies on the mass-based method. Under this method, emissions are calculated for the different processes according to the amount of waste treated. This approach has many advantages - it is easy to calculate the ratio of emissions to the amount of waste treated. However, for some cases this approach might lead to inaccurate estimates: for example, the types and quantities of heavy metals leached from landfills depend highly on the nature of wastes being landfilled. Extrapolating general landfill parameters to a specific case-study could lead to inaccurate results. This situation repeats itself for other processes – composting and incineration behave similarly. This is the nature of multiple-input processes: they depend on more than one variable to provide accurate results. The submodels themselves are considered as “black boxes” - for the purposes of WASTED only their inputs and outputs are relevant

In order to avoid this situation, the model might include a very comprehensive list of variables that the user must provide to attain more representative results. The drawback of this approach is that the model rapidly becomes exceedingly complex. Since the objective of the WASTED model is to aid in the evaluation of MSW management options, the emission models were kept simple, relying (with the exception of the landfill and incineration models) on a mass-based methodology. However, to better represent the case studied, the model parameters can be changed by the user if site-specific data are available.

2.2.4 Time-Frame Considerations

Although the temporal boundary in general is easy to establish for the LCA of solid wastes, there is one very important difference between the landfill process and the rest of the components of MSW management. Emissions from a landfill may prevail for a very long time. This is especially the case for heavy metals - these compounds might take thousands of years to leave the landfill site.

Different surveyable time periods have been used in different models – from 10 years in the ORWARE model (Eriksson, 2002) to thousands of years (Tammemagi). However, no amount of time stipulated is accepted beyond discussion. In the WASTED model, two time frames are adopted: for landfill gas generation, reaction kinetics are ignored, and the model will calculate gaseous emissions *to the end.* In other words, it will estimate the total gas generation according to the amount and nature of waste without regard to when these emissions will be released. However, when this approach is used for recalcitrant compounds (such as heavy metals) the time period for these emissions to reach background levels might be in the vicinity of millions of years (Finnveden & Huppes, 1995). To maximize flexibility in this topic, the WASTED model will allow the user to provide a surveyable time period consistent with his/her type of analysis, although a suggested time period of 100 years is used by default. This time period is consistent with models such as the CSR and the ORWARE Life Cycle Assessments.

2.3 Description Of The Sub-Models In The Wasted Model

2.3.1 Waste Generation

Although waste generation is not precisely part of the waste management system, it is the starting step of the WASTED model. An accurate prediction of the amount of wastes that enter the system will ensure the validity of the output data.

A MFA lies at the core of the waste generation sub-model. Activities that generate waste are not included - the model begins when waste is collected at the source, and is limited only by the availability of data on waste generation and characterization. There are several methods to estimate the amount of waste generated and the different fractions that comprise it. The WASTED model uses a *per capita* approach to calculate the amount of wastes. This is supported by the wide availability of data characterized in this manner. It also allows the user to calculate the average population in a given locale over a time period, given that population growth data are available.

WASTED uses the data reported by the OECD Report on Sustainable Consumption Patterns (1999), the IPCC Guidelines for Greenhouse Gas Inventories (1996), and the World Bank's Solid Waste Management in Asia database for waste generation rates (Hoornweg & Thomas, 1999). These sources also provide the data for the characterization of waste.

In the WASTED model, waste is classified in 6 different categories:

- Organic waste: this fraction includes food wastes, yard wastes and other degradable fractions. These are relevant since they are fit for composting and they degrade over time when placed in landfill,; there, they generate methane, carbon dioxide, and other less prevalent compounds.
- Paper: this category includes fine paper, newspaper, corrugated cardboard, and other cellulose fiber compounds. Some of them can be recycled, and other fractions might be sent for energy recovery or landfilling.
- Plastic: This fraction includes all the carbon polymer compounds. In MSW, plastic fractions are made up mostly of polyethylene (PE), polyethylene terephtalate (PET), polystyrene (PS), polypropylene (PP) and polyvinyl chloride (PVC).
- Metal: The metal component of the MSW stream is composed mainly of beverage and food cans used to preserve foods. The former are usually made of aluminum, and the later ("tin" cans) are made of steel. The recycling of these compounds is very advantageous, both economically and ecologically.
- Glass: Glass describes food and beverage containers, either clear or coloured. This material is also fit for recycling.

- Other wastes: This category includes miscellaneous wastes that do not belong to the other 5 categories. Examples are rubber, leather wastes, and construction debris.

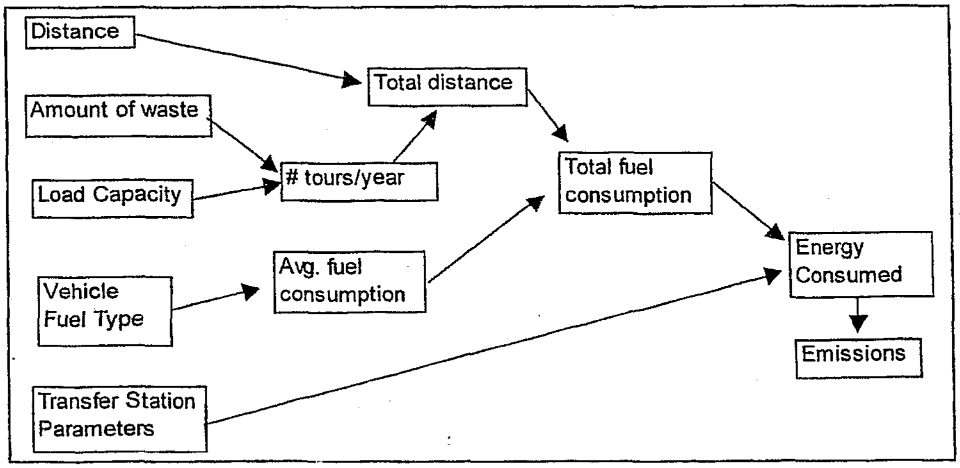
To begin an analysis, the WASTED model requires the user to input the simulation time, average population (or starting population and population change rate), waste generation rate and the waste fraction for each category of waste. It includes a database for typical national values for both waste generation and characterization. However, the data included are non-comprehensive and might not apply to the scenario being evaluated (clearly,not all the residents of the US generate 720 kg of waste per year, though this is the national average) (EPA, 1999). Therefore, it is recommended that the user provides as much site-specific data as possible.

The outputs of the waste generation submodel are the different fractions of waste, and the total amount of waste generated.

2.3.2 Waste Collection

The submodel for waste collection allows for separate collection of refuse and recyclable materials, as well as co-collection. It also allows the user to select whether a transfer station is present or not, and to modify its parameters of operation. The structure of this model is shown in figure 2.2

Figure 2.2 Waste Collection model



The number of loads per year required is calculated from the total amount of wastes and the load capacity of the trucks, either for co-collection or for separate trucks. The number of loads and the collection route are used in turn to calculate the total drive distance. The total drive distance is tallied with the average fuel consumption and the transfer station-consumed utilities to determine the total energy profile and emissions for the waste collection process. The source of the parameters of the diesel-powered trucks and transfer station utility use is the Danish EPA assessment (Baky & Eriksson). The parameters for gas-powered trucks are adapted from the DOE report on liquefied natural gas trucks (Chandler et al).

Route distance estimates for the WASTED model are based on a round-trip - starting and finishing at the transfer station or equivalent waste facility. However, transport routes are based on route length - that is, the distance between the transfer station and the different waste management facilities. The model automatically calculates total fuel consumption for the total distance covered by the waste transports.

It is important to note that the parameters introduced in this section are used throughout the WASTED model transport operations - for example, when transporting incineration ashes to a landfill. The model assumes that the methods of transportation are consistent through the waste management system. The following table describes the default parameters used in this submodel:

Table 2.1 Waste Collection Parameters[5]

Collection Fuel efficiency (km/L)	1.25	0.55
Waste Transport Fuel efficiency (km/L)*	3.00	1.82
Transfer Station Power use	2.50	KWh/Ton
Transfer Station Diesel use	0.125	L/Ton
Transfer Station Gas use*	0.00	L/Ton
Refuse Vehicle Capacity	8.00	tons
Recycle Vehicle Capacity	6.00	tons
Waste Transport Capacity	20.00	tons
Emissions (g/L)	**Diesel**	**Gas**
CO_2	2634.4000	918.4897
CO	0.0103	2.3928
CH_4	0.0356	7.0075
NO_x	18.8680	10.8359
VOCs	2.3496	0.0889
SO_x	3.3108	0.0068
PM	0.4628	0.0342
Pb air	1.282E-04	2.129E-05
Hg air	4.236E-06	5.570E-06
Cd air	3.044E-05	1.007E-06
TCDD Eq. air	3.916E-15	4.855E-13
Pb water	4.735E-04	1.119E-04
Hg water	4.877E-07	1.823E-06
BOD	3.987E-03	6.711E-05
MJ / L	35.6	17.034

*Note: For transfer station purposes, natural gas refers to gas at standard conditions (273 K and 1 atm); collection and transfer vehicles consume liquefied natural gas (LNG) - typically composed of >90% methane and is stored at 113 K. Source: Haight, 2004

[5] Unless otherwise indicated, all parameters are in metric units (i.e., Ton = Metric Ton = 1000 kilograms)

In the WASTED model, the totality of the MSW is assumed to undergo collection and transport processes. After collection, the fractions are sent to a material recovery facility (MRF), an EFW plant, or to a landfill.

2.3.3 Waste Flow

This is one of the simplest submodels in WASTED. In it the user is required to apportion the quantities of waste that are sent to the different waste management processes: material recycling, energy recovery and landfilling.. The user can introduce either the percentage of total waste that goes to each of the aforementioned options, or the user might input the quantity of waste that goes to each process; WASTED will calculate the complementary parameter and will notify the user when the sum of the different waste fractions do not match the total waste calculated in the waste generation submodel.

It is important to mention that the fractions sent for recycling, EFW or landfilling constitute *untreated and unsorted*[6] wastes, directly from collection or from the transfer station. For example, if 1000 tons of waste are sent for material recovery, it does not mean that the 100% of that waste will be recycled or composted – the actual mass of material recovered depends on the efficiency of the recovery processes. WASTED allows the user to then determine the fate of the un-recovered fraction of waste: landfilling or EFW.

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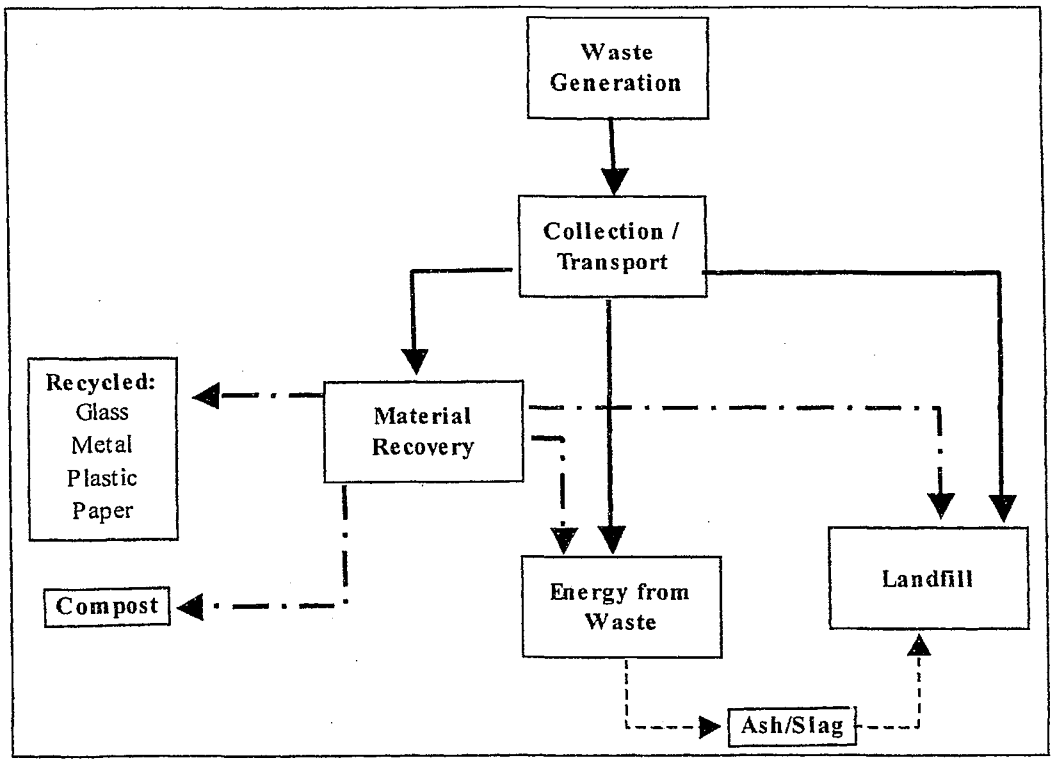
[6] This fractions might be source-separated (in a recycling bin, for example), but do not undergo further separation processes once they enter the system boundaries.

Figure 2.3 Material Flow Diagram



2.3.4 Material Recovery

Other LCAs have determined that, other than source reduction, recycling is the MSW alternative that generates more energy credits and has the largest impact on the reduction of emissions (EPA, 2002); furthermore, paper recycling also increases the sequestration of atmospheric GHG. Therefore, this submodel has special importance for the calculation of emission and energy credits.

In the context of the WASTED model, when a material is recycled, it is used in place of virgin inputs in the manufacturing process. The *avoided energy* parameter is calculated by deducting the energy used to manufacture a product from recycled raw materials from the energy used to manufacture a product from "virgin" raw materials. In some cases, this parameter can be quite significant – for example, recycling aluminum saves approximately 95% of the energy required to smelt aluminum from bauxite (Wang & Pereira). Note that this is not strictly true for the cases that already recycle materials, and therefore energy and emission estimates will not be accurate. In those cases, the user may modify the energy use parameters to allow for an allocation of pre-recycled material in the waste stream.

All the materials considered in this analysis are modeled as being recovered in a "closed loop". In reality, this not the case for all materials. Model reliability is preserved by expanding the system boundaries to include the reduction of energy use and emissions on a per ton basis for each recycled material. These parameters can also be modified by the user to better reflect the situation in a case study.

Recovered materials undergo the following process: first, they arrive at the material recovery facility (MRF). There, they undergo sorting and baling processes to ease their handling. Then, they are sent to a recycling plant or to a composting facility.

The WASTED model calculates the use of utilities in the MRF on a per ton basis. Then, the different material fractions are recovered, and an energy credit or charge is assigned on and individual level. Afterwards, emissions for this process are calculated based on the energy generation profile for the case being studied. A summary of the data is included in each subsection, and a full description of the parameters is included at the end of this section.

The materials covered under this submodel are:

- Metal: Aluminum and steel are the only metal components in the MSW considered to be fit for recycling in the WASTED model. Other metals are not considered to be viable for recovery due to their lack of economic appeal or scarcity in the waste stream. The estimates presented below are intended as average parameters, and include energy use and emissions on a de-localized perspective. In other words, the LCA accounts for the emissions incurred when a raw material has been imported.

    - Aluminum: most of the aluminum in the waste stream comes from beverage cans. From a recycling perspective, aluminum is one of the most attractive materials in the waste stream. This is because recycling aluminum is much less energy intensive than smelting aluminum ore: 17.3 GJ/ton Vs 239.4 GJ/ton (EPA, 2002). Aluminum is also a true closed loop material - it can be melted and used over and over again.

- Steel: The majority of this metal present in the MSW stream is in the form of "tin" cans. Although not as energy efficient as the recycling of aluminum, recycling steel also generates important energy credits. Recycled steel requires 13.7 GJ/ton to be processed, while steel from virgin raw materials requires 36.7 GJ/ton (Ibid).

- Glass: This material comes from food and beverage containers. In the WASTED model this fraction includes both coloured and clear glass bottles. Recycling glass is relatively easy – it merely involves rinsing, crushing and melting the glass containers. However, this is an energy intensive process that takes place at 1800 K (Wang & Pereira). Therefore, the energy use for the recycling of glass is 5 MJ/ton, against 7.5 MJ/ton for virgin raw materials. Glass can also be reused over and over, and can be recycled in a closed loop.

- Paper: Virgin and recycled paper undergo an essentially equivalent process: Paper is composed of cellulose fibres. To separate the fibres and manufacture paper sheets these fibres are made into a pulp. These fibres degrade in the recycling process, so eventually paper can't be reused anymore. Therefore, paper is not a true closed loop material. In WASTED, 4 different kinds of paper are considered for recycling: newspaper, fine paper, cardboard from packaging and mixed paper. This model disregards the (relatively insignificant) forest carbon sequestration of greenhouse gases reported by the EPA (2002).

- Newspaper: this category is essentially self-explanatory, and typically constitutes the majority of the paper that is available for recycling. (Ibid)
- Fine paper: this category is comprised of paper used for printing and photocopying.
- Cardboard: This is the typical material used for packaging. It includes both the smooth and corrugated fractions of this material.
- Mixed paper: This last category describes materials such as tissues and paper cups; it also includes a portion of recycled paper. (Ibid)

- Plastic: Although the technology to recycle most plastics exists, the sorting and preparation processes are complex. Therefore, most localities do not recycle all plastics. Currently, the industry classifies plastics into seven categories: high density polyethylene (HDPE-1), polyethylene terephtalate (PET-2), polyvinyl chloride (PVC-3), low density polyethylene (LDPE-4), polypropylene (PP-5), polystyrene (PS-6) and other plastics (Other-7). In general, the lower numbers are more readily recovered; for example, Toronto only recycles HDPE and PET (City of Toronto, 2003). The WASTE model allows the recycling of all these categories with two differences: HDPE (1) and LDPE (4) are amalgamated under polyethylene. The model doesn't allow for the recycling of "Other" plastics because few locations actually are able to perform this process.

The process of plastic recycling consists of sorting and washing the plastics, and melting them to be reused in new forms. This process is very sensitive to contaminants, and even a few parts of a different plastic can render a whole batch unusable (Vesilind & Rimer). The default fraction of total plastics that is recycled is based on the EPA GHG Inventory (2002), and the suggested individual plastic fractions are adopted from the post-consumer plastic recycling data in Europe (Greenpeace). The sources of plastics in the MSW stream are taken from the EPA MSW Handbook (1996).

- Polyethylene: This is one of the most widely used polymers. Its low density forms are used for wrapping, plastic bags and packaging; the high density polymers are used in bottles, containers and toys.
- Polyethylene Terephtalate: This plastic is impermeable to gases, and is therefore mostly used as a container for carbonated beverages.
- Polystyrene: As part of the MSW, this material is present in the form of containers used to insulate foods such as coffee cups, or as insulating household material.
- Polypropylene: This material is also used as in containers such as syrup bottles and yogurt tubs, and is also found in disposable diapers.
- Polyvinyl Chloride: This majority of this material comes from disposed plastic pipes. Other sources are oil bottles and meat wrapping. Recycling PVC is difficult, since this material contains significant amounts of plasticizers, fillers and additives (Greenpeace).

Table 2.2 Recycling Parameters for Metals and Glass

	Aluminium		Ferrous Metal		Glass	
Kg/Ton	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Energy (GJ)	140.00	11.70	25.20	9.43	14.10	9.23
CO_2	2900.00	4.36	1820.00	595.00	632.00	278.00
PFC (CO_2eq)	2226.00	0.00	0.00	0.00	0.00	0.00
CH_4	6.53	2.71	0.0097	1.29	1.11	0.83
NO_x	17.30	0.62	2.76	1.77	2.73	1.69
VOCs	24.50	0.30	0.23	0.02	0.24	0.17
SO_x	47.60	2.88	5.11	2.98	4.37	3.11
PM	10.00	0.00	1.31	7.22	0.89	0.43
Pb	1.93E-03	3.80E-01	7.60E-04	6.59E-04	5.01E-06	1.15E-06
Hg	na	na	na	na	1.30E-06	3.00E-07
Cd	na	4.37E-05	na	na	1.35E-05	2.95E-06
HCl	8.10E-01	5.81E+02	8.57E-02	1.01E-01	5.96E-02	9.75E-01
TCDD Eq.	na	na	na	na	na	na
Pb Water	1.47E-07	na	2.92E-02	2.90E-02	3.60E-08	1.90E-08
Hg Water	na	na	na	na	2.55E-08	1.95E-08
Cd Water	2.40E-01	6.00E-02	9.75E-05	9.38E-05	2.20E-04	2.55E-04
TCDD Eq. W	1.20E-06	4.42E-08	na	na	na	na
BOD	na	na	na	na	0.0069	0.0051

Source: Torrie Smith and Associates, as cited by Haight, 2004

Table 2.3 Recycling Parameters for Paper Products

	Newspaper		Fine Paper		Corrugated Board		Mixed Paper	
Kg/Ton	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Energy (GJ)	46.43	25.57	43.05	23.40	29.23	13.64	36.85	26.21
CO_2	2404.00	1385.00	1100.00	1507.00	896.00	1019.00	1304.00	1752.00
CO_2 seq.	0.00	-3060.00	0.00	-4580.00	0.00	-4580.00	0.00	-4580.00
CH_4	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.01
NO_x	10.40	5.26	8.74	5.38	6.25	5.56	7.94	5.44
VOCs	11.20	7.19	8.27	18.47	3.87	35.40	6.86	23.89
SO_x	16.30	9.40	12.88	9.80	7.74	10.40	11.23	9.99
PM	4.63	2.80	4.81	3.10	5.07	3.56	4.89	3.25
Pb	4.52E-04	2.63E-04	3.52E-04	2.67E-04	2.03E-04	2.73E-04	3.05E-04	2.69E-04
Hg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HCl	0.00E+00	3.87E-06	3.57E-06	4.51E-06	8.93E-06	5.46E-06	5.29E-06	4.81E-06
TCDD Eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pb Water	1.63E-07	6.35E-08	1.46E-07	6.59E-08	1.20E-07	6.95E-08	1.38E-07	6.71E-08
Hg Water	3.82E-08	2.33E-08	2.69E-08	1.40E-08	9.92E-09	0.00E+00	2.15E-08	9.51E-09
Cd Water	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TCDD Eq. W	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
BOD	3.51	3.09	2.71	3.29	1.52	3.58	2.33	3.38

Source: Torrie Smith and Associates, as cited by Haight, 2004, except Energy and CO_2 sequestration (EPA, 2002)

Table 2.4 Recycling Parameters for Plastic Products

	PET		PE		PP		PS		PVC	
Kg/ton	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Energy GJ	107.15	46.07	79.76	19.94	76.42	19.87	84.8	11.63	59.8	9.13
CO_2	2363	163	2400	163	2100	942	2200	942	2000	942
CH_4	25	0.0157	28	0.0157	28	0.0157	24	0.0157	22	0.0157
NO_x	9.5	0.0805	6.5	0.0805	6.4	0.0805	6.9	0.0805	6.3	0.0805
VOCs	7.2	6.95	7.8	6.95	7.7	6.95	5.9	6.95	5.8	6.95
SO_2	14	NA	4.9	NA	5.4	NA	5.2	NA	5.3	NA
PM	4.6	NA	1.5	NA	1.7	NA	2.4	NA	1.4	NA
Pb	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hg	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cd	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
HCl	0.0577	NA	0.011	NA	0.0104	NA	0.0143	NA	0.016	NA
TCDD Eq	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pb Water	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hg Water	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cd Water	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TCDD W	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BOD	2	NA	0.25	NA	0.083	NA	0.097	NA	0.29	NA

Source: Torrie Smith and Associates, as cited by Haight, 2004, except Energy (EPA, 2002; Eulalio, 2001)

2.3.5 Composting

The organic fraction of recovered waste is considered to be composted. This process consists of the aerobic degradation of wastes to produce compost, a natural fertilizer.

There are three basic types of composting: windrow, reactor and backyard composting. The former two are centralized processes, while the latter is done as part of household waste management. Wastes treated by backyard composting don't really enter the municipal solid waste stream, and are therefore excluded from the WASTED model.

Composting has several environmental advantages over landfilling. In first place, when done properly composting generates no methane (CH_4). This gas is produced by anaerobic degradation of wastes (for example, in a landfill), and has 21 times the greenhouse potential of CO_2. Furthermore, mature compost can be used as a fertilizer and does not generate long term environmental concerns. Finally, the aerobic degradation of organic compounds results in the "storage" of a small amount of carbon that is not degraded to CO_2, but transformed into slowly decomposable components. The EPA reports a lower bound of approximately 0.03 tons of carbon equivalent (CE) per ton of composted waste (EPA, 2003).

WASTED allows for the evaluation of windrow and reactor composting processes. The following assumptions are used in the compost model:

- The compost is well aerated during the whole process
- The compost is allowed to mature
- Humidity level of 50% is maintained
- CH_4 is not generated (However, the user may adjust this parameter)
- The resulting compost does not contain heavy metals

Windrow composting consists of laying the wastes into long, relatively narrow strips of waste called windrows. These are kept moist and at an optimal nutrient concentration (a C-N ratio of 30:1, Baky & Eriksson, 2003). Energy use comes from the machinery used to overturn the windrows to maintain aeration.

Reactor composting is done inside a vessel. It is more energy-intensive than windrow composting. However, it allows for cleanup of flue gases, and allows composting in cold weather or where vermin might be problematic. The following parameters are used for the compost submodel:

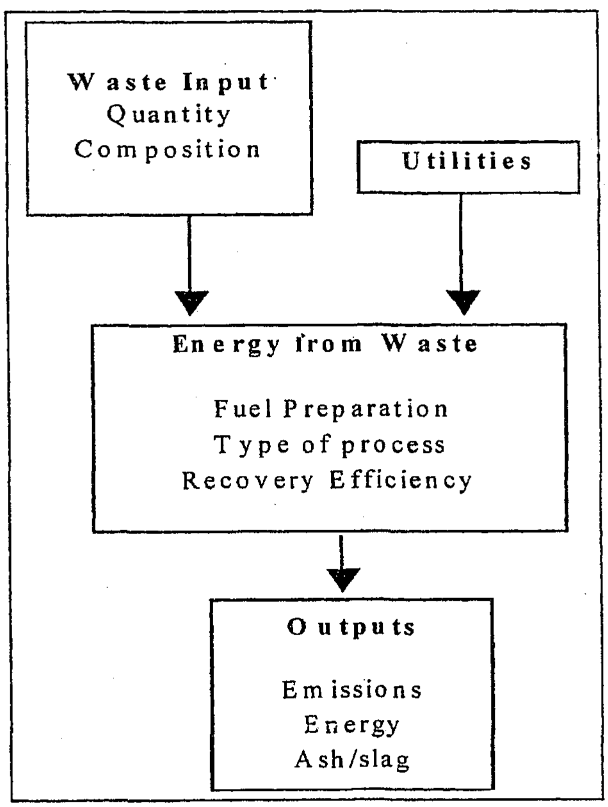
Table 2.5 Composting Parameters

Parameter	Amount	Unit	Source
Degradable Organic Carbon	35	%	Woodrising Inc, 1999
Conversion	400	kg/ton waste	Woodrising Inc, 1999
Residue	5	% total waste	Baky & Eriksson, 2003
Carbon Storage	0.183	Ton CO2/ton waste	EPA, 2002
NH3 Emissions	0.38	kg/ton waste	Baky & Eriksson, 2003
VOC Emissions	1.7	kg/ton waste	Baky & Eriksson, 2003
CH4 Emissions	0	% total DOC	EPA, 2002
Open windrow compost			Baky & Eriksson, 2003
Electricity consumption	0	MJ/kg waste	Ibid
Diesel consumption	0.00151	MJ/kg waste	Ibid
Compost gas cleaning	No		Ibid
Reduction of NH_3	0	%	Ibid
Reduction of NO_x	0	%	Ibid
Reduction of CH_4	0	%	Ibid
Reactor compost			Baky & Eriksson, 2003
Electricity consumption	0.1801	MJ/kg waste	Ibid
Diesel consumption	0.07551	MJ/kg waste	Ibid
Compost gas cleaning	Yes		Ibid
Reduction of NH_3	99.1	%	Ibid
Reduction of NO_x	90	%	Ibid
Reduction of CH_4	50	%	Ibid

2.3.6 Energy From Waste

Energy from waste (EFW) is the process to recover energy from the combustible fractions in the MSW. Wastes can provide significant amounts of energy: from 11 MJ/kg (EPA, 2002) for mixed wastes to the much higher calorific values of 33 MJ/kg for certain plastic fractions (Hall & Overend, 1987). Waste-to-energy (WTE) projects have been developed to recover the energy contained in wastes in forms of heat or electricity: Porteus (1998) estimates that around 500 kWh of electrical power is wasted with each ton of MSW that goes to a landfill.

Figure 2.4 EFW Model Diagram



The WASTED EFW submodel consists of four parts: fuel characterization, utility use, energy recovery and emission estimation:

- Fuel Characterization: The WASTED model calculates the composition of untreated MSW and its energy content. It may include the fractions of waste remaining after recycling/composting, if indicated by the user. Additionally, the user might also opt to treat the MSW as refuse-derived fuel (RDF). This results in a higher energy content per ton, but increases the utility use. The RDF characteristics are based on the European Commission RDF Study (Grendebien et al, 2003). Alternatively, the user might also supply specific data.

- Utility Use: Electricity is used for the preparation of wastes to be combusted. For "untreated" MSW, 14.5 MJ/ton are needed (Baky & Eriksson, 2003). When RDF is used, this value raises to 88.9 MJ/ton (Caputo & Pelagge, 2002). The electricity required for the operation of the plant is included in the overall energy efficiency of the process.

- Energy Recovery: WASTED calculates the amount of power generated by the EFW process - resulting in energy credits. The overall efficiency depends on the type of WTE facility[7] (incineration or gasification), and the type of energy recovery technology (either electricity, or power and heat recovery). Parameters for this section have been adopted from the Danish EPA's incineration model

[7] In WASTED, the typical incinerator is considered to recover energy through a steam cycle. These systems have a net electrical efficiency of around 23%. Waste gasification recovery is done through a gas turbine (Belgiorno et al). These parameters include losses in the electrical grid (EPA, 2002).

(Baky & Erikssson, 2003), and from waste gasification model parameters (Belgiorno et al, 2003). The user might also supply site-specific data.

- Emission Estimation: WASTED calculates the air emissions derived from direct combustion of the wastes. Emissions are based on the parameters described by both the Danish (Baky & Eriksson, 2003) and the US EPA (2000). Further data on the ratio of excess air used (necessary to calculate the dilution factors) were taken from Porteus (1998) and from Johnke et al (2000). Emissions from the EFW process are deducted from any credits resulting from the avoided emissions due to energy credits. CO_2 emissions are factored from material balances (carbon content, as reported in the Danish GHG Projections (2003)). In the case of CO_2 emissions, only those from non-biogenic sources are accounted (such as plastics). CO_2 generated from the combustion of organics is considered to be "carbon neutral".[8]

[8] When combustion of items such as wood takes place, the carbon dioxide emissions are considered to be equal to the atmospheric CO_2 that was "stored" into the material. Therefore, they don't count as GHG. In contrast, plastic is made from non-biogenic carbon sources (oil). These carbon fractions weren't part of the atmosphere and so must be accounted as emissions.

Table 2.6 Energy from Waste Parameters

Carbon Content	Amount	Units	Source
Organic	20	%	Fenham et al, 2003
Paper	40	%	Ibid
Plastic	85	%	Ibid
Heat Values	**Amount**	**Units**	**Source**
Organic	16	MJ/kg	Hall & Overend, 1987
Paper	17.5	MJ/kg	Ibid
Plastic	33.5	MJ/kg	Ibid
Performance Parameters	**Amount**	**Units**	**Source**
Utilities			
MSW feed	4.03	kWh/ton	Baky & Eriksson, 2003
RDF feed	88.89	kWh/ton	Caputo & Pelagge, 2002
Power Generation	**Amount**	**Units**	**Source**
Efficiency	20%	Incineration	Belgiorno et al, 2003
Efficiency	35%	Gasification	Ibid
Power + Heat	**Amount**	**Units**	**Source**
Efficiency	70%	Incineration	Baky & Eriksson, 2003
Efficiency	75%	Gasification	Ibid
Emissions	**mg/m3**	**g/Ton**	**Source**
HCl	62.00	341.00	EPA, 2000
NOx	388.00	2134.00	Ibid
VOCs	5.00	27.50	Ibid
SOx	20.00	110.00	Ibid
PM	70.00	385.00	Ibid
Pb	0.00	0.02	Ibid
Cd	0.04	0.22	Ibid
Hg	0.47	2.59	Ibid
TCDD Eq. (ng)	0.41	2255.00	Ibid
Air balance	5640	m^3/ton waste	Ibid

2.3.7 Landfill

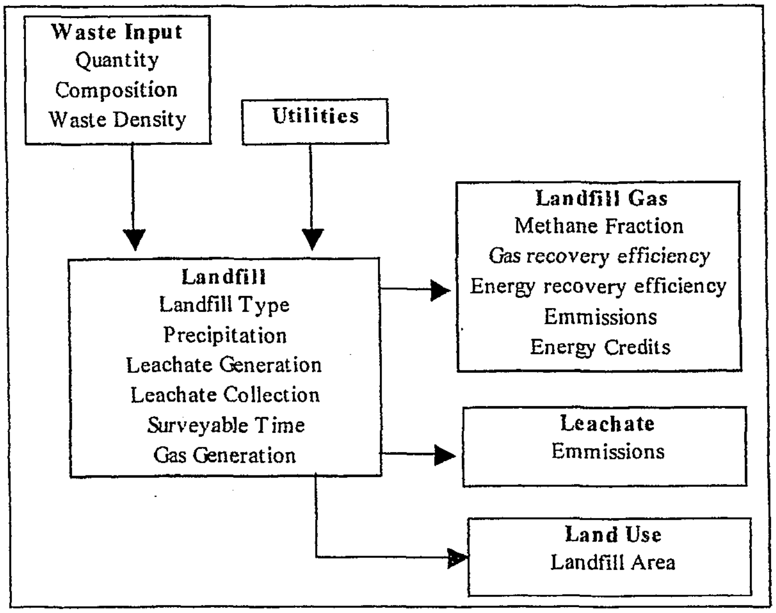
Ideally, sanitary landfills are facilities that constitute the final resting place of wastes that are irrecoverable. According to the American Society of Civil Engineers are:

> "a method of disposing [wastes] on land without creating nuisance or hazard to public or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical volume" (ASCE, 1959)

It should be stressed that that modern engineered landfills are not dumps, they are planned facilities that are destined to provide proper disposal for wastes that can't be recovered. Landfilling is the last step in the integrated waste management plan. Although the ideal case is that 100% of every good produced is re-introduced to the production cycle, it is thermodynamically impossible. Therefore waste disposal facilities are still required.

Pollution from landfill occurs in three forms: loss of land as a resource, emissions to atmosphere from landfill gas (LFG) and/or LFG combustion, and emissions to water in form of leachate. WASTED estimates these emissions, and tallies them with the emissions from utility use in landfill generation and the avoided emission credits if landfill gas is collected for energy recovery.

Figure 2.5 Landfill Submodel



The landfill submodels starts with the waste characterization. This is done by a MFA of the different waste fractions that are destined for landfilling. They include residues from recycling and composting, as well as ashes or slag from the EFW process. These materials are compacted in order to minimize the landfill area.

WASTED allows for four different kind of landfills:

1. Sanitary Landfill: This is the typical landfill used in the US and other parts of the world. It consists of layers of waste separated with a "daily" material cover to prevent scavenging by vermin, and includes bottom liners and a leachate collection system (EPA, 1996). Upon closure, these

landfills are covered with impermeable covers to minimize water infiltration (and the subsequent leachate generation). In general, the design objective of this type landfill is to insure the "inertness" of the contents by keeping them as dry and isolated from the exterior as possible.

2. Bioreactor landfill: In contrast with the typical sanitary landfill, the purpose of the bioreactor landfill is to promote a rapid degradation of the organic fraction of wastes. This is done by circulating water (and sometimes nutrients and other additives) to promote the optimum conditions for either aerobic or anaerobic degradation. Bioreactor landfills normally have higher LFG collection efficiencies than typical landfills.[9]

3. Unlined landfill with leachate collection: This type of system is rare, but occurs when a landfill is retro-fitted with leachate collection systems. Alternatively, a landfill is also consider to belong to this category when it has no cover (because it is an active landfill cell) or when the top liner has been so deteriorated that its effects are considered negligible.

4. Unlined landfill with no leachate collection: This type of landfill has little or no engineering. It basically consists of a "convenient" place to dump wastes. It offers no energy recovery or pollution containment. In certain

[9] The amount of LFG is determined by the nature of the wastes stored in it – the carbon content determines the total gaseous emissions either in the form of CO_2 or CH_4. In a LCA the speed with which the gas is generated (reaction kinetics) is irrelevant - *all* the emissions must be accounted, regardless of when they take place. In this context, the main difference between a typical landfill and a bioreactor is their gas collection efficiency.

aspects, this option can prove worse than letting households deal with their own wastes.[10]

Irrespective of the type of landfill, leachate is generated when precipitation infiltrates into the waste. The kinetics for the generation of leachate are quite complicated, and have been described extensively in the EPA's HELP model. In WASTED, a simplified approach is used. The adopted model is similar to the one adopted by the Danish EPA (Baky & Eriksson, 2003):

- Leachate generation is directly proportional to the precipitation in the study locale and the area of the landfill. WASTED includes a database for the precipitation in some representative cities, but this list is by no means exhaustive[11]. The amount of precipitation that infiltrates to form leachate depends on the type and quality of the landfill cover (Ecobalance, 2003). Inorganic pollutants exit the landfill in the leachate during the *surveyable time.*
- Greenhouse gas emissions are based on the IPCC guidelines for GHG inventories (1996). These guidelines estimate the percentage of degradable organic carbon (DOC) contained in the different fractions of the waste stream. These parameters are used as baselines for carbon emissions.
- Gas collection efficiency depends on the type of landfill. The data were adopted from the Danish EPA (Baky & Eriksson, 2003) and the US EPA (2002) reports.

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[10] When organic wastes are degraded anaerobically in a landfill, they produce methane. This gas is 21 times more potent as a GHG than CO_2, the typical product from aerobic degradation. (EPA, 2002). Furthermore, these dumps often constitute sources of pollutants or fire-hazards to the nearby localities.
[11] Precipitation data was obtained from the average precipitations reported by World Climate (2003)

- Collected gas can be combusted with or without energy recovery. This transforms methane into carbon dioxide. The energy content in the LFG depends on the fraction of CH_4 (EPA, 2002). The energy recovery efficiency from LFG was reported to be 30% (Baky & Eriksson, 2003).
- Pollutants in leachate are difficult to estimate. "Average" parameters were adopted (Lee et al,1994; Warith, M, 2002), but this set can vary widely from location to location. Other parameters evaluated are the differences between the leachate from a bioreactor and a typical landfill (Yolo County, 2000).
- Emissions from LFG were adopted from Hodgson et al. Parameter for emissions from LFG *after* flaring were obtained in the Danish EPA report (Baky & Eriksson).

Table 2.7 Landfill Parameters[12]

Typical Landfill	Parameter	Units	Reference
Leachate Generation	5	% Precipitation	ECOBALANCE, 2003
Leachate Collection Efficiency	99.8	% Leachate Gen.	Ibid
Gas Collection Efficiency	50	%	Baky & Eriksson, 2003
Bioreactor Landfill			
Leachate Generation	5	% Precipitation	ECOBALANCE, 2003
Leachate Collection Efficiency	99	% Leachate Gen.	Ibid
Gas Collection Efficiency	65	%	Baky & Eriksson, 2003
Unlined Landfill w. Leachate coll.			
Leachate Generation	60	% Precipitation	ECOBALANCE, 2003
Leachate Collection Efficiency	30	% Leachate Gen.	2003
Gas Collection Efficiency	0	%	Baky & Eriksson, 2003
Bioreactor Landfill			
Leachate Generation	60	% Precipitation	ECOBALANCE, 2003
Leachate Collection Efficiency	0	% Leachate Gen.	ibid
Gas Collection Efficiency	0	%	Baky & Eriksson, 2003
Leachate Characteristics			
BOD	10500	mg/l	Lee et al, 1994; Warith, M, 2002; Yolo Cty. 2000
COD	15000	mg/l	Ibid
Pb	0.063	mg/l	Ibid
Cd	0.05	mg/l	Ibid
Hg	0.0006	mg/l	Ibid
NH_3	1000	mg/l	Ibid
Aromatics	200	mg/l	Ibid
Landfill Gas			
Methane content	50	% total LFG	EPA, 2002
Energy content	51	GJ/ton CH_4	EPA, 2002
CO_2 content	(100 - CH4)	%	
VOCs	2420	mg/m^3	Hodgson et al, 1992
H_2S	35	mg/m^3	Ibid
Landfill Gas Combustion			
CH_4	430	mg/MJ	Baky & Eriksson, 2003
NO_x	100	mg/MJ	Ibid
VOCs	4	mg/MJ	Ibid
SO_x	0	mg/MJ	Ibid
PM	0	mg/MJ	Ibid

[12] As with all other parameters in the model, leachate parameters are based on publicly-available studies. However, they vary widely from site to site. Appendix C presents other landfill parameters, including typical value ranges.

2.4 Energy Sources And Compensatory Systems

In order to preserve the accuracy of the model certain parameters must be included to make different systems equivalent. This is the purpose of the compensatory system: to "internalize" effects that affect the LCA but are not necessarily directly related to the solid waste management system.

There are two types of compensatory systems: upstream and downstream. Both are included in the WASTED model.

- Upstream: This system calculates the effects of raw material extraction, refining and related effects which are *avoided* when a material is recycled. In the wasted model, this consists of utility credits.[13]
- Downstream: This system calculates the effects of the generation of useable energy as part of the MSW management system. This energy *replaces* utilities that would be generated in some other manner; for example, by the combustion of fossil fuels.

Both the upstream and downstream systems depend heavily on "regular" sources of energy. If these sources are environmentally friendly, EFW strategies might not be

[13] The production of certain raw materials may generate pollutants – i.e. the smelting of aluminium generates CF_4, a perfluorocarbon. These gases are important because of their high global warming potential. These are included in the compensatory system for recycling.

advantageous. Therefore, it is essential to describe accurately the power generation scheme for the studied site[14].

2.4.1 Emissions From Utilities

The MSW management processes invariably consume energy. This energy is provided in the form of electricity or fossil fuels such as diesel or gas. This section will discuss the model used by WASTED to estimate the emissions from the fossil fuels used in the MSW management processes. The emissions generated from electric power use are calculated as described in the Power Generation Emissions section of this document.

Each submodel in WASTED calculates the amount of diesel and gas used. The transport model includes the fuels used during waste collection and all the different waste transfer operations (for example, transporting ashes from the EFW facility to the landfill site). Then, emission parameters are used to estimate the pollutants released.

[14] During the presentation of this thesis it was noted that describing the power generation scheme for a particular site may prove exceedingly difficult, especially in areas where there is energy trade across jurisdictions.

Table 2.8 Emissions from Utilities

Emissions (g/L)	Diesel	Gas (Vehicles)	Gas (facilities)	Source
CO2	3018.8800	994.9724	47.6633	(1)
CO	0.0103	2.3928	0.1146	(1)
CH4	3.6312	8.1828	0.3920	(1)
NOx	21.2140	14.3620	0.6880	(1)
VOCs	9.3272	0.2762	0.0132	(1)
SOx	5.7494	0.3305	0.0158	(1)
PM	1.6839	0.2488	0.0119	(1)
Pb air	1.282E-04	2.129E-05	1.020E-06	(2)
Hg air	4.236E-06	5.570E-06	2.668E-07	(2)
Cd air	3.044E-05	1.007E-06	4.823E-08	(2)
TCDD Eq air	3.916E-15	4.855E-13	2.326E-14	(2)
Pb water	4.735E-04	1.119E-04	5.361E-06	(2)
Hg water	4.877E-07	1.823E-06	8.731E-08	(2)
Cd water	5.126E-05	1.455E-06	6.969E-08	(2)
BOD	3.987E-03	6.711E-05	3.215E-06	(2)
MJ/L	35.6	17.034	0.816	(1)

Sources: (1) Baky & Eriksson;. (2) Pira Intl., 1996, as cited by Haight, 2004.
Note: Gas in Vehicles corresponds to liquefied natural gas (-260° C). Gas in facilities is at 0 °C and 1 atm.

2.4.2 Power Generation Emissions

WASTED includes a database of national power generation profiles. It provides information on the contribution of different power sources to the total, in a given country. The data were obtained from the International Energy Agency (2001).

In the EPA Greenhouse Gas LCA (2002) the upstream compensatory systems are evaluated considering fossil fuels as the sole source of energy for power generation - a "worst case" scenario. However, the WASTED model considers more representative to use the national average to calculate the avoided emissions from recycling and energy recovery.

The five sources of energy for electric power generation are:

- Coal: This classification includes all types of coal used to generate power.
- Oil: This category contains both heavy and light diesel fuels, and other types of combustible liquids.
- Gas: This fraction refers to the electricity generated from the combustion of natural gas (methane).
- Nuclear: Power generated by nuclear fission in dedicated generating facilities.
- Hydroelectric: "Green" power from water turbines that results in negligible emissions.
- Other: Other sources are not considered for the WASTED model, but the user may input a general emission rate for overall power generation.

The emission credits from recycling, EFW or LFG combustion are calculated by multiplying the energy credits generated by the emission factors from the specific fuel mix used to generate electricity. These parameters are included in the next table.

Table 2.9 Emissions from power generation per fuel type

Kg / KWh	Coal	Oil	Gas*	Nuclear	Hydro
CO_2 (1)	1.1218E+00	1.0948E+00	4.5400E-01*	5.4832E-03**	0.0000E+00
CH_4 (1)	5.4594E-04	6.8243E-05	4.0946E-04*	0.0000E+00	0.0000E+00
NO_x (1)	2.1643E-03	4.8088E-03	2.5000E-04*	3.6000E-05	1.6704E-05
SO_x (1)	5.0824E-03	3.2107E-03	2.5000E-05*	6.4440E-05	1.1988E-05
HCl (2)	2.9844E-04	1.2132E-05	1.6920E-06	9.3600E-07	3.3480E-07
PM (1)	2.2863E-04	4.9799E-04	7.0000E-06*	1.3824E-05	2.4516E-04
VOCs (1)	1.3356E-04	2.1420E-03	1.7136E-04	8.4600E-05	3.9240E-06
Pb (2)	1.9800E-07	5.4000E-07	1.6200E-08	4.3200E-09	3.9600E-09
Hg (2)	3.9600E-08	3.0960E-09	3.1680E-09	1.6920E-10	1.3320E-10
Cd (2)	5.7600E-08	5.7600E-08	8.2800E-10	3.1680E-10	2.4120E-10
TCDD (2)	5.0400E-14	1.1880E-15	7.9200E-16	1.9080E-16	6.1200E-17
Pb water (2)	4.9680E-06	1.4760E-07	5.4000E-07	5.0400E-07	2.4840E-08
Hg water (2)	1.4040E-09	1.7640E-10	7.9200E-10	1.4040E-11	2.0160E-12
Cd water(2)	5.0400E-08	1.5480E-08	5.4000E-09	2.6280E-05	1.7640E-10
BOD (2)	1.5840E-07	6.1200E-07	4.6800E-08	4.3200E-08	3.1320E-09

Sources: (1) OTPCO, 2003
(2) Haight, 2004, except: * Northwest Power, 2002; ** EPA, 2002

Once the user provides the data for the electric grid, WASTED will estimate the total energy use and emissions, grouped by source (collection & transport, landfill and such), and will also calculate the total amount of each pollutant generated by class (air, water). When emission or energy credits exist, WASTED presents the result as *negative* numbers. These results are presented in an Excel sheet once the user has provided all the data for the simulation.

2.5 Differences between WASTED and other LCA models

As mentioned in the project introduction, WASTED is not the first life-cycle assessment model designed to estimate the impact of MSW management. It was designed to circumvent the perceived shortcomings of other publicly-available LCA models, following two basic premises: ease of use and adaptability. These two premises are kept by using widespread software with an easy-to-use interface (Excel and Visual Basic, instead of the more specialized Matbal used in ORWARE), allowing the user to modify almost all parameters (unlike ISWM), and by generating diverse environmental indicators instead of focusing in one or two (such as WARM's devotion to GHG). While we don't believe the model is perfect, we think it is a useful tool for analyzing WM systems – both as a screening tool or for in-depth analyses of different MSW management alternatives.

3. MODEL COMPARISON AND EVALUATION OF WM ALTERNATIVES

3.1Introduction

Life-cycle assessment is being increasingly used to quantify the environmental impacts of MSW decisions. Different tools have been developed to perform these analyses. This chapter will compare WASTED to other software tools in order to determine the similarities and differences between them.

Ideally, to evaluate the validity of WASTED it would be necessary to compare the results from the model to data obtained from field studies. In practice this is difficult, since data are difficult to obtain on a consistent basis and often consist of extrapolations from either laboratory tests or short-term field experiments. Instead, WASTED will be compared to other models: EPA's WARM model and the IWM model developed by EPIC-CSR.

This chapter also includes a sensitivity analysis. This type of analysis not only illustrates the relative contributions of each solid waste unit operation to the total life-cycle inventory for the selected scenarios, but also helps the researcher determine areas of opportunity to improve the model *and* to the MSW management system.

3.2 Greenhouse Gas Generation from MSW in the City of Toronto.

Toronto is the largest city in Canada. As of 2001, its population was tallied at 2,481,500 inhabitants (City of Toronto, 2003b). Garbage generation was determined at 355 kg/year (Toronto Community Foundation, 2003). Approximately 28% of total waste was diverted from landfilling (Ibid).

The waste management situation for Toronto is quite complicated since the closure of the Keele Valley Landfill in December 2002. Since then, the city made an agreement to ship Toronto's garbage to the Carleton Farms Landfill in Sumpter, Michigan. Although it is widely acknowledged that this is hardly the optimal solution, other alternatives have met with much resistance.

Toronto currently employs separate collection methods for recyclables, garbage and yard waste. It is estimated that the inhabitants of Toronto generate an average of 355 kg of refuse per year – much lower than the 630 kg/y reported by the OECD (1999). The reason for this discrepancy is that the OECD data include all sources of waste, while the City of Toronto only reports the household waste collected. This study will use the data reported by the City of Toronto, since it also includes a complete description of the waste fractions and an estimate of the population growth.

Table 3.1 Waste Generation Data for Toronto (2001-2021)

	2001	2021	Avg. Pop.
Population *	2,594,000.00	2,915,000.00	2,754,500.00

Waste Gen.	355	kg/year
Composition	Fraction	Total Tons
Organic	33%	6,453,793.50
Paper	38%	7,431,641.00
Plastic	8%	1,564,556.00
Metal	3%	586,708.50
Glass	6%	1,173,417.00
Other	12%	2,346,834.00
Total	100%	19,556,950.00

Source City of Toronto, 2001; * Population growth source: City of Toronto, 2003b

The city of Toronto also has performed an analysis of the nature of the refuse generated by households. In the 2000/2001, the City of Toronto performed a waste composition study consisting of the manual sorting of the waste materials by weight. The results of this study are included in table 3.2, extrapolating the data for the forecasted population and waste generation presented in table 3.1

Table 3.2 Waste Characterization Data for Toronto

	Fraction	Total	Recovered	Rec. %	Landfilled
Newspaper	16.030%	3,134,979	2,570,683	82.00%	564,296
Fine paper	5.110%	999,360	325,634	32.58%	673,726
Cardboard	4.520%	883,974	683,877	77.36%	200,097
Mixed Paper	11.980%	2,342,923	1,007,457	43.00%	1,335,466
Glass	6.000%	1,173,417	555,026	47.30%	618,391
Ferrous metal	1.570%	307,044	177,545	57.82%	129,499
Aluminium	0.550%	107,563	54,252	50.44%	53,311
Other metal	1.110%	217,082	0	0.00%	217,082
PET	1.170%	228,816	146,442	64.00%	82,374
HDPE	0.610%	119,297	67,527	56.60%	51,771
LDPE	2.690%	526,082	0	0.00%	526,082
PP	0.150%	29,335	0	0.00%	29,335
PS	0.720%	140,810	0	0.00%	140,810
PVC	0.110%	21,513	0	0.00%	21,513
Other plastics	2.760%	539,772	0	0.00%	539,772
Organics	32.000%	6,258,224	1,905,160	30.44%	4,353,064
Others	12.920%	2,526,758	0	0.00%	2,526,758
Total	100.000%	19,556,950	7,493,603	38.32%	12,063,347

Source: City of Toronto 2001

Besides waste generation and characterization data, there are more parameters needed to estimate the emissions generated from the management of wastes. These parameters include waste collection and transportation distances, recycled material content in raw materials, etc. All the data required for the simulations is not readily available – individual model's default data is used in these cases. A list of the data available is presented in the next table. These parameters were introduced to the models to generate the emission information for the case study. For the analysis of the results, no model outputs are assumed to be "valid" –the comparison will focus on the general tendencies , since the models differ in the system boundaries they have adopted.

Table 3.3 Simulation parameters for Waste Management in the City of Toronto

Parameters	Units	Source
Collection and Transportation		
Avg. Collection Route (km)	25	Baky & Eriksson
TS to Landfill (km)	420	Kurth, 2002
Power Generation in Ontario		
Hydro	24%	
Nuclear	45%	TSA, 2003 cited by Haight, 2004.
Coal	21%	
Gas	10%	
Oil	0%	
Total	100%	
Landfilling		
Pr[illegible]tion	824 mm/y	World Climate Organization
[illegible]e	Engineered/Dry	Landfill Energy Systems
[illegible]ery	Yes	
L[illegible]covery	Yes	
[illegible]e Collection	Yes	
Landfill Sequestration	Yes	
Compost	Per individual model defaults	
Recycling	Per individual model defaults	
EFW	N/A. Toronto does not incinerate wastes.	

3.3 Simulation Results

3.3.1 WARM

The EPA's Waste Reduction Model requires only the data for waste generation, characterization and recovery rates (either by recycling or composting). It also allows the user to input the waste collection and transfer distances. At this time, it only estimates the emission of greenhouse gases to the atmosphere as well as the energy budget for the MSW management processes. This specialization makes it less versatile than the other two models. Unlike the other two models, the WARM model estimates GHG generation using landfilling (without CO_2) sequestration as the baseline. The election of this system boundary generates emissions credits for all the waste management operations. Table 3.4 presents the results from WARM.

3.3.2 ISWM

The Integrated Solid Waste Management Model developed by CSR/EPIC uses a life-cycle approach to estimate a variety of environmental indicators.

The ISWM model uses the IPCC conventions for CO_2 emissions, meaning that emissions derived from biogenic[15] sources are not counted. Therefore, CO_2 emitted from compost and landfill would not be counted. However, CH_4 is counted since methane is considered the result of a human activity (IPCC, 1996). EFW emissions are separated according to their origin: plastic is non-biogenic, while the rest of CO_2 sources are considered CO_2 neutral. However, material recycling and landfilling in this model start from a "zero burden[16]" perspective. This has a deep impact on the way this model performs LCA and it will be analyzed in the next section. Table 3.5 presents the results from the ISWM model

3.3.3 WASTED

The Waste Analysis Software Tool for Environmental Decisions also uses a life-cycle approach to estimate emissions. It includes separate entries for biogenic and non-biogenic CO_2 sources. Therefore, it presents both the actual CO_2 emissions from each of

[15] Biogenic sources are renewable, "carbon-neutral" CO_2 generators. Examples are paper, yard and food wastes.
[16] "zero burden" perspective considers the materials that enter the LCA as they are, with no associated burdens or credits. This contrasts with the WARM model that establishes landfilling as the starting point for study.

the MSW management processes and the changes in carbon dioxide inventory as per the IPCC guidelines. The results are presented on Table 3.6

Table 3.4 WARM model results

Material	Baseline Generation of Material (Tons)	Projected Recycling (Tons)	Annual GHG Emissions from Recycling (MTCO$_2$E)	Projected Landfilling (Tons)	Annual GHG Emissions from Landfilling (MTCO$_2$E)	Projected Composting (Tons)	Annual GHG Emissions from Composting (MTCO$_2$E)	Total Annual GHG Emissions (MTCO$_2$E)
Aluminium Cans	118,462	59,749	-878,352	58,713	14,233	NA	NA	-864,119
Steel Cans	338,154	195,534	-351,639	142,620	34,575	NA	NA	-317,065
Glass	1,292,309	611,262	-173,321	681,047	165,102	NA	NA	-8,219
HDPE	131,385	74,369	-104,789	57,016	13,822	NA	NA	-90,967
LDPE	579,385	0	0	579,385	140,457	NA	NA	140,457
PET	252,000	161,280	-251,130	90,720	21,993	NA	NA	-229,138
Corrugated Cardboard	973,540	753,168	-1,959,481	220,372	-78,924	NA	NA	-2,038,405
Newspaper	3,452,620	2,831,149	-9,865,573	621,472	-600,458	NA	NA	-10,466,031
Office Paper	1,100,617	358,628	-892,093	741,989	435,193	NA	NA	-456,900
Mixed Paper, Broad	2,580,311	1,109,534	-2,743,555	1,470,777	-503,813	NA	NA	-3,247,368
Mixed Metals	239,077	0	0	239,077	57,958	NA	NA	57,958
Mixed Plastics	805,540	0	0	805,540	195,282	NA	NA	195,282
Mixed Recyclables	0	0	0	0	0	NA	NA	0
Mixed Organics	6,892,317	NA	NA	4,794,123	-574,555	2,098,194	-424,566	-999,121
Mixed MSW	2,782,773	0	NA	2,782,773	-11,379	NA	NA	-11,379
Total	21,538,491	6,154,673	-17,219,935	13,285,625	-690,514	2,098,194	-424,566	-18,335,015

Notes:

1. WARM manages materials in short tons (1 short ton = 2000 lb = 0.908 MT)
2. This data was estimated with the default settings for WARM, for materials made with 100% virgin raw materials. This option was selected to avoid discrepancies from the use of different parameters for recycling.
3. WARM model estimates GHG generation using landfilling as the baseline process – this means that all the MSW processes generate credits on the basis of carbon sequestration, energy use and emission avoidance.
4. Negative emissions represent credits (avoided emissions)

Table 3.5 ISWM model results

	Recycling	Composting	Landfill	Total Waste Management System	Virgin Material Displacement Credit	Reprocessing of Recycled Materials	Net Life Cycle Inventory
Tonnes Managed (***)	*5,588,351*	*1,905,160*	*12,063,439*	*19,556,950*			
Energy Consumed (GJ)	92,203,647	9,454,339	106,072,992	207,730,977	-189,059,051	83,895,347	102,567,273
CO2 (tonnes)	13,219,210	661,841	6,001,965	19,883,016	-4,510,698	1,237,665	16,609,983
CH4 + NOx (tonnes)	24,750.6	6,062.03	275,412	306,224	-5,503.2	0.0	300,721
CO2 Equivalents (tonnes)	20,143,661	2,644,873	25,002,529	47,791,064	-4,626,264	1,237,665	44,402,465
NOx (tonnes)	20660.29	5986.224	42635.23	69281.74	-36647.5	19306.9	51941.1
SOx (tonnes)	1199.86	37.453	11519.14	12756.45	-54977	34840.7	-7379.4
HCl (tonnes)	12.880	2.538	492.046	507.46	-90465.1	535.14	-89422.5
NOx (tonnes)	20660.29	5986.224	42635.23	69281.7	-36647.5	19306.9	51941.1
PM (tonnes)	3605.94	1185.8	14322.5	19114.3	-19406.4	11081.1	10789.0
VOCs (tonnes)	3771.57	1124.80	16689.4	21585.8	-33267.1	20216.3	8535.0
Air							
Pb (kg)	75.990	1.867	519.47	597.3	-1,532.65	939.10	3.8
Hg (kg)	21.964	0.350	72.763	95.08	-5.85	0.15	89.38
Cd (kg)	3.492	0.062	54.093	57.65	-9.55	1.52	49.62
Dioxins (TEQ) (g)	0.0031	0.00148	0.469	0.474	n/a	0.0000	0.474
Water							
Pb (kg)	551.872	53.299	10826.14	11431.31	-4660.4	4062.1	10833.06
Hg (kg)	6.0321	0.01533	21.687	27.735	-0.40	1.10	28.430
Cd (kg)	6.484	0.503	1168.08	1175.06	-189.1	150.85	1136.841
BOD (kg)	227.75	3.055	7,855,769	7,856,000	-10,338,544	11,859,733	9,377,189
Dioxins (TEQ) (g)	n/a	n/a	0.07850	0.0785	n/a	n/a	0.07850
Residual Waste (tonnes)	279,418	95,258	12,063,439	12,438,115	-1,125,412	932,411	12,245,114

Notes:

1. This data was estimated with the default settings for ISWM.
2. The ISWM model assumes a "zero burden" tally for all its sub-models. Therefore, baseline for emission generation is 0.
3. Negative emissions represent credits (avoided emissions).

Table 3.6 WASTED model results

Summary	Collection / Transport	Recycle	Compost	EFW	Landfill	Total**
Tonnes Managed	*1.9557E+07*	*5.5849E+06*	*1.9045E+06*	*0.0000E+00*	*1.2068E+07*	*1.9557E+07*
*Energy Consumed (GJ)****	*7.1044E+06*	*1.4111E+06*	*2.8748E+03*	*0.0000E+00*	*-1.1470E+07*	*-2.9516E+06*
Air Pollutants						
Total CO_2 (tonnes)*	6.0245E+05	-2.0096E+07	2.0958E+06	0.0000E+00	2.4458E+06	-1.4951E+07
Non-Biogenic CO_2 (tonnes)*	6.0245E+05	-2.0096E+07	-3.4828E+05	0.0000E+00	-1.1355E+06	-2.0977E+07
CH_4 (tonnes)	7.2461E+02	-5.4813E+03	2.9322E-01	0.0000E+00	3.2498E+05	3.2022E+05
CO_2 Equivalents (tonnes)	6.1767E+05	-2.0211E+07	2.0959E+06	0.0000E+00	9.2704E+06	-8.2268E+06
Non-Biogenic CO_2 Eq. (tonnes)	6.1767E+05	-2.0211E+07	-3.4828E+05	0.0000E+00	5.6891E+06	-1.4252E+07
NO_x (tonnes)	4.2332E+03	-2.9830E+04	1.7131E+00	0.0000E+00	-1.7806E+03	-2.7376E+04
VOCs (tonnes)	1.8612E+03	3.0390E+04	3.2384E+03	0.0000E+00	2.7322E+03	3.8222E+04
SO_x (tonnes)	1.1474E+03	-2.3623E+04	4.6427E-01	0.0000E+00	-4.4229E+03	-2.6898E+04
PM (tonnes)	3.3603E+02	-8.4171E+03	1.3598E-01	0.0000E+00	-4.4848E+02	-8.5294E+03
HCl (tonnes)	1.1133E-02	3.2001E+04	0.0000E+00	0.0000E+00	-2.6255E+02	3.1739E+04
Pb (tonnes)	2.6314E-02	2.1428E+01	1.0352E-05	0.0000E+00	-1.7277E+01	4.1774E+00
Cd (tonnes)	2.0835E-03	4.0741E+00	0.0000E+00	0.0000E+00	-4.9136E+01	-4.5060E+01
Hg (tonnes)	8.4681E-04	2.5744E-03	3.4206E-07	0.0000E+00	-3.6225E-02	-3.2804E-02
NH_3 (tonnes)	0.0000E+00	0.0000E+00	[illegible].2372E+02	0.0000E+00	0.0000E+00	7.2372E+02
Dioxins (kg)	2.6760E-12	3.7181E-09	3.1622E-16	0.0000E+00	-4.4680E-08	-4.0960E-08
H_2S (tonnes)	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	4.2731E+01	4.2731E+01
Water Pollutants						
BOD (kg)	7.9559E-01	1.2477E+03	3.2196E-04	0.0000E+00	2.3215E+06	2.3227E+06
COD (kg)	7.9559E-01	1.2477E+03	3.2196E-04	0.0000E+00	3.3164E+06	3.3176E+06
Pb (kg)	9.4718E-02	4.2462E-01	3.8236E-05	0.0000E+00	8.4143E+00	8.9336E+00
Cd (kg)	1.0229E-02	-1.7478E+02	4.1393E-06	0.0000E+00	1.1055E+01	-1.6371E+02
Hg (kg)	9.7385E-05	1.0540E-04	3.9382E-08	0.0000E+00	1.3108E-01	1.3128E-01
NH_3 (Tonnes)	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	2.2109E+05	2.2109E+05
Dioxin Eq. (Tonnes)	0.0000E+00	-6.2710E-05	0.0000E+00	0.0000E+00	0.0000E+00	-6.2710E-05
Landfill Area	135.14	ha				

Notes:

1. Data estimated with the default settings for WASTED
2. Negative emissions represent credits (avoided emissions)

3.4 Analysis of Results

The models in this case study all treat LCA from a slightly different perspective. This section will compare their results and explain their differences.

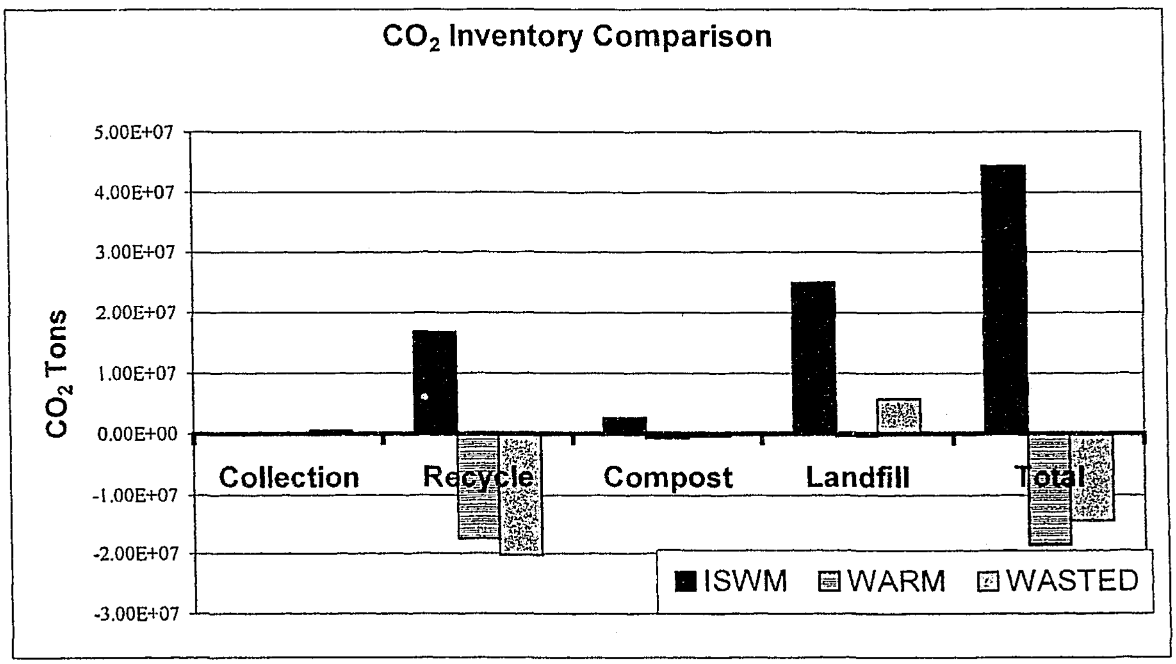
The most important parameter in this case study is the comparison of CO_2 inventories generated by each model. Table 3.7 presents these results.

Table 3.7 CO_2 Emissions Inventory

Total CO_2 (Tons)	Collection	Recycle	Compost	Landfill	Total
ISWM	N/A	16,755,062	2,644,873	25,002,529	44,402,465
WARM	N/A	-17,219,935	-690,514	-424,566	-18,335,015
WASTED	617,666	-20,210,700	-348,276	5,689,083	-14,252,227

Note: Negative values indicate emission credits.

Figure 3.1 CO_2 Inventory Comparison



Note: Negative values indicate emission credits

It is evident from the last figure that while WARM and WASTED present similar tendencies for the estimated CO_2 generation from MSW management, the ISWM model estimates are widely different. This is due to the "zero burden" perspective that this model uses; this defines the baselines for all the estimated emissions as zero. In contrast, both WARM and WASTED consider the landfilling of waste as the baseline. Therefore, the results for recycling (for example) in the WARM and WASTED models are *negative* (indicating a reduction in emissions, when compared to landfilling), while they show a positive number – net emissions, since the emissions resulting from landfilling are not deducted. This difference in the system boundaries between the models makes it difficult to compare them directly. However, model comparison is still useful when evaluating WM alternatives. This analysis will be shown on section 3.5.

It must be stated that since each LCA follows a different methodology, these comparisons are not necessarily representative of a model credibility. It also exemplifies the importance of establishing boundaries: even while the WARM model does not follow the IPCC guidelines for CO_2 inventories, it is the ISWM that is dissimilar. This is because both WASTED and WARM consider landfilling[17] the basis for assessment, while the ISWM model starts at "zero" emissions..

Table 3.7 shows that the discrepancies in the CO_2 inventories between the WARM and WASTED models are not overtly large (18.3E06 Vs. 14.2E06 MT, or 22.3% of the final CO_2 inventory). Furthermore, when only the non-biogenic sources of

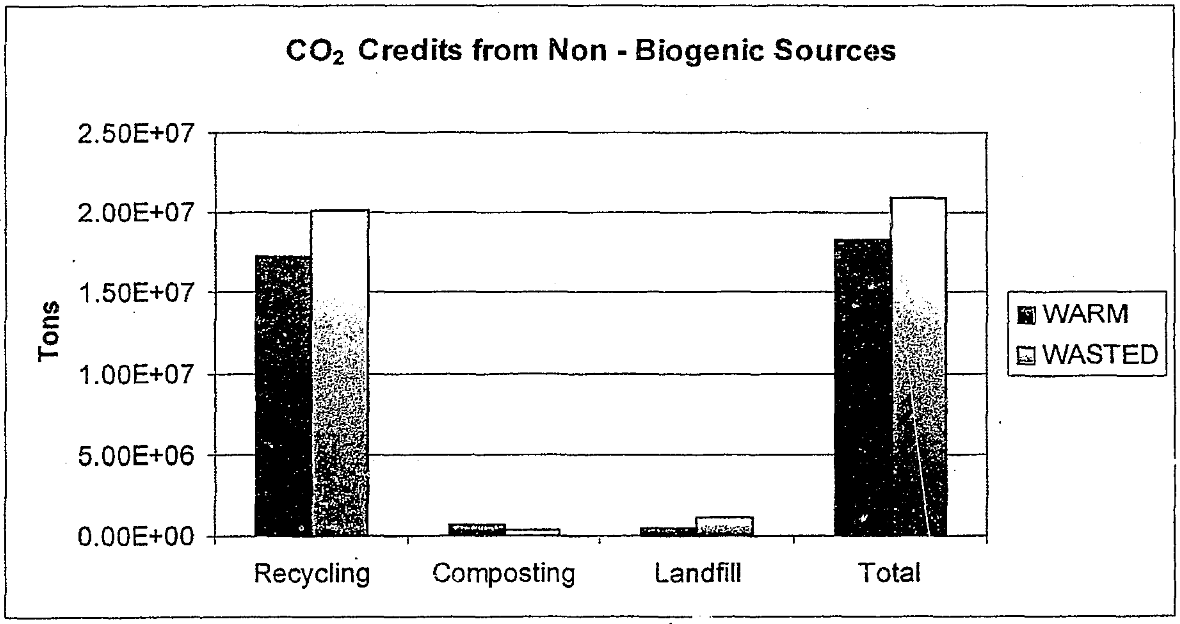
[17] In this case, landfilling without energy recovery or carbon sequestration.

CO_2 are compared (the WARM model tallies only the non-biogenic GHG contributions) the results are closer at 14.4%. The results for the comparison of the non-biogenic CO_2 emissions are presented on table 3.8.

Table 3.8 CO_2 Credits (non-biogenic sources)

1,000,000's of Tons	Recycling	Composting	Landfilling	Total
WARM	17.22	0.69	0.42	18.34
WASTED	20.10	0.35	1.14	20.98
Difference	16.7%	49.6%	167.4%	14.4%

Figure 3.2 Non-Biogenic CO_2 Credits



The results of the two models are quite similar. Discrepancies are due to the different emission factors used for calculation. For example, the default parameters for landfilling and composting in WASTED are adopted from the Danish EPA's Model and some recycling data were obtained from sources other than the US EPA (i.e. the International Aluminium Institute); default emission parameters for fossil fuels and power generation are different as well.

3.5 Evaluation of MSW Management Alternatives

The *raison d'être* of environmental life-cycle assessment is to evaluate process alternatives that may result in lower burdens to the environment. This section will compare the environmental impacts of different waste management alternatives applied to the case study of the City of Toronto described previously in this chapter. Since the WARM model only calculates GHG inventories, the results presented will only deal with this pollutant.

3.5.1 Incineration as an alternative for Toronto

Incineration is a much-maligned WM alternative: it is reported to be unwieldy, polluting, and to promote the generation of wastes (GAIA). However, Tammemmagi describes EFW as an effective component of integral waste management.

Incineration has several advantages: first, it reduces the quantity of waste to less than 10% of the original volume. It also generates power that offsets the use of fossil fuels. If planned properly, incineration can be used for energy recovery from waste fractions that are difficult to recover in other ways.[18]

For the evaluation of this potential WM alternative, incineration rate is arbitrarily set at 30% of the total waste stream. Additionally, the residues from waste sorting in a

[18] Although anti-incineration activists strive for "zero pollution" alternatives based separation, recycling and composting, these options are not always viable due to technological impediments (waxed paper from food packaging is difficult to reuse/recycle; plastics can not be recycled indefinitely), economical, or life-cycle considerations (transporting materials thousands of km to be reused makes little environmental sense). Though waste reduction is the least polluting alternative, the laws of thermodynamics do not always favour this premise.

MRF are also considered to be sent for incineration. The energy recovery rate is set at 25% - implying that heat is not recovered, only electricity. Finally, the distance to the EFW facility was set at 100 km for the purpose of estimating the emissions resulting from the transportation of waste. These parameters *do not* reflect any currently studied alternative for MSW management for Toronto; they are only established to provide background for the incineration scenario.

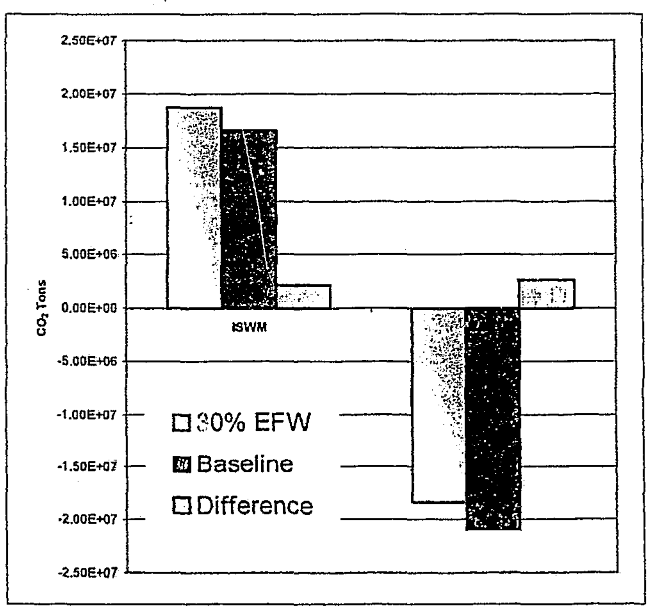
According to the IPCC guidelines, the CO_2 emissions from incineration are accounted in this fashion: the CO_2 resulting from the combustion of paper and organic waste is renewable and results in zero net emissions; CO_2 generated by the combustion of plastic is non-biogenic and should be tallied. This seems to indicate that EFW generates more carbon dioxide than landfilling. Table 3.9 includes the results from this simulation. Results for WARM are not included since it only calculates CO_2 equivalents.

Table 3.9 CO_2 Emission Contrast

Data in MT	ISWM	WASTED
30% EFW	1.87E+07	-1.84E+07
Baseline	1.66E+07	-2.10E+07
Balance	2.10E+06	2.59E+06

Note: Negative values indicate emission credits.

Figure 3.3 CO_2 Balance (EFW comparison)



Note: Negative values indicate emission credits.

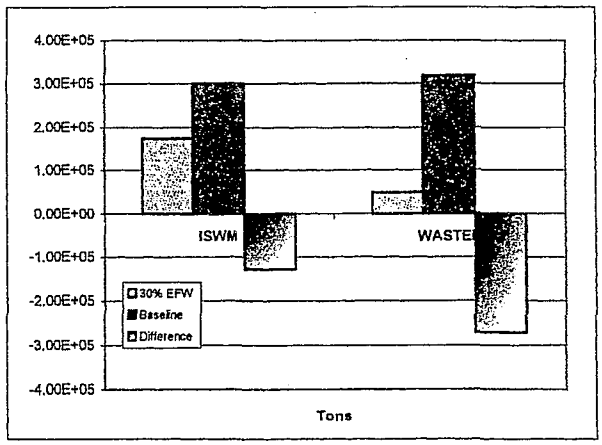
Although direct CO_2 emissions are higher in the scenario that considers waste incineration, they are offset by a decrease in generated methane. CH_4 is a powerful GHG, 21 times more potent than CO_2 (IPCC, 1996) and offsets this increase in carbon dioxide production. Both the ISWM and WASTED models predict a decrease in methane generation when 30% of the waste is sent for incineration. This is the consequence of the reduction of waste undergoing anaerobic decomposition in a landfill.

Table 3.10 CH4 Emission Comparison

Data in MT	ISWM	WASTED
30% EFW	1.73E+05	4.85E+04
Baseline	3.01E+05	3.20E+05
Balance	-1.27E+05	-2.72E+05

Note: Negative emissions represent credits.

Figure 3.4 CH_4 Balance (EFW comparison)



Note: Negative emissions represent credits.

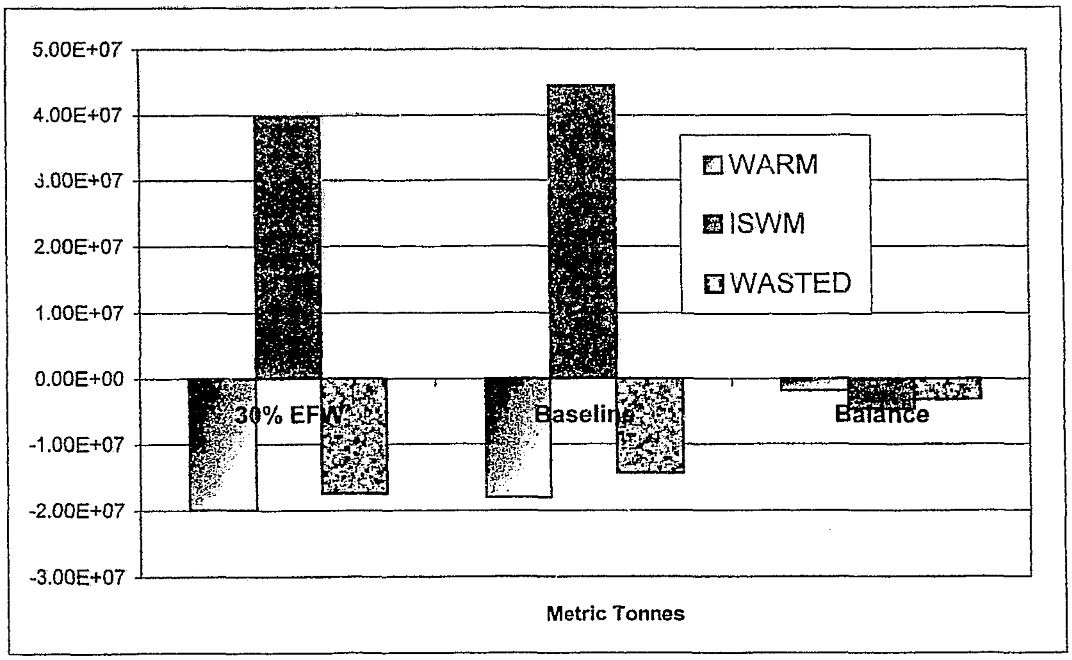
Since methane is such a powerful GHG, it is necessary to evaluate the combined effect of CO_2 and CH_4 emissions. This parameter is denominated CO_2 equivalents, and in all models also includes other sources of GHG (such as perfluorocarbons from aluminium production). The results of this combined GHG inventory are shown next, and the results from WARM are included. Figure 3.5 shows first the results for the incineration scenario for each of the three models, and then the results for the "base" WM evaluation.

Table 3.11 CO2 Equivalents from EFW

CO_2 Eq Tons	30% EFW	Baseline	Balance
WARM	-19,877,831	-18,011,919	-1,865,912
ISWM	39,713,229	44,402,465	-4,689,235
WASTED	-17,367,112	-14,252,227	-3,114,884

Note: Negative values represent emission credits.

Figure 3.5 CO_2 Equivalents Comparison



Note: Negative values represent emission credits

3.5.2 Analysis of Incineration Results

The predicted emission inventories for all three LCA models indicate that there is an overall decrease in GHG emissions when 30% of the total waste is sent for incineration instead of directly to the landfill. WARM is the most conservative model: it estimates the generation of 1.86 million tonnes of CO_2 equivalent[19] credits; the ISWM model estimates credits for 4.69 million tonnes of CO_2 eq. and the WASTED model estimates the generation of 3.11 million tonnes of CO_2 eq. credits. These results are largely due to the decrease in methane emission from the landfill and to a lesser extent to the reduced waste transfer emissions to the distant landfill in Sumpter, Michigan. It is important to note that these CO_2 credits are not at the expense of the current recycling or composting operations. Given these considerations, it makes *environmental sense* to divert some of Toronto's waste for energy recovery.

It must be remembered that the results derived from this model cannot be considered a definitive guide – other concerns such as environmental risk assessments, economic considerations and (especially in the case of waste incineration) public perception need to be addressed in order to implement the optimal solution for waste management. This is a very important limitation of LCAs - by themselves, they can not indicate an "optimal" solution that considers all the factors needed to make a decision.

The results shown in this section demonstrate that the WASTED model is a useful tool for estimating the environmental burdens associated with waste management operations. The overall tendencies when evaluating alternatives for the case study were

[19] CO_2 equivalents account for carbon dioxide, and the equivalent amount (in CO_2 MT) of other GHG.

the same - this shows that WASTED is at least consistent with the currently available life-cycle assessment models available for municipal solid waste. The discrepancies between the results of these three models are largely due to the different parameters (i.e., power required in an EFW plant, diesel consumed in waste transfer, etc.) chosen to estimate emissions; a table of this parameters is presented in the Appendix B. These parameters can be finely tuned for a particular case study in order to make the results more representative.

3.6 Sensitivity Analysis

Sensitivity is the influence that one parameter (independent variable) has on the outputs of the model (Björklund, 2002). A sensitivity analysis can be performed to analyze systematically the effects of the chosen methods and data on the outcomes of the study (Ibid).

The method selected is the *tornado diagram analysis.* Tornado diagrams illustrate the change in output parameter values when the model is run with low and high input parameters (Ibid). The results are then sorted in decreasing order of sensitivity (the most sensitive parameter will be on top).

The base case study consists of a fictitious scenario, and the data used is arbitrary. The parameters for this simulation are presented on table 3.12

Table 3.12 Base Parameters for Sensitivity Analysis

Parameter	Value	Parameter	Value
Waste Generation		**Composting**	
Waste Quantity (MT)	1,000,000	Process	Windrow
Waste Composition		DOC	35%
Organic	34%	Conversion	400 kg/ton
Paper	28%	Residue	5%
Plastic	11%	C storage	0.183 ton CO2/ton waste
Metal	7%	Emissions	See section 2.3.5
Glass	8%	Distance to landfill	15 km
Others	12%	**Energy from Waste**	
Waste Distribution		Fuel	Untreated MSW
Recovery	33%	Process	Incineration
EFW	33%	Energy recovery	20%
Landfill	34%	Calorific value	10.21 MJ/kg waste
Collection/Transportation		Ash	10% input
Avg. Collection Route (km)	20	Distance to landfill	15 km
TS to Landfill (km)	20	Emissions	See section 2.3.6
TS to MRF (km)	10	**Landfill**	
TS to EFW (km)	15	Waste Density	600 kg/m^3
Fuel Eff.-Collection (km/L)	1.25	Landfill depth	15 m
Fuel Eff.-Transport (km/L)	3	Precipitation	800 mm/y
Garbage coll. capacity (MT)	8	Landfill Type	Engineered, Traditional
Recycle coll. capacity (MT)	6	Leachate Generation	5% Precipitation
Waste Transport cap. (MT)	20	Leachate Collection	99.8% Generation
Waste Transport cap. (MT)	20	Surveyable Time	100 y
Recycling		DOC	1.4740E-01
Recovery Rates		Paper Carbon Seq.	0.82 MT CO2/MT of Paper
Organic	80%	Org. Waste. C. Seq.	0.07 MT CO2/MT Waste
Paper	70%	Methane in gas	50%
Plastic	35%	CH4 Oxidation	0%
Metal	85%	Gas Recovery	60%
Glass	70%	Energy recovery	30%
Others	0%	Power Consumed	0 kWh/ton
Recovered Metal Ratio		Gas Consumed	0 L/ton
Aluminium:Steel	20:80	Diesel Consumed	1.12 L/ton
Recovered Paper Ratio		Emissions	See section 2.3.7
Newsp: Fine P: Board : Mixed Paper	60:10:13:17	Power Generation	
Recovered Plastic Ratio	Yes	Coal	20%
PET:PE:PS:PP:PVC	21.3:49.5:10.3:16.4:2.5	Oil	3%
Residue	Landfilled - 15 km	Natural Gas	6%
Distance to Composting	15 km	Nuclear	13%
Power Consumption	25 kWh/MT	Hydro	57%
Gas Consumption	35 L/MT	Others	1%
Diesel Consumption	0 L/MT	Emissions from utilities	See section 2.4
Emissions	See section 2.3.4		

The different high-low parameters are described in table 3.13. A total of 5 different cases will be studied. The outputs to be observed (dependent variables) are energy balance, CO_2 equivalent emissions, total heavy metal emissions (air + water), acid gases[20] ($HCl + NO_x + SO_x$) and photochemical pollutants ($VOCs + NO_x$).

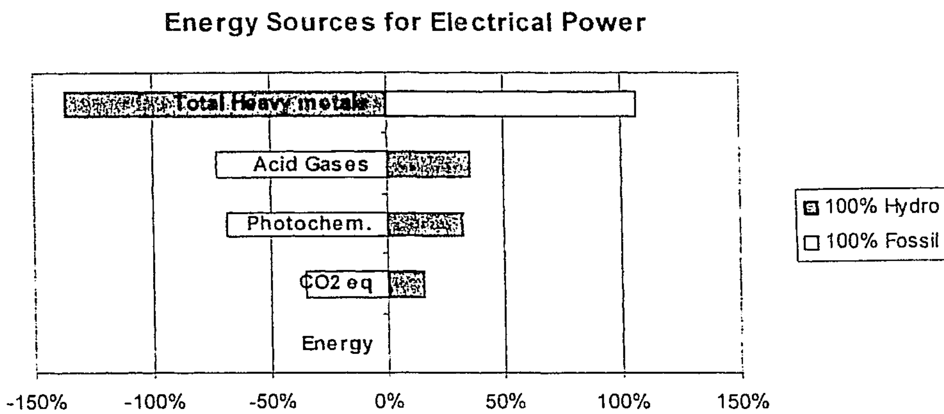
Table 3.13 Sensitivity Analysis High-Low Scenarios

Case	High	Low
1. Energy Generation	100% Fossil Energy (60% Coal, 10% oil, 30% gas)	100% Hydroelectric
2. Landfilling Vs Recovery	100% wastes sent to landfill	100% Wastes sent for recovery, subject to default rec. efficiency
3. Fuel Consumption	0.25 km/L (collection); 0.7 km/L (transport)	5.0 km/l (coll.); 12 km/l (trans.)
4. Carbon Sequestration	0 carbon sequestration from recycling and landfilling	Double C seq. parameters
5. Landfill Surveyable Time	1000 years	10 years

The results of these different cases will be presented in figures 3.6 through 3.10. Since the different indicators have different orders of magnitude (for example, CO_2 equivalents are much greater than the combined heavy metals) the tornado graph results will be presented as *% change*.

[20] Acidification potential is determined as kg SO_2: $SO_x = 1$, $HCl = 0.88$, $NO_x = 0.7$, $NH_3 = 1.88$ (Baky & Eriksson, 2003)

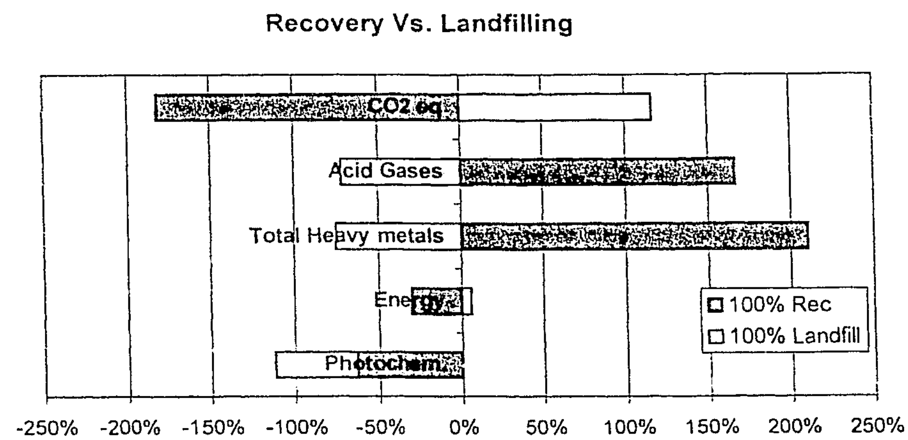
Figure 3.6 Tornado Graph: Energy Sources



	Energy	CO2 eq	Photochem.	Acid Gases	Total Heavy metals
100% Fossil	0%	-35%	-68%	-73%	107%
100% Hydro	0%	16%	32%	36%	-137%

When the power generation scheme shifts between fossil fuel and hydroelectric generation, the largest impact is on the emission of total heavy metals, followed by acid gases, photochemical pollutants, and CO_2 eq.. The energy balance is not affected at all. Keeping in mind that in WASTED *negative* results represent emission *credits*, this means that when energy sources are relatively clean, it is not advantageous to recover energy through EFW and landfill gas recovery systems. It is initially surprising to observe that more heavy metals are actually emitted when 100% of the electric power comes from hydroelectric plants; this is because the emissions from EFW and landfill gas energy recovery projects (relatively "dirty" sources of energy) are greater than those generated by hydroelectric plants.

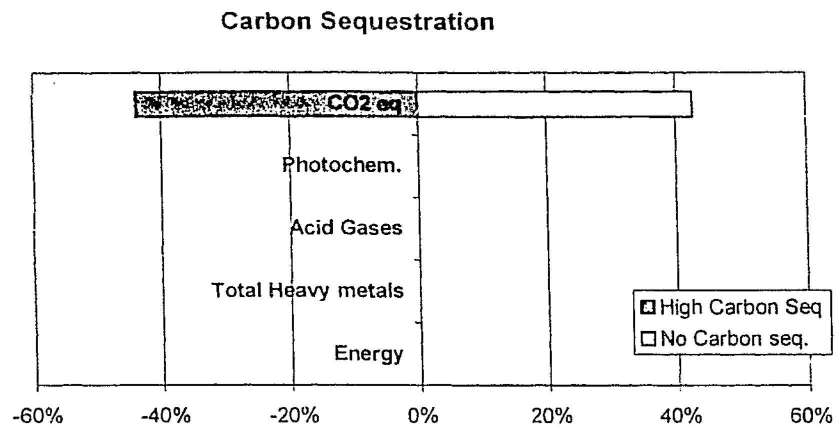
Figure 3.7 Tornado Graph: Waste Landfilling Vs. Waste Recycling



	Photochem.	Energy	Total Heavy metals	Acid Gases	CO2 eq
100% Landfill	-49%	6%	-75%	-72%	117%
100% Rec	-64%	-30%	210%	166%	-182%

In this case, the GHG balance was the most affected, followed closely by acid gas, and heavy metal emissions, as well as the energy balance. CO_2 emissions are heavily reduced by recycling (by means such as carbon sequestration from paper and PFC emission reduction from aluminium recovery). Acid gases are increased because of the ammonia emissions from composting, and heavy metal emissions are increased in the high recycling scenario because some recycling operations produce significant amounts of heavy metals (for example, re-smelting steel). A higher fraction of recycled waste results in a reduction in the energy consumed; this is because the energy credits from material recycling outweigh the energy utilized in their recovery. Finally, both scenarios show a decrease in photochemical gas emissions – this is due to the avoided VOC and NO_x emissions derived from the incineration of wastes in the base scenario. It is worth noting that all parameters varied in more than 100%, indicating that this is a very sensitive variable.

Figure 3.8 Tornado Graph: Carbon Sequestration

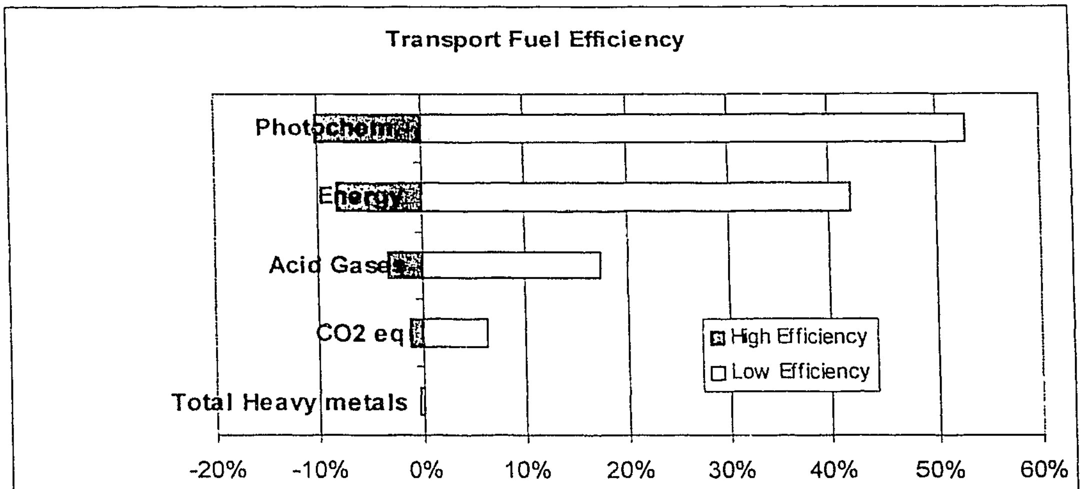


	Energy	Total Heavy metals	Acid Gases	Photochem.	CO2 eq
No Carbon seq.	0%	0%	0%	0%	43%
High Carbon Seq	0%	0%	0%	0%	-44%

As expected, no outputs changed from the change in the carbon sequestration parameters except the greenhouse gas balance. Furthermore, since the parameters used were zero carbon sequestration ("low") and twice the default parameters[21] ("high"), the baseline is neatly located almost exactly in the middle of the two bars. Interestingly, this single variable has a very high impact on the output: more than 40%. Given the uncertainty in predicting the future of forests and carbon sequestration, this is a potential key issue to be addressed to reduce model inaccuracies.

[21] These parameters were described in sections 2.3.4, 2.3.5 and 2.3.7

Figure 3.9 Tornado Graph: Fuel Consumption in Vehicles



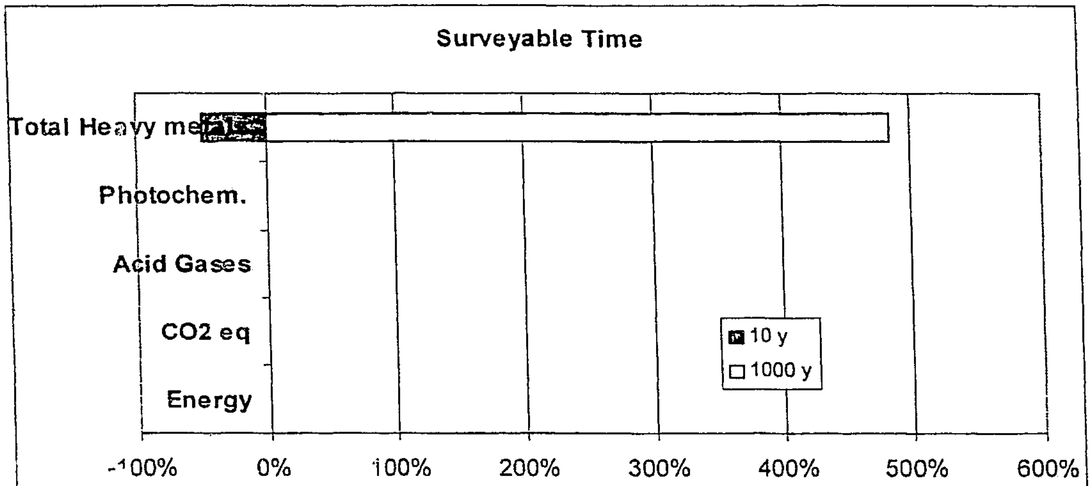
	Total Heavy metals	CO2 eq	Acid Gases	Energy	Photochem.
Low Efficiency	0%	6%	18%	42%	53%
High Efficiency	0%	-1%	-3%	-8%	-10%

Obviously, in this case all the parameters show reduced emission (or increased credits, as the case might be) for the high fuel efficiency scenario[22]. It can be perceived that fuel efficiency has a very high impact on the total emitted photochemical pollutants (VOCs + NO_x) ant the total energy balance in the model. Heavy metal emissions were not altered significantly; the model utilizes parameters for "clean" truck fuels.

Since energy consumption and photochemical pollutant emissions are quite sensitive to changes in this parameter, it is recommended to choose fuel efficiency parameters that reflect the studied scenario most closely.

[22]The parameters used were 5x fuel efficiency (for the high efficiency scenario), and 1/3 of the fuel efficiency (for the low efficiency scenario). These parameters are found in section 2.3.2.

Figure 3.10 Tornado Graph: Surveyable Time



	Energy	CO2 eq	Acid Gases	Photochem.	Total Heavy metals
1000 y	0%	0%	0%	0%	485%
10 y	0%	0%	0%	0%	-48%

For changes in surveyable time, only the heavy metal output is affected. This is because the model calculates leachate generation and concentration on a yearly average basis (based on user parameters such as yearly precipitation and leachate composition). The model does not allow for leachate "weakening" until emissions reach background levels. To avoid major inaccuracies, the user is advised to choose a well-accepted surveyable time period; most LCAs use a period of 100 years to determine leachate emissions. Since in WASTED the landfill leachate generation and composition occur at fixed rates (although they can be modified by the user), this becomes especially important; this is definitely an area of opportunity in the WASTED model.

4. CONCLUSIONS

Life-cycle assessment models are useful tools to estimate the environmental burdens of a product or activity. Under this light, WASTED is valuable: by using a "cradle-to-grave" approach it is possible to obtain a comprehensive understanding of the environmental implications of waste management decisions.

WASTED is not the first model devised to analyze the environmental implications of waste management; however, WASTED attempts to build on the current publicly-available LCA programs and overcome their limitations, especially those regarding ease of use and flexibility. The first of these objectives is met by using a visual interface; this interface guides the user throughout the different screens that describe the WM alternatives in an intuitive and straightforward manner. Flexibility is attained by allowing the user to effect extensive modifications to the default set of data included in the model. In this manner, WASTED can be used to "screen" a WM scenario *and*, by finely tuning the model parameters, to perform detailed, site-specific analyses.

All LCAs depend on large amounts of data. These data support the different submodels used in WASTED to estimate the emissions generated and the energy use for a particular case study. The data used in WASTED come from very diverse sources with varying quality; therefore, it is hard to evaluate the credibility of the results of the model when parameters are extrapolated, averaged or otherwise estimated from other studies instead of measured directly and applied to a particular analysis. This is a very serious issue, given the large number of variables involved[23]. The sensitivity analysis demonstrates that the model results can vary significantly even with moderate changes in a small number of model parameters, especially when they are related to the distribution of wastes across the different WM processes (such as recycling). This illustrates the importance of using the best available data to minimize the discrepancies between the model and reality. To better understand the relationship between dependent (output) and independent (input) variables, it is recommended that each case study is accompanied by a sensitivity analysis, especially when the independent variables are subject to high levels uncertainty.

Furthermore, it is important to note that although WASTED is useful to compare the overall environmental efficiency of different WM scenarios, it can not prescribe the "optimal" waste management alternative. Waste management is very complex and environmental considerations are only one of the factors that must be considered to make a decision; geographic, economic, social and political factors (to name a few) should all be analyzed in order to determine what is the best choice for the management of wastes in a particular site.

It is hard work to collect and codify all the data needed to support WASTED. Further efforts are required in order to obtain and characterize the data used to support the different submodels in WASTED, and to expand and improve the default model

[23] Currently, WASTED allows the user to modify more than 600 different parameters. This is a good example of the old computer programmer's adage: "garbage goes in - garbage comes out" regarding the quality of the data used for simulations.

parameters. In the end, only a reliable database of model parameters and thorough testing will improve the representativity of this program.

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Appendix A: WASTED User's Manual

Waste Analysis Software Tool for Environmental Decisions

Version 1.2

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Ryerson University

May 2004

Introduction

The purpose of this analysis model is to provide researchers, waste managers and decision makers with a software tool that helps them to estimate the environmental impact of municipal waste management decisions, and to suggest alternatives that may improve the environmental efficiency of the municipal waste management system.

The Waste Analysis Software Tool for Environmental Decisions (WASTED) uses a life-cycle ("cradle-to-grave" methodology to estimate the energy use and emission generation for the different waste management processes. The model has been structured to allow the user to introduce data specific to the case study to maximize accuracy; and also provides default data to perform preliminary analyses.

Model Limitations

- WASTED is not intended as a stand-alone tool – Waste management is very complex and environmental considerations are only one of the factors involved in decision making.
- WASTED does not cover all the available practices for waste management
- Since the system boundary for WASTED is set at the collection of wastes, it does not evaluate waste reduction activities directly. It can be used to compare two scenarios, where one of them presents a reduced generation of wastes
- It is based on data available to the public. It uses averages and extrapolations of data which might be unfit for a particular case study
- The model can not prescribe the "optimal" waste management system – *political, social,* economical and environmental factors particular to the case studies should be considered.

Indicator Parameters

WASTED provides estimates for the energy balance and emissions to air and water. The specific parameters evaluated by WASTED are:

- Energy Use
- Carbon Dioxide emissions
- Methane emissions
- Nitrogen Oxides
- Sulphur Oxides
- Volatile Organic Compounds
- Suspended Particle Matter
- Hydrochloric Acid (air)
- Dioxins (air)
- Heavy Metals (air)
- NH_3 (air)
- H_2S (air)
- Heavy Metals (water)
- NH_3 (Water)
- Chemical Oxygen Demand (COD)
- Biochemical Oxygen Demand (BOD)
- Dioxins (water)
- Land Use

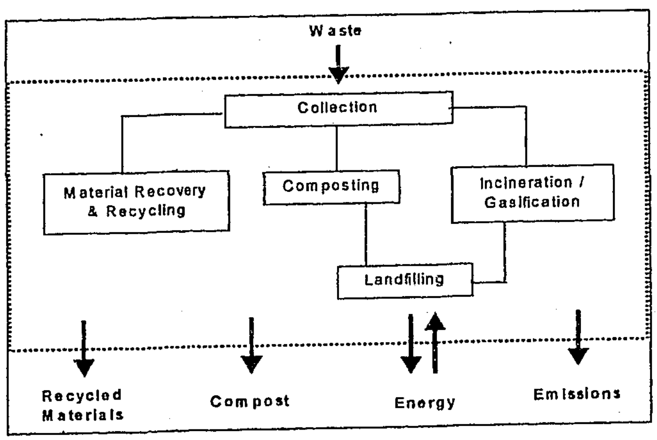
Environmental System Definition

WASTED evaluates the environmental burdens of the following waste management processes:

- Collection
- Recycling
- Composting
- Energy from Waste
- Landfilling

The system boundaries for the model are described in Figure 1.

Figure 1. System Boundaries



WASTED calculates the environmental impacts of the different waste management practices from the point of waste material collection until it is disposed or converted into a recoverable resource (material or energy). It uses a global perspective and therefore does not consider the geographic location where pollutant emissions and source depletion occur.

Recycling, composting and energy recovery result in the production of resources. These are tallied in the form of energy and emissions "credits", to account for the avoided emissions and energy use.

Landfilling is a special case since its emissions occur very slowly – spanning hundreds of years for some pollutants. Two time frames are adopted for landfills: gaseous emissions are calculated disregarding reaction kinetics, but factoring carbon storage from biological wastes. For emissions derived from landfill leachate a surveyable time frame of 100 years has been used; this period may be modified by the user. After the surveyable time has expired the landfill is considered to be inert.

System Requirements

WASTED 1.2 was codified using Visual Basic.Net™.

The following system specifications are required to run the model:

- Pentium processor or higher;
- Microsoft Excel™ 97 or better;
- Driver files (incluc d with the WASTED software):
  - Interop.VBIDE.dll
  - Interop.OWC.dll
  - Interop.Office.dll
  - Interop.Excel.dll
  - AxInterop.OWC.dll

The support (Driver files) need to be located in the same directory as the WASTED file for the model to run correctly.

Data Input

The graphical interface in WASTED allows the user to insert data in a very simple fashion: the user merely need to input the data into the text boxes of the input screens. Navigation between screens is achieved by using the 'Previous' and 'Next' buttons in each screen.

WASTED contains seven main input screens that require user input. These screens describe main waste management processes and the profile for electric power generation for the case studied:

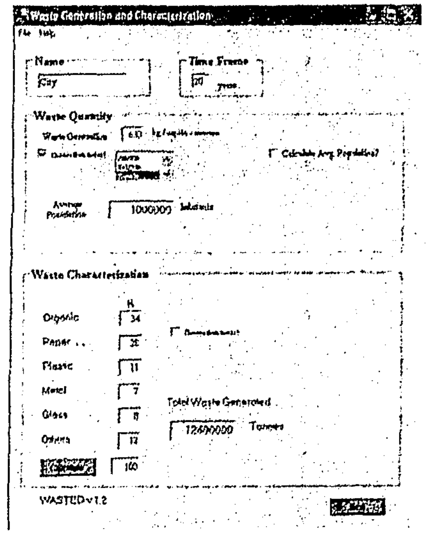
- Waste Generation
- Waste Distribution
- Waste Collection/Transfer
- Recovery
- Composting
- Energy From Waste
- Landfilling
- Power Generation

In addition, the model contains subsidiary screens that allows the user to finely tune the simulation by allowing him to enter additional information. These screens are:

- Emissions from Fossil Fuels
- Recycle Parameters
- EFW Emissions
- Landfill leachate composition
- Landfill gaseous pollutants

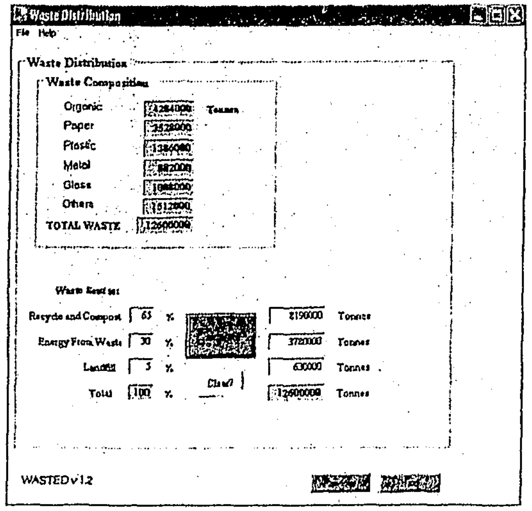
Each of the main screens in WASTED has brief description. This is accessible through the 'Help' Menu.

Input Screen: Waste Generation



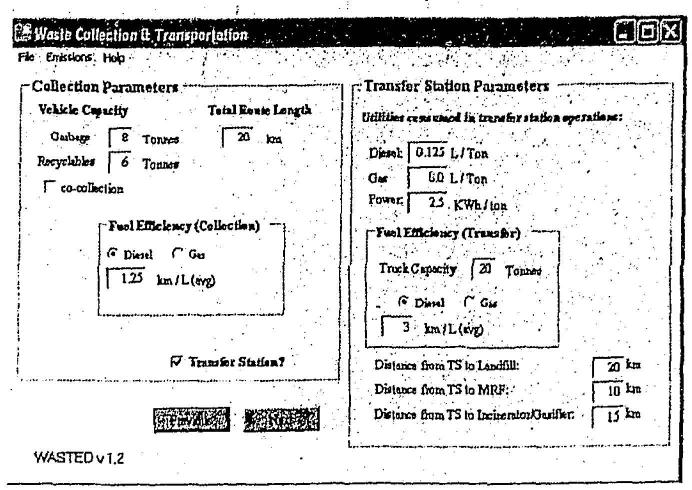
This screen requires the user to enter the population and waste generation parameters for the case studied. It includes a small database of waste generation parameters for different countries. The model applies this data to estimate the quantities for the different waste fractions.

Input Screen: Waste Distribution



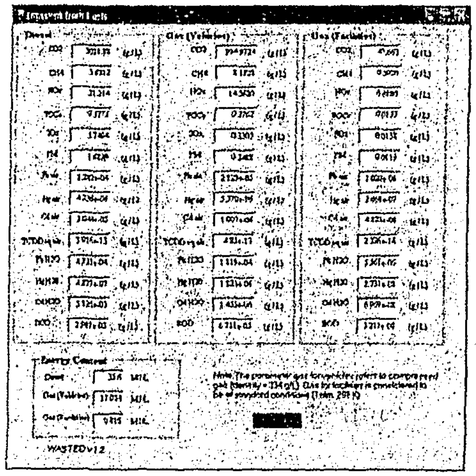
This screen requires the user to enter the fraction of wastes sent to the different waste management processes. It is important to note that this screen describes the primary destination for the waste fraction – WASTED allows the user to send the unrecovered materials for either landfilling/energy recovery.

Input Screen: Waste Collection



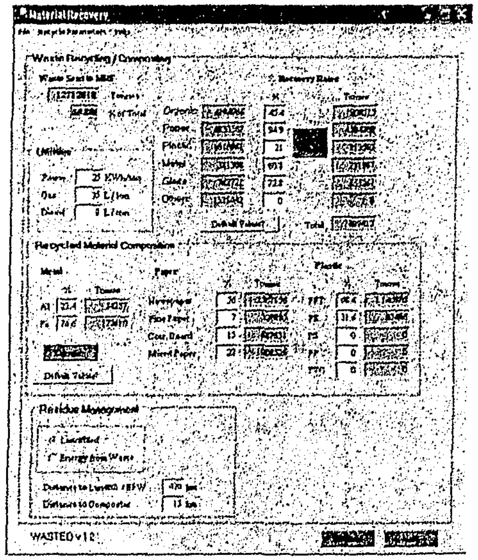
The waste collection screen requires the user to input the data for collection route and waste transfer distances, type of fuel and fuel efficiency. It also requires the data for the utilities consumed in a transfer station. Alternatively, the user may also opt to deactivate the TS option, or to select co-collection of garbage and recyclable wastes.

Input Screen: Fossil Fuel Emissions



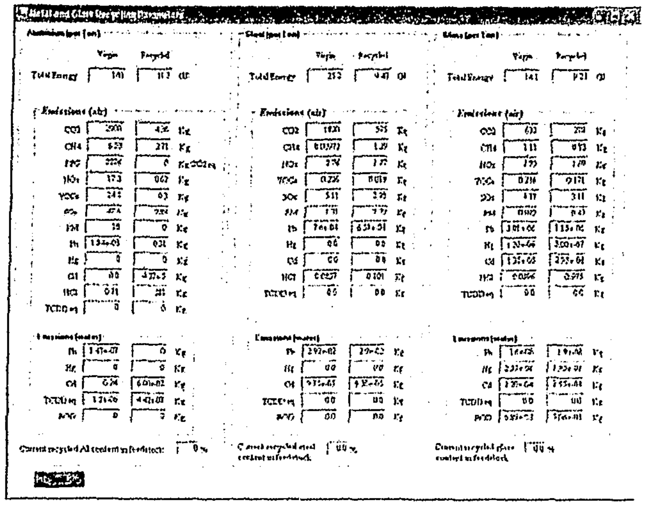
In this subsidiary screen the user may provide data for fossil fuel combustion. It includes default values for the emission of different pollutants and an estimate for energy content. The user may modify this data if desired.

Input Screen: Material Recovery



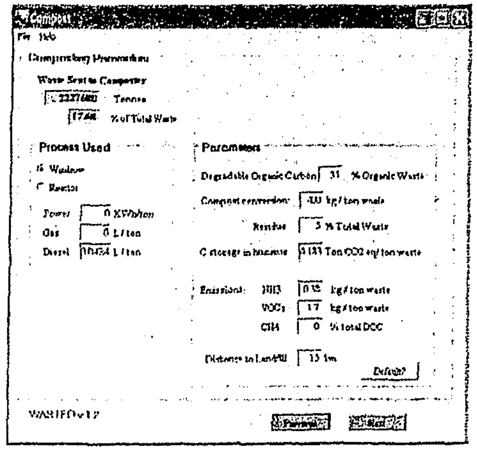
This screen requires the user to calculate the recovered fractions of waste for composting and recycling. The model then calculates the recovered mass from each pertinent waste category. The user must also determine the consumption of utilities for material recovery, and whether the residues are Landfilled or sent for energy recovery.

Input Screen: Recycle Parameters



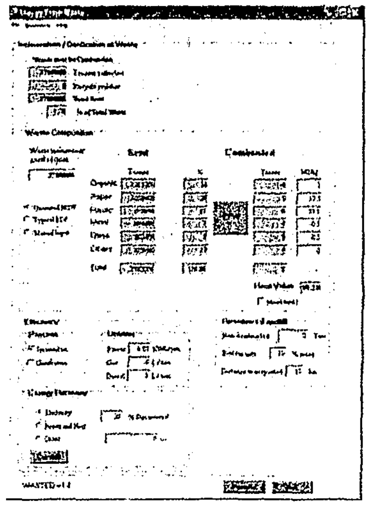
This is actually a set of 3 subsidiary screens: the first describes the parameters for metal and glass, the second the parameters for paper and the third the parameters for plastics. It also allows the user to establish the content of recycled material for each material category.

Input Screen: Composting



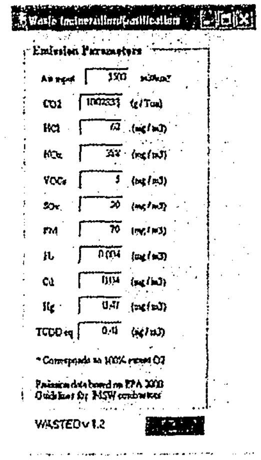
The composting screen allows the user to modify the parameters for this waste management process. It offers the option to choose between windrow and reactor (in-vessel) composting. This screens offers default values for degradable carbon content, compost conversion rate, utilities consumed, generated residues and emissions; the user may modify these parameters at will.

Input Screen: Energy From Waste



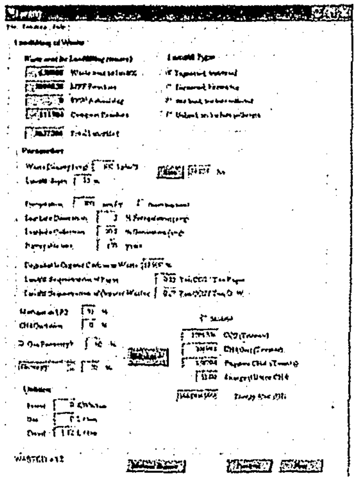
The user is required to select the type of EFW process and the nature of the fuel fractions combusted, as well as the energy content in waste. The user must also stipulate the amount of ashes generated, utilities consumed, and the distance EFW residues and ashes need to be transported. WASTED provides default parameters.

Input Screen: Emissions from EFW



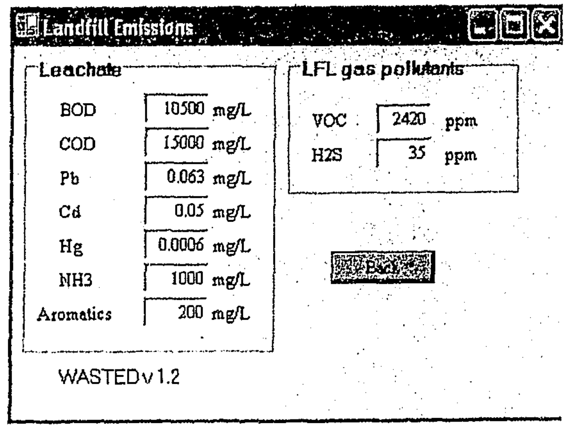
This sub-screen contains the data for the emissions generated by waste combustion. It includes a material balance estimate based on 100% oxygen excess. The user may modify any of these parameters.

Input Screen: Landfill



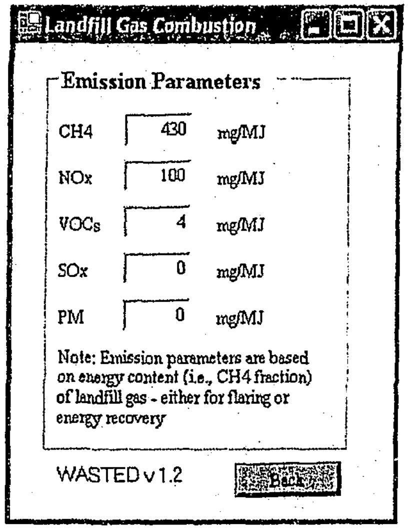
This screen requires the user to select between different landfill options and annual precipitation rate (used to estimate leachate generation). It also allows him to set the parameters for gas, leachate and energy recovery, organic carbon sequestration and utility consumption.

Input Screen: Landfill emissions



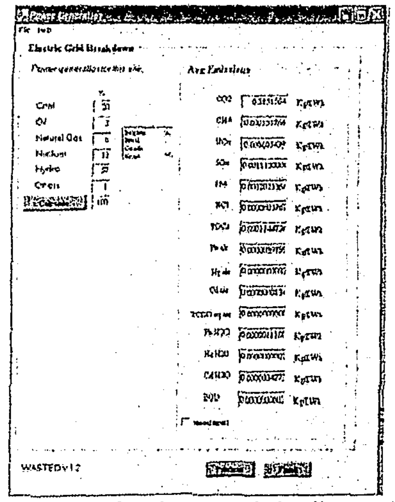
In this sub-screen the user may modify the default emission levels for leachate and landfill gas pollutant levels.

Input Screen: Landfill Gas Combustion



This sub-screen allows the user to set the emission data for the combustion of landfill gas, either as flaring or for energy recovery.

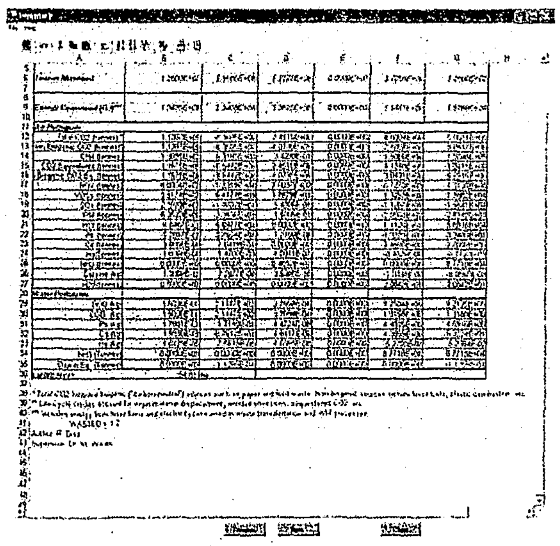
Input Screen: Power Generation Emissions



The last input screen in the model allows the user to provide data for the power generation breakdown. WASTED then generates an estimation of the average emissions derived from power generation This data is used to calculate both emissions and credits from utility use and generated energy from the waste management process.

Inventory

Results from WASTED are presented in an Excel™ spreadsheet. This includes pollutant generation and energy use. Negative values indicate emission and energy credits. The user may elect to save the parameters for this simulation and to export the data to an external spreadsheet for saving.



Model Information

WASTED was elaborated by Rodrigo Diaz under supervision of Dr. Mostafa Warith as part of a graduate research project to obtain the degree of Master in Applied Science in the Environmental Applied Science and Management Program at Ryerson University.

Comments , model inquiries and user support can be addressed to:

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Appendix B. Model Parameters for the City of Toronto Case Study

The general model parameters used for the Toronto case study are described in section 3.2. For the parameters not mentioned, they have been adopted the default parameters for each model For WASTED, the model parameters chosen are those described in the section 2.3 of this document. The ISWM model does not include a list of the default parameters used, and therefore can not be listed. WARM uses data published by the EPA. These parameters are included in the following table.

Material	GHG Emissions per Ton of Material Source Reduced (MTCE)	GHG Emissions per Ton of Material Recycled (MTCE)	GHG Emissions per Ton of Material Landfilled (MTCE)	GHG Emissions per Ton of Material Combusted (MTCE)	GHG Emissions per Ton of Material Composted (MTCE)
Aluminum Cans	-2.47	-4.01	0.01	0.02	NA
Steel Cans	-0.79	-0.49	0.01	-0.42	NA
Glass	-0.14	-0.08	0.01	0.01	NA
HDPE	-0.49	-0.38	0.01	0.23	NA
LDPE	-0.61	-0.47	0.01	0.23	NA
PET	-0.49	-0.42	0.01	0.28	NA
Corrugated Cardboard	-0.51	-0.71	0.08	-0.19	NA
Magazines/third-class mail	-1.04	-0.74	-0.12	-0.13	NA
Newspaper	-0.81	-0.95	-0.21	-0.21	NA
Office Paper	-0.80	-0.68	0.62	-0.18	NA
Phonebooks	-1.28	-0.91	-0.21	-0.21	NA
Textbooks	-1.23	-0.75	0.62	-0.18	NA
Dimensional Lumber	-0.55	-0.67	-0.10	-0.22	NA
Medium Density Fiberboard	-0.60	-0.67	-0.10	-0.22	NA
Food Scraps	NA	NA	0.17	-0.05	-0.05
Yard Trimmings	NA	NA	-0.09	-0.06	-0.05
Grass	NA	NA	0.01	-0.06	-0.05
Leaves	NA	NA	-0.29	-0.06	-0.05
Branches	NA	NA	-0.10	-0.06	-0.05
Mixed Paper, Broad	NA	-0.67	0.10	-0.19	NA
Mixed Paper, Resid.	NA	-0.67	0.07	-0.18	NA
Mixed Paper, Office	NA	-0.83	0.15	-0.17	NA
Mixed Metals	NA	-1.74	0.01	-0.26	NA
Mixed Plastics	NA	-0.41	0.01	0.25	NA
Mixed Recyclables	NA	-0.76	0.05	-0.17	NA
Mixed Organics	NA	NA	0.03	-0.06	-0.05
Mixed MSW	NA	NA	0.07	-0.04	NA

Source: WARM model, 2003. Available from www.epa.gov

Appendix C. Landfill Leachate Parameter Ranges

Table 3-1. Leachate Characteristics and Common Constituents.

Constituent (in mg/L except where noted)	Concentration Range *	Typical Concentration Range
Biochemical Oxygen Demand, 5-day (BOD)	4-57,70	1,000-30,000
Chemical Oxygen Demand (COD)	31-89,520	1,000-50,000
Total Organic Carbon (TOC)	0-28,500	700-10,000
Total Volatile Acids (as acetic acid)	70-27,700	**
Total Kjeldahl Nitrogen (as N)	7-1,970	10-500
Nitrate (as N)	0-51	0.1-10
Ammonia	0-1,966	**
Total Phosphates	0.2-130	0.5-50
Orthophosphates	0.2-130	**
Total Alkalinity (as $CaCO_3$)	0-20,850	500-10,000
Total Hardness (as $CaCO_3$)	0-22,800	500-10,000
Total Solids	0-59,200	3,000-50,000
Total Dissolved Solids	584-44,900	1,000-20,000
Specific Conductance (umhos/cm)	1,400-17,100	2,000-8,000
pH (units)	3.7-8.8	5-7.5
Calcium	60-7,200	100-3,000
Magnesium	17-15,600	30-500
Sodium	0-7,700	200-1,500
Chloride	4.7-4,816	100-2,000
Sulfate	10-3,240	10-1,000
Chromium (total)	0.02-18	0.05-1
Cadmium	0.03-17	0-0.1
Copper	0.005-9.9	0.02-1
Lead	0.001-2	0.1-1
Nickel	0.02-79	0.1-1
Iron	4-2,820	10-1,000
Zinc	0.06-370	0.5-30
Methane Gas (percent composition)	(up to 60%)	**
Carbon dioxide (percent composition)	(up to 40%)	**

* Based on data collected by U.S. Army Corps of Engineers, Construction Engineering Research Laboratory
** No data presented

Source: Sanitary Landfill Technical Manual. Department of the Army. USA, 1994