DECISION SUPPORT FOR MUNICIPAL SOLID WASTE MANAGEMENT AND PLANNING

by

KIMBERLY D. BARLISHEN

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AUTHOR:	Kimberly D. Barlishen, B.Sc. (University of Manitoba) M.Sc. (University of Manitoba)
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ABSTRACT

A thorough review of mathematical models, based on the application of systems analysis techniques, that have been developed for municipal solid waste (MSW) management and planning problems is presented as evidence of the growing number and complexity of the available models. A survey of practising waste management professionals indicated a general interest in systems analysis techniques to assist with decision-making. However, a lack of practical applications of these techniques was also indicated, particularly by local and regional waste management agencies. The lack of practical model applications may result from the past reliance on landfills to manage MSW and the many non-economic implications (social, environmental, political, etc.) of MSW management and planning decisions. Research, to date, has not directly addressed the perceived deficiencies with the current problem solving techniques, nor has the application of knowledge-based system techniques been adequately explored within the field of MSW management and planning.

Three general approaches are proposed for the integration of knowledge found in the technical literature and possessed by experienced waste management engineers and planners, and existing mathematical models. These approaches are based on the creation of knowledge-based systems to interface with individual models, or assist with model selection and integration. A range of suitable application problem areas within the domain of MSW management and planning are described. As a means of demonstrating the validity, and potential benefits and limitations of the suggested decision support approaches, a prototype decision support system was developed to assist with the preliminary planning of MSW management systems. This prototype system combines knowledge-based system components with spreadsheet, optimization and simulation models to assist with the major planning activities: waste forecasting; technology evaluation; composting and recycling program design; facility sizing, location and investment timing, and waste allocation; and MSW management system analysis using simulation. The user is guided through the complex process of long-range program and facility planning, and is assisted with applying and integrating the various modelling components. Potential users of the prototype decision support system are local and regional waste management engineers and planners, consulting firms, and municipal decision-makers. Based on the opinions expressed by several practising waste management professionals, and two case study applications, the prototype decision support system is considered to represent a reasonable, useful, and practical (with respect to data requirements and cost) planning tool. This research has also produced knowledge bases for the prototype decision support system that represent a collection and organization of a significant amount of waste management expertise and mathematical modelling expertise contained in the MSW management and planning literature.

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TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The waste management crisis, faced by many North American municipalities, has caused them to look more seriously at how they manage their municipal solid waste. Municipal solid waste (MSW) refers to the non-hazardous waste generated in the households, commercial establishments, institutions, and light industries of a community, in addition to municipal services waste arising from activities such as street cleaning and landscaping. It is becoming increasingly more difficult to manage MSW. Increasing waste generation, diminishing landfill space, increasing pollution standards, rising disposal costs and uncertain technologies are a few of the problems facing waste management engineers and planners (Clark and Gillean, 1974; Chertow, 1989).

In the past, communities have relied almost exclusively on landfills to dispose of the MSW they generated. Transfer stations were also commonly used to reduce transportation costs if long distance hauling of waste to a landfill was required. However, due to the potential for environmental damage from landfill sites, the scarcity of land near urban centres and growing public opposition, many communities have been forced to consider other means to manage their wastes. This has given rise to the trend towards creating integrated MSW management systems, which rely on a combination of approaches including incineration, recycling and composting, to minimize the dependence on landfills. Additional facilities may be included in an integrated system: energy-from-waste facilities, which incinerate waste with the option of recovering steam and/or electricity; centralized composting facilities, which convert organic waste separated at-source by waste generators to a useful soil conditioner; materials recovery facilities, which accept source separated recyclable materials for further processing to meet end market requirements; and mixed MSW processing facilities, which separate out and process the compostable, the recyclable and, in some cases, the combustible portions of MSW. Landfills are still needed to dispose of the residuals from these processing facilities. This progression of MSW management systems is illustrated in Figure 1.

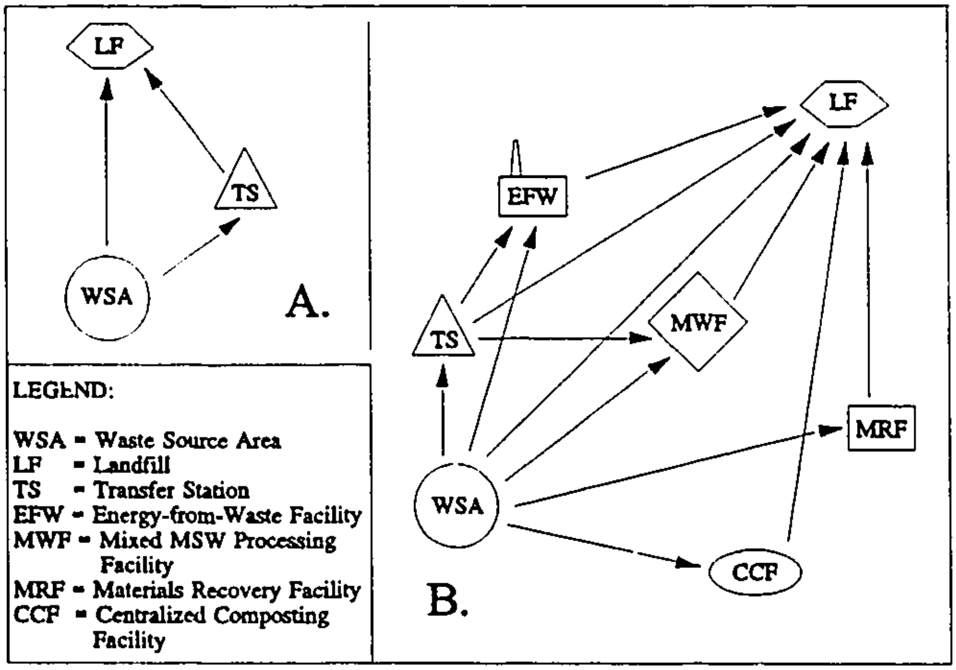

Figure 1. The progression of MSW management from a reliance on landfills (A) to the creation of integrated systems (B)

Solid waste management engineers and planners in North America are under pressure to produce long-term waste management plans, which specify the combination of facilities, and waste reduction, recycling and/or composting programs that will be used to collect, process and dispose of present and future waste streams in an environmentally and economically sound manner. Since many different options exist for MSW management technologies, and composting and recycling programs, MSW management plan development requires strategic planning (Environmental Protection Agency, 1989). The increasing number of options makes it more challenging to decide on the combination of collection, processing and disposal systems that will best serve the present and future needs of a particular community. The systems analysis techniques listed in Table 1 may be helpful in assisting the decision-making processes on a local or regional basis due to the increasing complexity of the systems and the growing number of alternatives.

Table 1. Partial listing of systems analysis techniques

*** Optimization Models and Related Techniques:**
- linear programming
- quadratic programming
- nonlinear programming
- integer programming
- dynamic programming
- goal programming
- geometric programming
- Lagrangian analysis
- control theory
- network analysis

*** Probabilistic Techniques:**
- queuing theory
- information theory
- statistical decision theory
- inventory analysis

*** Statistical Techniques:**
- multivariate analysis
- regression analysis
- factor analysis
- principal component analysis

*** Related Techniques:**
- benefit-cost analysis
- game theory
- input-output analysis

*** Simulation**

*** Decision Analysis and Utility Theory**

Source: adapted from Rogers and Fiering (1986)

Attempts have been made, over the past 30 years, to apply a variety of systems analysis techniques to model solid waste management and planning problems in order to alleviate some of the complexity involved. Existing mathematical models (defined as models which use or apply the systems analysis techniques listed in Table 1), range in their complexity and scope in addressing such issues as the development of regional solid waste management systems and the design of efficient refuse collection systems. Ongoing research is continuing to create more realistic and appropriate models for MSW management and planning (Lawver et al., 1990; Carlson, 1991).

However, the mathematical models have generally been limited to a consideration of economics, while the majority of previous waste management studies have primarily focused on the siting, design, construction, and operation of landfill sites. The nature of this public sector problem makes it unacceptable to simply base decisions on cost considerations, particularly given the potential for landfill technology to produce serious environmental, social and political impacts. Other types of decision-making approaches have been applied by practising waste management engineers and planners. Based on a review of the MSW management and planning literature, the convention in practise has been the use of techniques such as overlay or constraint mapping to select and evaluate landfill sites, and the use of mathematical models to assist with landfill design and performance assessments. The need to plan, design and operate integrated MSW management systems may necessitate the development and use of additional approaches to providing decision support to waste management engineers and planners.

There is also a rapidly increasing body of literature devoted to the expertise gained by waste management engineers and planners as they investigate and implement alternative MSW management systems. However, much of the available expertise is dispersed in numerous guides and handbooks being produced to aid waste management engineers and planners. In addition, this technical literature generally fails to make reference to the availability and potential benefits of mathematical models. Therefore, although models have been developed by researchers to assist decision-makers, indications are that these models are not being widely applied in actual practise.

Waste management knowledge and the number of mathematical models created specifically for MSW management and planning problems have expanded, but in isolation of each other. The potential thus exists to extend and support the use of the available systems analysis techniques by creating decision support systems, which couple the abilities of experienced waste management professionals and mathematical models, for applications in the area of MSW management and planning.

Decision support systems may be defined, in general, as systems of software designed with the objective of improving the performance of human decision-makers (Ludvigsen and Dupont, 1989). Traditionally, decision support systems have been designed to support quantitative, mathematical and computational reasoning (Turban and Watkins, 1986). Knowledge-based systems generally contain declarative knowledge of a problem domain often directly acquired from the literature, and may be utilized as a means of providing advice and expertise to support the user of a decision support system (Ludvigsen and Dupont, 1989). Knowledge-based systems are also recognized for their abilities to represent qualitative information, and the heuristic knowledge and rules-of-thumb possessed by domain experts (Han and Kim, 1989). The addition of knowledge-based system components can make a decision support system a "more active, and potentially more valuable participant" in a decision-making process (Turban and Watkins, 1986). The development of a decision support system integrating knowledge-based system components to address a specific problem is an iterative process involving several major steps (Waterman, 1986):

1) identification of the scope, goals and necessary resources for the project by gathering information on the problem;
2) conceptualization of the key problem solving components, relationships and constraints;
3) formalization and implementation of the conceptual model in a representation that conforms with the system development tools;
4) testing or assessing the validity of the individual system components and evaluating the performance of the system as a whole to determine the need for changes or refinements.

The advantages of the integrated use of several decision-making tools have been recognized within the domain of MSW management and planning (Clark and Gillean, 1981; Wilson, 1981). The resulting decision support systems may have several uses including training waste management engineers and planners, and identifying local data collection requirements (Light, 1990). Ultimately, the development and use of decision support systems which incorporate knowledge-based system techniques within the domain of MSW management and planning may lead to more efficient and cost-effective management of waste.

This research involves several preliminary activities: an investigation of available mathematical models which use systems analysis techniques as a means of exploring

MSW management and planning problems; the identification of the extent to which these types of models are being used; and the identification of deficiencies in the current, more conventional, approaches as perceived by practising waste management professionals. The investigation was carried out through a combination of a review of the existing literature and a survey of North American waste management professionals and academic institutions. The scope of the research is limited to systems analysis work done primarily in the area of municipal, non-hazardous, solid waste management. This research also attempts to develop a method for improving current modelling environments through the integration of knowledge-based systems and mathematical models, in an effort to extend and support the use of systems analysis techniques in actual MSW management and planning decision-making situations. The remaining objective of this research is to illustrate the potential of applying the proposed method for improving decision support in this domain by suggesting suitable application problem areas and by describing the development of a prototype decision support system for one of these suggested application areas.

The literature review encompasses modelling applications in several problem areas: integrated environmental systems modelling; hazardous waste management; and MSW management including regional solid waste management systems planning, waste generation and composition forecasting, collection systems design, assessing the potential for materials and energy recovery, facility design and operation, and facility siting. The results of the survey of waste management professionals and institutions are presented, following the review of systems analysis models developed in MSW management and planning. A review of recent attempts to create knowledge-based systems to accompany more traditional computer models is also presented. A case is made for the need for improved modelling environments within the domain of MSW management and planning based on the results of the technical survey and the literature review. The applicability of specific problem areas for applications of knowledge-based system techniques to create decision support systems is examined. The identification stage of the development of decision support systems for MSW management and planning problems is described in chapters two and three.

To demonstrate the potential applicability of the suggested decision support approaches, a microcomputer-based tool has been developed to support the preliminary planning of MSW management systems at the local or regional level. The tool has been designed to assist waste management engineers and planners in creating strategic, long-range, MSW management plans. This is done through the integrated use of optimization, simulation and spreadsheet models, and knowledge-based system components which contain waste management expertise, to produce a support system for MSW composting and recycling program design, and facility planning. This planning tool, or prototype decision support system, addresses not only a very timely and complex problem, but an area currently lacking in sufficient decision support. The planning tool is also an attempt to collect, organize and encode waste management expertise and mathematical modelling expertise with respect to these planning activities. Potential users of the prototype decision support system are waste management agencies, consulting firms, and municipal decision-makers and planners. The tool was designed to provide both introductory and more advanced information and modelling tools for program and facility planning applications. The conceptualization phase of the chosen decision support system development project is described in chapter four. The results of the formalization and implementation of the necessary knowledge and mathematical models within the decision support system to conform with the chosen development tools are provided in chapter five. Finally, the testing or evaluation phase of the chosen decision support system development project is detailed in chapter 6 with discussions of the validity, benefits and limitations of the current prototype system. Preliminary program and facility planning for two case study communities is presented, in chapters seven and eight, to demonstrate the uses and capabilities of the planning tool.

Sample listings of selected knowledge-based system components of the planning tool are provided in Appendices B, C and E. Interested parties may contact the author for further details regarding the knowledge-based system components and the spreadsheet models developed for the planning tool.

CHAPTER 2

LITERATURE REVIEW

A significant amount of research has dealt with aspects of waste management and planning. Most of the research occurred in the late 1960's to early 1970's, although the field has seen a resurgence of interest as concern for the environment has increased. The review of the literature in waste management is organized according to the application area: integrated environmental systems management, hazardous waste management, and MSW management. Specific problems areas are addressed with respect to MSW management: regional solid waste management systems planning, waste generation and composition forecasting, collection systems design, assessing the potential for materials and energy recovery, designing and operating solid waste facilities, and facility siting. The majority of the systems analysis techniques listed in Table 1 have been applied in the models created to address these waste management problem areas.

2.1 Literature review approach

Several approaches were used to gather information related to the use of systems analysis models for various aspects of waste management and planning. Both electronic and manual searches were conducted to elicit information from scientific journals and publications, including doctoral theses. Literature searches were conducted using the Science Citation and Engineering Indices, and then proceeded to manual searching of pertinent journals and references derived from the papers collected. Doctoral dissertations were surveyed using Dissertation Abstracts International. Several North

American universities and colleges were contacted to ascertain the types of current research projects being conducted in the area of MSW management. The literature review was also aided by the work of Wilson (1977), and Wenger and Cruz-Uribe (1990), who completed survey papers of mathematical models in waste management.

In addition, technical surveys were developed and mailed to North American municipalities and consulting firms handling MSW management problems. Copies of the survey forms are included in Appendix A. Approximately 100 surveys were sent out, of which approximately 30% were returned. The objectives of such a survey were to indicate the prevalence of computer modelling in actual practise and the perceived deficiencies in current solid waste management and planning procedures. This information is used to supplement the literature review.

2.2 Integrated environmental systems management

The conversion of natural resources into forms usable by society results in the creation of a residuals management problem. Air-borne, liquid and solid wastes result from the activities of industry, agriculture, commerce and residents. The main objective of waste management is to minimize the impacts these residuals have on the environment. Petak (1980; 1981) notes the need for a systems approach to integrated environmental systems management by describing the links within this multi-disciplinary problem. Guruswamy (1985) describes the problem qualitatively, whereby, objectives with respect to the protection of air, water and land resources are set, and residuals are managed to meet these objectives within the legal, political and economic frameworks. The system described by Petak (1981) for integrated environmental systems management is shown in Figure 2. Societal, environmental, political and regulatory constraints, as well as economic and technical assessments, are involved in the decision-making process.

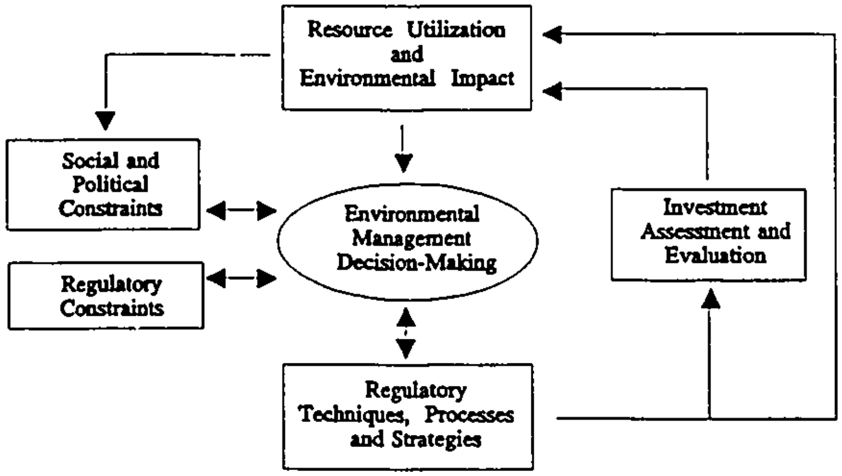

Figure 2. Integrated environmental systems management
Source: adapted from Petak (1981)

Management strategies and plans have been developed with the assistance of analytical tools and systems analysis techniques, since it is not feasible or practical to experiment with full-scale environmental systems. Several systems analysis approaches have been suggested for the integrated management of environmental systems. Panagiotakopoulos (1972) applies network analysis and linear programming to the impact of wastes on the environment to ensure its absorbing capabilities are not exceeded. This same researcher uses goal programming to deal with conflicting economic, environmental and technological objectives in environmental residuals management (Panagiotakopoulos, 1975*a*), and also develops a waste management network model linking wastes and the environment to allow trade-offs with the economic system (Panagiotakopoulos, 1975*b*). A linear programming model, suggested by Bishop and Narayanan (1979), determines optimum pollution control strategies for air, water and solid wastes resulting from resource development. Seo and Sakawa (1979) develop an alternative to goal programming to solve multi-objective optimization problems for environmental systems by combining the use of utility functions and pareto-optimal solutions (i.e., solutions in which no change in decision variable values will improve the solution with respect to one goal without hurting another).

The management of residuals within the natural environment may also be modelled as one component of regional economic planning models, as shown by Gibson (1976). Kawamura (1984) describes the Strategic Environmental Assessment System (SEAS), developed by the United States Environmental Protection Agency, which models production activities, the flow of goods and services and the required residuals management system. Sushil and Vrat (1989) note the need to incorporate waste as a parameter in national planning, and suggest several modelling techniques: simulation, input-output analysis, and goal programming.

Several of the authors note a tendency for modellers to create large models to achieve a higher level of realism, and warn of the problems that may arise if such an approach is taken. For example, Kawamura (1984) describes the SEAS model as outgrowing its utility, and requiring work to make it more transparent and understandable to decision-makers.

2.3 Hazardous waste management

An ever increasing amount of attention is being directed at the management of hazardous wastes, generally created through industrial or development activities. Shimizu (1981) develops a multi-objective linear programming procedure to formulate comprehensive radioactive waste management plans. Peirce and Davidson (1982) apply linear programming techniques to identify cost effective schemes for the transportation, transfer, processing and disposal (storage) of such wastes. These planning and management activities are common to all waste management systems, including non-hazardous MSW management systems. Peirce and Davidson employ the Waste Resource Allocation Program (WRAP), primarily used in non-hazardous waste management, to select, locate and size hazardous waste management facilities. Jennings and Sholar (1984) also use the WRAP program in their application of network analysis to represent regional hazardous waste management as a routing problem. They note several deficiencies with WRAP; it may produce only a local optimum and is a large code, making confirmation and modification of the solution procedure difficult. Baetz et al. (1989*b*) formulate a dynamic programming model to investigate waste reduction and treatment strategies in industry.

Research has also been done to apply systems analysis techniques to more specific elements of hazardous waste management and planning: expansion planning, using multi-objective linear programming (Shimizu, 1983); and siting, through the use of network and statistical analyses (Schwartz et al., 1989). RAWSYM (Radioactive Waste Management System), a model reported by McLeod and Park (1982), may be used to evaluate the future time behaviour of wastes with regards to type, amount, location, processing, transport and disposal. Buchnea (1983) proposes a systems model to evaluate environmental impacts of disposal systems for low-level radioactive wastes.

As noted in the area of integrated environmental systems modelling, care must be taken to state the limitations and most appropriate applications of systems analysis techniques. Buchnea (1983) suggests that computer modelling may be a valuable tool in choosing between alternative disposal systems and determining design and site requirements. It is proposed by Schwartz et al. (1989) that complex optimization models are not always better; simpler models are more understandable and useful to policy makers, and are more appropriate when data quality is poor (a problem that tends to exist in the waste management field).

2.4 Municipal solid waste management

This research is most concerned with the management of solid wastes, as opposed to liquid, or air-borne wastes. The solid waste management area itself is often explored within the individual generation sectors of agriculture, industry, and municipalities or commercial establishments.

Mathematical modelling using systems analysis techniques has been more extensively applied to non-hazardous solid waste management and planning. The majority of this work took place in the late 1960's to the early 1970's. The use of systems analysis techniques for MSW management and planning problems has been qualitatively addressed and promoted by MacLaren and Sexsmith (1970), and Haynes (1981). The overall MSW management planning process for composting and recycling programs, materials collection systems, or waste receiving facilities is illustrated in Figure 3.

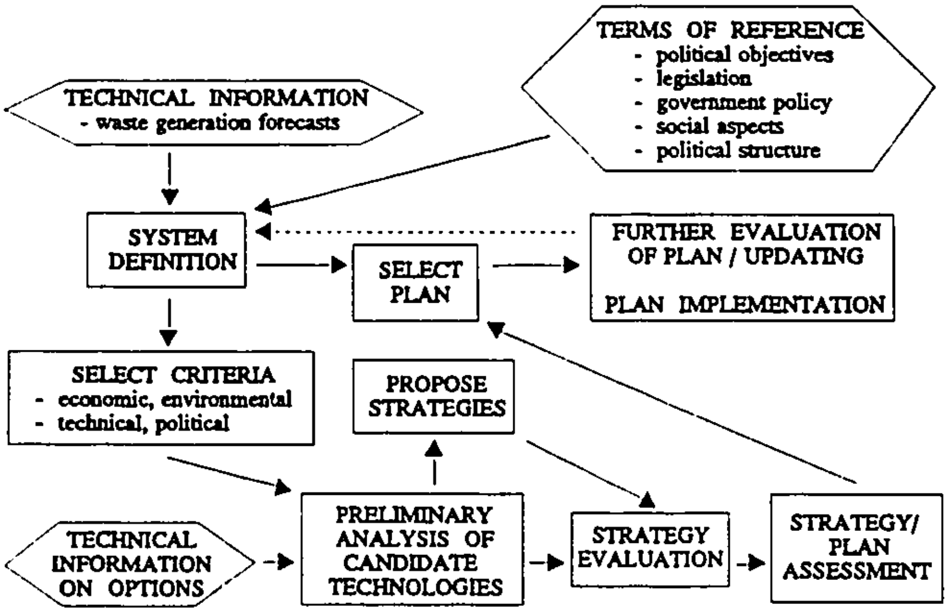

Figure 3. Conceptual model of MSW management planning
Source: adapted from Wilson (1977)

A plan should specify the type, size, location and timing of investment of technologies to be used, and the allocation of waste to the technological options. The initial step is to define a set of criteria on which alternative plans are to be assessed. The criteria are usually based on economic, technical, environmental, social and political objectives. Possible waste collection, processing and disposal options are evaluated and the most promising options are included in alternative strategies. For each strategy, the evaluation procedure is continued until an 'optimal' plan is identified and further evaluated (Wilson, 1977). According to Wilson, systems analysis techniques may aid the planning process, primarily in the area of strategy evaluation, i.e., the evaluation of a large number of alternatives against several criteria on a routine and consistent basis.

Systems analysis techniques have been applied to the following MSW management and planning problems, and these will be discussed in greater detail in the following material:

- regional solid waste management systems planning;
- waste generation and composition forecasting;
- collection systems design;
- assessing the potential for materials and energy recovery;
- designing and operating solid waste management facilities;
- and, facility siting.

In Figure 4, the principal processes in urban or regional solid waste management systems are depicted. Each major MSW management activity (waste generation, collection, processing and disposal) is affected by many, often difficult to quantify, factors. In addition to being dependent on many external factors, these activities are also interdependent. These dependencies complicate the tasks of planning, designing and operating MSW management systems. They also complicate attempts to create adequate models to facilitate decision-making in actual practise, thus limiting the potential role of systems analysis techniques in critical decision-making situations. The available mathematical models are also often restricted in scope to dealing with one of the MSW management and planning activities or quantifying one or more of the external factors in isolation of the rest of the system.

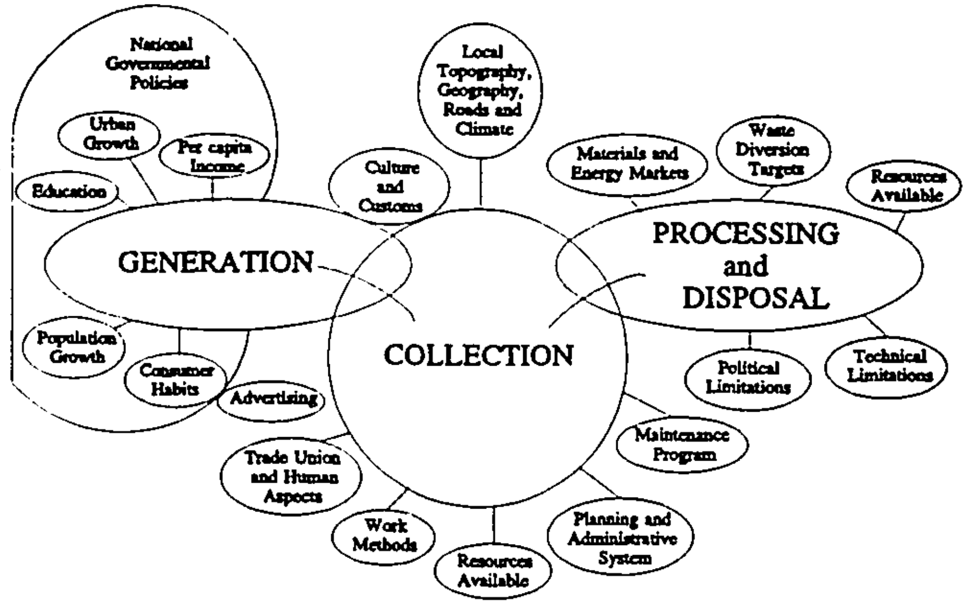

Figure 4. Principal processes of MSW management systems
Source: adapted from Haynes (1981)

2.4.1 Regional solid waste management systems planning

Solid waste management engineers and planners recognize the benefits of creating a regional waste management system to take advantage of economies of scale and combined land resources, and reduce the number of assumptions and site constraints. A MSW management system refers to a network of facilities that are required to collect, process, treat and dispose of the non-hazardous waste generated in the residential, commercial, industrial and institutional sectors of a municipality (Smith, 1989). Systems analysis techniques may assist in developing Solid Waste Management Master Plans, which specify the type, size, location and investment timing for required facilities over a planning horizon of 20 to 30 years.

Regional solid waste management systems planning models range from simple cost estimation models to more complex computer models which select system technologies, scales and sites to meet the given constraints at minimum cost. The latter models, for the most part, involve a combination of facility selection and location, facility sizing, facility investment decisions, and waste allocation to the facilities. Waste generation and composition forecasting, and the curbside collection system, are not generally considered explicitly. Regional solid waste management systems planning begins from the point when collection vehicles have completed the curbside collection activity. Model complexity is dependent on the characteristics of the region. Complex models are designed for communities with several appropriate technological options, markets for recovered materials and energy, several available sites for potential facilities and a set of restrictions or goals set by the public or government.

The types of systems analysis approaches taken in modelling regional solid waste management systems are varied. Kuhner and Heiler (1973) review modelling applications in waste management concentrating on solution algorithms. Clark (1973) discusses available regional planning models for solid waste management formulated as linear programs and fixed-charge problems (or mixed-integer linear programs), and solved using branch-and-bound or heuristic algorithms such as that developed by Walker (1976). Fixed-charge models include costs, such as site acquisition and construction, that are incurred regardless of the level of activity at a site. These costs are considered for all existing facilities, and are brought into the solution only for those potential sites that are selected. Thus, facility capital and operating costs are represented for modelling purposes as a fixed cost and a variable cost (linearly dependent on facility capacity).

Wilson (1977) critically reviews a comprehensive list of available waste management planning models. Light (1990) describes six commercially available software packages for planning integrated solid waste management systems. The models rely on optimization or simulation, and vary in their level of detail, data requirements, user-friendliness, and cost. The regional solid waste management systems planning models reviewed for this research are grouped according to the type of systems analysis technique employed.

• Optimization models and related techniques

Optimization models use mathematical programming techniques to search systematically among a range of feasible solutions for the optimum, generally least-cost, solution to recommend facility sites, sizes, and investment timing (Light, 1990). An optimization model developed by Esmaili (1972), and solved through enumeration using heuristic techniques, selects solid waste processing and/or disposal facilities that minimize the cost of haulage, processing and disposal. The non-linearity of MSW management systems, with economies and diseconomies of scale, are taken into account and solved using geometric programming by Yale (1978).

Marks (1969) formulates a fixed-charge facility location model to establish transfer station locations. Marks et al. (1970) and ReVelle et al. (1970) study the more general problem of locating and sizing solid waste facilities as a fixed-charge problem within the public and private sectors. Helms and Clark (1971) select solid waste disposal facilities by modelling existing regional waste management systems as a fixed-charge problem. Kuhner and Harrington (1975) pay special attention to the extension of mixed-integer linear programming, within a paretian environmental analysis framework, to solve a dynamic (multi-period) investment model for regional solid waste management. This research is viewed by Wilson (1977) as being the most comprehensive attempt to specifically consider costs and benefits among interest groups and communities. Clayton (1976) relies upon mixed-integer linear programming to investigate alternative waste management systems including the issue of individual versus regional systems. Walker (1976) analyzes the determination of disposal facility requirements as a fixed-charge problem, and presents an algorithm, used by many researchers, for the approximate solution of the resulting mixed-integer linear program. The optimum located may, however, only be a local optimum. Jenkins (1980) investigates the optimal location of recycling facilities for MSW within different solid waste management systems using mixed-integer linear programming. Hasit and Warner (1981) describe WRAP (Waste Resource Allocation Program), which contains static and dynamic models solved through mixed-integer linear programming, and which has been used to plan solid waste management systems. Jenkins (1982) also utilizes mixed-integer linear programming techniques for a fixed-charge model in an actual planning study for Toronto, Ontario. Jenkins refers to other attempts to use the approach in planning studies for Halifax, Toronto and the Quinte Region. Jenkins also criticizes WRAP for its poor computational performance and insufficient output. In a more recent application, Gottinger (1986) creates a fixed-charge model for MSW management systems, to determine processing and disposal facilities requirements, analyzed as a network flow problem. A fixed-charge model is presented by Khan (1987), which optimizes the location of, and allocation of waste to, transfer station sites using a branch-and-bound procedure.

Linear and dynamic programming techniques have also been applied to the problem of developing regional solid waste management systems. Fuertes et al. (1974) describe the generation of trade-off curves for costs versus equity in a linear programming approach to the facility location problem. They note the importance of having solutions that are both equitable and pareto-optimal. Using linear programming, Kampmann (1975) analyzes regional post-collection alternatives based on financial costs. Greenberg et al. (1976) also apply linear programming to an actual waste management system planning study. Chapman and Yakowitz (1984) describe the use of the Resource Recovery Planning Model (RRPLAN). RRPLAN relies on the use of linear programming techniques to size and site facilities, and a detailed cost accounting system to incorporate economies of scale and estimate the effects of siting, routing, marketing and financial decisions on a waste management system.

The dynamic programming approach is applied by Rao (1975) to the planning of rural waste disposal systems. Baetz et al. (1989*a*) also use dynamic programming to determine the optimal sizing and timing for regional landfills and EFW facilities.

- **Simulation**

Simulation programs require the user to supply a framework of the system to be modelled; in a MSW management system this would include the facilities and the possible links. DISCUS is a solid waste management game developed by Klee (1970) to simulate the development of a solid waste management system of transfer stations, incinerators and landfills. Wright (1975) applies his stochastic simulation model to solid waste management in small communities. RECYCLE, a simulation model described and applied by Clapham (1987), allows planners to consider a vast range of options for recycling, within the waste generation, collection and disposal systems, based primarily on simplified cost calculations. A more general decision-making model for evaluating competing alternatives is described by Klee (1989), with an application to hazardous waste management. A recent effort relies on simulation to evaluate different integrated MSW management systems (Lawver et al., 1990). The model allows planners to compare system costs and waste flows given a specification of elements and links in a MSW management system. Default values are provided as a basis for preliminary studies.

*** Related techniques**

A simple cost analysis approach for selecting a disposal system is demonstrated by Miller and Craig (1977). Leech et al. (1985) describe a computer program that helps the user develop capital and operating costs for solid waste facilities. The user is also prompted to consider all factors relevant to the prediction of the financial implications of future MSW disposal and recycling projects. Spreadsheet models may be useful tools in planning and operation, particularly for economic modelling. Vigil et al. (1987) describe a spreadsheet-based financial model that aids in data entry and computations for planning waste management strategies.

A study conducted at the University of California at Berkeley in the 1950's is viewed by Clark and Gillean (1981) as being the most broad-scale study of the entire waste management system. The study included the development of several modules: waste generation and collection; treatment and disposal; regional economics; and population, public health, land use and process technology considerations. Wilson et al. (1984) and Rushbrook (1987) describe the Harbinger system, developed by Harwell Laboratory, that helps waste management engineers and planners create waste management plans, with its generation, transportation and treatment/disposal sub-models.

- **Decision analysis and utility theory**

Most of the previously mentioned studies were based on cost considerations, and tended to overlook the environmental and social impacts of decisions. Other researchers have attempted to address and quantitatively analyze these issues within their modelling procedures. Wenger and Rhyner (1972) select enumeration as a method of evaluating solid waste management system alternatives using a matrix of environmental, social and engineering criteria combined into a single index value using decision analysis techniques. Hekimian (1972) applies optimization for haul and disposal, and utility and decision theory in order to integrate the value judgments of three regional decision-making groups. The model was used in the development of the Kansas City Metroplan regional solid waste management system. The Solid Waste Environmental Evaluation Procedure (SWEEP), developed by Collins (1974), models disposal system environmental effects, using decision analysis to produce and combine utility functions for these effects. Chen et al. (1979) propose a similar approach to social decision-making involving several decision-makers and concerned parties, demonstrating its use for the problem of installing a solid waste shredding facility. Collins and Glysson (1980) utilize decision analysis and utility theory for the selection of preferable projects with regards to environmental impacts, and demonstrate their approach with a waste disposal example. Comprehensive multi-criteria procedures for comparing alternative solid waste management solutions are also discussed by Sobral et al. (1981) and Maimone (1985).

2.4.2 Waste generation and composition forecasting

Information regarding waste quantities and composition is required to assess current collection, processing and disposal methods, and also to plan or evaluate future alternatives, including land and equipment resources (Musa and Ho, 1981). Modelling of solid waste generation has generally been restricted to statistical techniques such as regression analysis to determine important economic and social factors for estimating waste generation and composition (DeGeare and Ongerth, 1971; Grossman et al., 1974; Ali Khan and Burney, 1989). Statistical research has also taken place on issues such as optimal sample weights (Klee and Carruth, 1970), and sample size (Musa and Ho, 1981; Lohani and Ko, 1988) necessary for waste generation and composition estimation. A dynamic simulation model is developed by Chikte and Levis (1976) to represent the generation of litter in urban areas.

2.4.3 Collection systems design

Perhaps because the curbside collection of waste traditionally accounted for the largest expenditure for MSW management (including storage, transfer and transport), this area has received a great deal of attention for the application of systems analysis techniques.

Quon et al. (1968) study changes in quantities of refuse, resulting from pick-up frequency changes, using statistical analysis. Statistical techniques have also been applied to developing efficiency measures for collection crews (Quon et al., 1970). Clark et al. (1971) and Petrovic (1976) model the costs of MSW collection by identifying the important influencing factors using regression analysis.

Quon et al. (1969) and Truitt et al. (1969) use simulation to study operational policies for waste collection. Simulation provides a means to determine optimized routes for individual collection vehicles, as shown by the work of Bodner et al. (1970). McCoy (1971) develops a simulation model incorporating equipment selection, routing and scheduling for the collection problem. Clark and Gillean (1974) report on the successful application of a data collection system and simulation model to the redesign of the collection system of a large metropolitan area. Simulation techniques have also been applied to the problems of refuse vehicle size determination and their allocation to collection areas (Cardile and Verhoff, 1974). Ouano and Frankel (1976) study factors affecting collection costs using simulation. ROSS (Refuse Operation System Simulation), described by Cox (1986), helps the user determine resources required to collect waste and devise alternative collection methods and costs.

A number of other systems analysis techniques have been employed in the study of routing and collection. Wahi and Peterson (1972) combine transportation and maximal flow problems with management science and gaming to produce a game that may be applied to areas of ecology, including solid waste collection. Beltrami and Bodin (1974) and Chiplunkar et al. (1981) apply heuristic networking techniques to examine the efficient routing of collection vehicles. Beltrami and Bodin (1974) state that many large scale problems do not fit into classical models, and need a combination of formal and heuristic techniques to investigate near-optimal solutions. Inventory analysis has been utilized to optimize the refuse storage systems used in developing countries with respect to sites, containers and collection parameters (Ali Khan, 1984).

Other researchers have examined waste collection scheduling using linear programming (Tanaka, 1970). Clark and Helms (1970) formulate a fixed-charge model to determine the most efficient location of garages for collection vehicles. Clark and Helms (1972) apply linear programming techniques to determine the number and types of collection vehicles required for a large metropolitan area.

2.4.4 Assessing the potential for materials and energy recovery

Materials and energy recovery from MSW are becoming increasingly more important. Planners and citizens must be made aware of all potential resource recovery opportunities so they do not adopt less efficient or less environmentally sound options. Research efforts have been directed at the evaluation of the potential for materials and energy recovery from MSW.

Glassey and Gupta (1974) present a linear programming model formulation to estimate maximum feasible recycling rates, and to study the effects of collection, sorting and transportation on waste paper recycling. Palmer (1975) develops a mixed-integer linear programming model to select optimal resource recovery process choices, which allows testing of the effects of demand, legal and policy constraints. Clifford et al. (1978) introduce the use of linear programming as a planning tool for the paper industry. Findley (1978) incorporates dynamic programming, utility theory and fuzzy set theory to investigate alternatives and constraints in resource recovery investment decision-making and policy analysis. Ogbudinkpa (1978) uses linear programming to investigate the economics of recycling aluminum beverage cans. A stochastic decision model, to determine costs associated with returnable beverage containers, is developed by Kahalas and Leininger (1979). A planning model, based on network analysis, has been developed by the United States Environmental Protection Agency to assist waste management engineers and planners with the management of resource recovery projects (Felago and Stoller, 1979).

More recently, Milke and Aceves (1989) use linear programming to determine the most economical combination of recycling methods. Lund (1990*b*) develops a linear programming model formulation that provides a least-cost recycling plan based on the economics of landfill operation, closure and replacement with other disposal facilities. Lund also explains how to incorporate market effects for recycled materials or an incinerator that disposes of ash in a landfill. The systematic lack of knowledge by engineers in the area of formulating recycling options, and estimating costs and effectiveness, is also mentioned by Lund.

Many investigations have been restricted, however, to simple cost-benefit analysis, for example, the work done by Malina and Morgan (1972) which evaluates technical and marketing aspects of recycling and solid waste management systems that include recycling. Abert and Vancil (1977) create a graphical technique to determine the economic feasibility of a recovery facility based on waste characteristics and economic parameters. Other economics-based models of resource recovery are presented by Lidgren (1986) and Bertolini (1987).

2.4.5 Designing and operating solid waste facilities

Modelling the performance of waste receiving facilities, such as landfills, transfer stations, and incineration or energy-from-waste (EFW) facilities, may help designers or facility managers make decisions. Queuing theory has been applied to forecast the congestion at solid waste facilities with an illustrated example for transfer stations (Humphries, 1986), and to simulate the actual operation of such a waste receiving station (Yaffe, 1974). Hartz and Ham (1981) apply queuing theory to investigate the optimum number of receiving bays for solid waste facilities, also using a transfer station example. Ouano (1983) uses simulation to study feasible locations for transfer stations. Capacity planning for waste processing and disposal facilities has been investigated using dynamic programming by Baetz (1988). Baetz also considers optimal and near-optimal solutions for finer time increments and stochastic demand through simulation. Arey (1991) uses queuing theory and simulation to develop models for sizing solid waste receiving facilities. Andrews et al. (1991) report of the development of a decision support system created around a linear programming algorithm to determine the optimal combination of materials received at a composting facility to produce optimal composting conditions.

Christensen and Haddix (1974) describe analytical techniques, with linear programming formulations, for the design and efficient operation of landfills. Ostro (1976) creates an urban model that investigates the interaction of optimal waste disposal site location and the degree of regionalization. Ostro also uses cost-benefit analysis to evaluate various disposal and recovery methods, and how economic feasibility of waste disposal systems relates to aspects of urban structure such as land costs. More recently, Lund (1990*a*) combines optimal depletion theory and the capacity expansion problem to set prices for landfill capacity and select the optimal lifetime for a landfill. This methodology may help set tipping fees or demonstrate the need for recycling and reduction efforts.

Second Opinion is a model created to facilitate the evaluation of the engineering, financial and economic aspects of landfills and EFW facilities (Carlson, 1991). The model provides sample data bases for required parameters and detailed models of these technologies, which allows investigation of such issues as landfill liner selection and air emissions from EFW facilities.

Much recent research has focused on the chemistry and microbiology of landfilled wastes, particularly the production of leachate and gases (Wilson, 1981). Researchers have utilized modelling techniques, primarily simulation, to investigate many landfill related issues: methane migration (Moore et al., 1982), moisture transportation (Korfiatis, 1984), liner design (Demetracopoulos et al., 1984), leachate production (Demetracopoulos et al., 1986), and the movement of trace gases (Lang, 1989). Forgie and Byer (1984) describe two leachate leakage models that may be used in conjunction with a cost model to determine the cost-effectiveness of leachate control systems. Gebhardt and Jankowski (1987) introduce analytical techniques to protect groundwater resources at disposal sites, such as the use of computer models to assess groundwater contamination sensitivity at landfill sites, landfill performance and contaminant transport. Baetz and Byer (1989) investigate moisture control during landfill operation using a simulation model.

2.4.6 Facility siting

An important aspect of MSW management and planning is the siting of waste management facilities. The factors to be considered in evaluating the suitability of a site include topography, hydrogeology, agricultural potential and proximity to developed areas. As previously noted in the introductory chapter, mathematical models based on the application of systems analysis techniques have not been widely applied in facility siting studies. Suitability analysis using overlay or constraint mapping, or multi-criteria evaluation using weighting techniques, appear to be the most dominant methods for landfill site selection and evaluation in practise (Lane and McDonald, 1983; Han and Kim, 1989; MacLaren Engineers, 1989). As described in section 2.4.5, mathematical models may provide assistance in assessing the attributes chosen to represent the various decision criteria. For example, Gebhardt and Jankowski (1987) describe several simple analytical modelling techniques for preliminary landfill site evaluation, and Ruth et al. (1980) describe the use of remote sensing techniques to evaluate landfill site characteristics. Investigations have also been carried out on less quantifiable aspects of the siting problem such as the impacts and acceptance of solid waste facilities by host communities (Zeiss and Atwater, 1987;1989).

2.5 Survey results

Letters were sent to 35 North American academic institutions requesting information on current research projects related to MSW management and planning. The institutions chosen for the survey had specialized waste management research centres, waste management programs, or individuals with expertise in waste management.

Approximately one half of those surveyed responded. Although a significant amount of research is taking place in the field of waste management, particularly in the areas of hazardous waste treatment and site remediation, few projects were reported relating to the planning or design of MSW management programs or facilities, or integrated MSW management systems modelling. Two relevant projects were noted: the economic impacts of recycling on EFW facilities, and planning for MSW recycling.

Technical surveys were formulated to determine the degree to which computer modelling tools are utilized in actual MSW management and planning activities. The waste management professionals surveyed were asked to describe the techniques/tools utilized for integrated MSW management systems planning and for facility planning, data collection policies, the current use and effectiveness of materials recovery programs, current facility planning procedures, and the major deficiencies perceived in the current approaches to MSW management and planning. Copies of the survey forms may be found in Appendix A.

Approximately 100 surveys were sent to local and regional public works departments and environmental consulting firms in Canada and the United States. Forty-seven percent of the 60 public works department surveys were returned, while only ten percent of the 39 consulting firms returned their survey forms. This resulted in an overall return rate of 32%. Survey forms were returned by only three American public works departments and one American consulting firm. It was therefore difficult to draw any conclusions regarding the effects of the different regulatory, economic and political environments on MSW management and planning procedures between Canada and the United States.

The population base of the communities and municipalities surveyed ranged from approximately fifteen thousand to one million. While the majority of communities and municipalities rely on landfills for managing the bulk of their MSW, six communities (21% of respondents) incinerate a portion of their MSW. Ninety-three percent of the communities and municipalities that responded to the survey have initiated pilot-scale or full-scale composting and recycling programs; however, there was no evidence that extensive planning was conducted prior to implementation of these programs. The majority of respondents indicated that either no specific tools or techniques are used for the planning, design and operation of MSW management systems, or the activities are handled by consultants and they are unaware of the tools and/or techniques being applied. Computer modelling was only mentioned with respect to landfill design, vehicle routing and waste haul optimization in approximately 21% of the completed surveys. Approximately 25% of the respondents stated that their community or municipality is now in the process of developing or has recently completed a Solid Waste Management Master Plan, detailing the future direction of their waste management systems. No mention was made of specific computer modelling tools or techniques that were, or will be, employed in these planning studies. Approximately 21% of respondents indicated that no new facility planning activities are occurring or are expected to occur in their communities in the near future due primarily to a reliance on landfills and the existence of a site(s) with substantial remaining capacity. Major deficiencies were identified in the current MSW management and planning process: the difficulties that arise due to the political nature of this public sector problem (18% of respondents); the complexity, length and cost of the environmental assessment process required for new landfill sites

(14% of respondents); the lack of knowledge on the part of the public regarding waste management (11% of respondents); the difficulty in securing and forecasting markets for recovered materials (7% of respondents); and the difficulty in predicting trends in waste generation (3% of respondents).

As very few consultants responded to the survey, it was difficult to assess the degree to which computer modelling tools and techniques are utilized in the MSW management projects undertaken, including Solid Waste Management Master Plan studies. Conventional landfill design models and siting approaches (eg., groundwater quality and leachate flow models, and overlay or constraint mapping) are being utilized. Simulation and optimization models are providing assistance in designing efficient transportation systems and planning regional solid waste management systems. Several deficiencies were identified regarding the MSW management and planning process: the inadequacy of knowledge of waste composition; the inadequacy of data and analytical tools needed to make objective assessments of the relative impacts (environmental, social, etc.) of various waste management strategies, the lack of understanding on the part of the public and politicians with respect to facility siting, and the difficulty in predicting the effectiveness and impacts of recycling programs.

The results of the technical survey indicate that the majority of decision-making in the MSW management and planning area occurs without the assistance of computer modelling tools; systems analysis techniques in particular. However, there appears to be a demand for techniques and/or tools that facilitate the forecasting of waste generation and composition, that allow the comparison of waste management technologies, and that model integrated MSW management systems such that the impact of materials recovery programs may be measured more readily. Consultants appear to be responsible for the large majority of the MSW management and planning activities.

2.6 The need for improved modelling environments

The literature indicates that although all subject areas in solid waste management and planning have received varying degrees of attention, deficiencies are apparent in the work done to date. This field has received limited attention, when compared to other research areas such as water resources management or wastewater treatment. Several problem areas have not yet been the subject of applications of all available systems analysis techniques such as dynamic programming or goal programming. However, many areas, such as collection vehicle routing, facility design and operation, and regional solid waste management systems planning, have been thoroughly investigated using numerous modelling techniques.

The evidence seems to indicate that, despite these research efforts, mathematical models applying systems analysis techniques are not finding their way into common waste management and planning practise. Rich (1990), in his review of new commercially available environmental systems software, mentions one non-hazardous solid waste management tool designed to assist with the tracking and billing of waste haulers. The survey results also indicate that although mathematical models exist for a range of issues, they are not being widely applied, particularly in small communities. Although most of the studies reported in the literature used realistic data for their sample applications, few were actually involved in a local or regional waste management and planning process.

This conclusion is consistent with the work of Rogers and Fiering (1986) that demonstrates a distinct lack of practical applications of optimization models by water resources management agencies, despite over 30 years of systems analysis research. They go on to postulate reasons for this situation. Their observation that there are no set of standard or generally applicable models for water resources management, despite the recurrence of problems with similar characteristics, applies equally well to MSW management and planning. Past efforts in solid waste management and planning research have centred on developing models to aid decision-makers, and work similar to that done by Rogers and Fiering has not occurred with respect to identifying the extent of use of systems analysis techniques by waste management agencies.

Several model developers also refer to the lack of model applications in actual practise and suggest improvements to the existing modelling environments. Clark and Gillean (1981) state that the systems approach has not proven to be of much use to solid waste management engineers and planners. They note the substantial savings that may be obtained by applying these techniques, if the usefulness and useability of the models is improved. Chapman and Yakowitz (1984) note the proliferation of systems analysis models and the disappointing extent to which they are applied. They point to unrealistic data requirements and complexity as two of the main problems. To be helpful to municipalities, they feel a model should be able to derive the effects of alternative financial and cost sharing arrangements, and economies of scale, and be amenable to sensitivity analysis. Carlson (1991) suggests that there may be a limited role for planning models unless they are designed to be flexible and easy to use.

Perhaps a more interesting question then is not what systems analysis techniques have yet to be applied in models for specific MSW management and planning problems, but why the existing mathematical models are not being utilized for decision-making purposes. The lack of model applications in actual practise may be due to the perceived complexity of the models, general skepticism regarding their capabilities, the lack of decision support for their use, and the perceived high cost of commercially available software packages. Communities, therefore, usually depend on consultants for waste management and planning studies. Chertow (1989), in a guide for public officials, reports that consulting costs for a basic county waste management plan that investigates a range of technologies often exceed $200,000 U.S.; if a waste characterization study and detailed site analysis are needed, costs may realistically reach over $500,000 U.S.

There still appears to be interest by waste management professionals in the abilities of systems analysis techniques to assist decision-making. A recent survey of waste management professionals in the United States indicated that a microcomputer program for estimating solid waste management costs would be useful if it were easy to use and cost less than $1000 U.S. (Light, 1990). Light also reports that nearly half of American local and regional waste management engineers and planners use PC AT class microcomputers and the majority recognize the merit in programs to assist with MSW management and planning activities. The use of MSW management programs may bring about more cost-effective planning and management by allowing waste management engineers and planners to compare alternatives quickly and make more appropriate and efficient use of available resources. Thomas et al. (1990) indicate there is a clear need for planning tools to investigate the increasing number of waste management technologies and their associated constraints.

The United States Environmental Protection Agency, in developing a model for resource recovery project management, consulted 50 recognized authorities in the field to establish the need for an aid to implementing resource recovery projects (Felago and Stoller, 1979). They reported receiving unanimous support for a model which would help communities avoid common problems: inadequate analysis of waste streams; inadequate study of available options, and economic and political sensitivities; inadequate consideration of marketing issues; inadequate timing and budget projections; and turnover of project personnel and elected officials.

A number of researchers suggest the use of a set of modelling tools to alleviate some of these problems (Meenan, 1974; Clark and Gillean, 1981; Wilson et al., 1984). It is, however, of little benefit to suggest a more comprehensive approach to solid waste management and planning problem solving through the combined use of available models without providing support for their use. One approach to providing added support in the use of a set of modelling tools is to develop decision support systems using knowledge-based system techniques.

2.7 Expert systems and knowledge-based systems

According to Rolston (1988), expert systems offer intelligent advice in situations that would, otherwise, require some form of expertise. As such, expert systems incorporate knowledge elicited from human experts in an attempt to reach or exceed the problem solving capabilities of these domain experts, and potentially act as a surrogate for these experts (Bonczek et al., 1984; Turban and Watkins, 1986; Ludvigsen and Dupont, 1988). The main components of an expert system are a knowledge base and an inference engine. The knowledge base contains facts and rules associated with a problem domain. The inference engine controls the execution of the system and ultimately determines how a particular problem is solved. This is done by modifying and expanding problem specific parameters entered by the user by using the facts and rules contained in the knowledge base.

The most commonly used method for representing heuristic knowledge (or rules-of-thumb) within an expert system is the use of IF-THEN rules, where the IF statement checks the agreement between the current facts and the parameter settings, and the THEN statement indicates the actions to perform if the premise is found to be true (Behncke, 1989). However, other methods of knowledge representation exist, including the use of semantic nets and frames. In most cases, the inference engine either forward chains - from initial information to the goal of the system - or backward chains - from the goal of the consultation to the requirements to fulfil this goal (Waterman, 1986).

These systems offer some advantages over traditional systems analysis models as they are generally designed to achieve higher levels of user interaction and support. Depending on the method of representing knowledge and the organization of this knowledge, expert systems may be designed to ease the updating of the system. Traditional programs are quite often difficult for people not involved in the development stage to modify. Expert systems also allow heuristic information to be more easily encoded, and exhibit a higher degree of transparency as they generally have the capability to explain or justify conclusions they reach (Gupta and Chin, 1989).

Expert systems cannot truly emulate the problem solving capabilities of human experts. They generally suffer from several drawbacks: the inability to recognize when a problem is not within their domain of expertise, the inability to determine whether a conclusion is reasonable, a lack of general knowledge and common sense, and an inability to learn from their mistakes (D'Ambrosio, 1985). Due to their potential shortcomings, these systems are best designed to provide advice and assistance as opposed to being a surrogate expert. Knowledge-based systems are defined as a subset of expert system applications designed to provide advice and assistance as opposed to being designed to model the problem solving capabilities of a domain expert. Expert-level problem solving by a computer model is possible only for problems that are well-defined, bounded, routine and knowledge intensive (Bobrow et al., 1986).

The acquisition of knowledge from experts is perhaps the main stumbling block in creating expert systems. Often the proportion of the knowledge that must be derived from human experts, as opposed to rules-of-thumb and other knowledge previously compiled for codes and standards or reported in the existing literature, determines the success of a knowledge-based system project. The acquisition of knowledge from a human expert has been termed "knowledge engineering", and has emerged as a field of its own, with its own body of literature, and its own experts (Kahn et al., 1985; Boose, 1986; Cohn et al., 1988).

Expert system development tools have been created to reduce the effort required in developing an expert system or a knowledge-based system. The tools vary in the support environments included. Most tools offer, to varying degrees, user and developer interfaces, explanation facilities, graphics capabilities, debugging aids, integration capabilities and methods for representing uncertainty. Programming languages, such as PROLOG, Lisp and C, offer flexibility, but do not offer extensive assistance in knowledge representation and inference engines. Development environments, however, often offer a developer several knowledge representation and inference engine techniques, providing flexibility and very sophisticated control, but often at a high price. Finally, expert system shells support rapid expert system prototyping by providing support environments. They are less flexible than the development environments as the shells are typically limited in the methods of representing and manipulating knowledge (Waterman, 1986).

The development of an expert system, or a knowledge-based system, generally begins with the selection of an appropriate focus for a prototype system, to demonstrate the feasibility of the approach. If successful, the knowledge base and the sophistication of the system may be expanded, along with the comprehensiveness of the user interface. The creation of a full-scale system is a very time consuming task. The knowledge base must be slowly incremented, and continuously tested so it properly represents the desired problem solving approach.

Most expert system applications in waste management have occurred in the hazardous waste management field. Expert systems have been designed for fault diagnosis in hazardous waste incineration facilities (Huang et al., 1986), for characterization of inactive sites (Law et al., 1986), and for landfill site selection (Rouhani and Kangari, 1987). Mikroudis (1987) describes GEOTOX, a knowledge-based consultant program designed to identify and classify waste disposal sites. Ortolano and Steinemann (1987) briefly describe 13 unpublished expert systems being developed for hazardous waste issues such as remedial action at contaminated sites and spill response. No systems were reported for MSW management and planning. Although not applied specifically to waste management, expert system techniques have been applied to the general problem of site selection (Findikaki, 1986), and site selection and analysis for urban planning (Han and Kim, 1989). Han and Kim (1989) make a special note of the need to include heuristic analysis, or the intuitive judgment of experienced planners.

The design of expert systems to interface with more traditional decision-making tools has received limited attention in the field of civil engineering. Expert systems have been created to interface with databases and finite element programs for rating bridges (Kostem, 1986), and interpreting sensor data on materials and structures in situ (Maser, 1986). Palmer and Tull (1987) describe the combined use of a linear program and an expert system to interpret and synthesize the results for improving water supply operations under drought conditions. Other applications have included the use of expert systems to aid in parameter estimation for a watershed model (Fenves et al., 1984), a groundwater flow model (Lennon et al., 1988), and a stormwater flow model (Baffaut and Delleur, 1989).

Ortolano and Steinemann (1987) describe applications of expert systems to the interpretation of output data from environmental analyses, primarily in the areas of hazardous waste management and wastewater management. For example, Ludvigsen and Dupont (1988) discuss DEMOTOX which was designed to act as an "artificially intelligent" pre- and post-processor for a hazardous chemical transport model.

To a lesser degree, there have been reports of attempts to use expert systems in the model selection process for problems that may be modelled using several techniques.

FLOOD ADVISOR is an expert system that provides advice on the use of an appropriate program to perform flood estimation and interpret the results (Fayegh and Russell, 1986). The use of an expert system to select an appropriate optimization algorithm and to derive pareto-optimal solutions to multi-criteria optimization problems has been demonstrated by Balachandran and Gero (1987). Behncke (1989) describes an expert system for selecting the best subroutine for data regression from a statistical library, and reports on several other applications in the area of model selection for commercially available statistical packages, and for production or inventory models. Simonovic and Savic (1989) have created a consultation program for the selection and application of optimization and/or simulation programs for reservoir analysis. The existing literature does not include the application of expert systems or knowledge-based systems for MSW management and planning model selection.

The approach of utilizing the capabilities of expert systems to assist in MSW management and planning has been proposed by Thomas et al. (1990). Suitable applications are suggested: linking expert systems with traditional economic analysis and optimization approaches to address economic considerations, technology selection, and using expert systems to list potential environmental and political considerations and to recommend approaches to achieve public approval. In a related application, Schibuola and Byer (1991) discuss and demonstrate the use of knowledge-based systems to assist in the dissemination and presentation of information to public groups involved in Environmental Impact Assessment review processes in Ontario.

Despite the research efforts, there have been relatively few reports of using expert systems in actual decision-making processes. This lack of practical applications is attributed to the trend towards developing clearly defined problem solvers, while the majority of potential applications entail providing advice based on a collection of knowledge (Coombs and Alty, 1984).

Knowledge-based system techniques may be used to provide advice and therefore an increased level of support in the MSW management and planning field. They may be used to increase the modelling knowledge of practitioners, and thus potentially extend the use of modelling as an aid to decision-making. The problem domain of MSW management and planning has characteristics which make it suitable for the investigation of knowledge-based system techniques: due to the complexity and uncertainty involved, few individuals would possess expertise in all relevant aspects of waste management and planning; judgment and expertise is required to make management and planning decisions; and many qualitative issues are involved. Waste management professionals may benefit from the permanent collection of expertise in the knowledge bases, and the provision of a framework for investigating problems. As well, knowledge-based system tools allow these components to be more user-friendly and understandable than traditional models.

2.8 Summary of the results of the literature review

The review of the existing MSW management and planning literature indicates that numerous systems analysis techniques have been proposed to assist with the management and planning of MSW management systems. However, the consensus appears to be that there has been a disappointing lack of model applications in local or regional MSW management and planning studies. This suggestion was substantiated by the results of a survey of waste management professionals. Both model developers and waste management professionals recognize the potential benefits of the use of systems analysis techniques in MSW management and planning. However, there has been limited success in uniting mathematical modelling and waste management expertise. There are precedents from other application areas for the use of knowledge-based system techniques to improve modelling environments in order to make mathematical models more accessible and useful to practitioners.

A review of potential application areas for the use of knowledge-based systems to assist MSW management engineers and planners with the selection and application of mathematical models is contained within the following chapter. This discussion is followed by a description of the conceptual model development for a single application area selected for further study within this research.

CHAPTER 3

REVIEW OF POTENTIAL APPLICATION AREAS

Previous research has not dealt effectively with identifying the extent of application and perceived deficiencies in current MSW management and planning procedures, nor have knowledge-based systems been applied to help narrow the gap between waste management engineers and planners, and systems analysis techniques. This research proposes the utilization of knowledge-based system techniques, which to date have seen very limited application within the solid waste management field, to extend and support existing MSW management models. Decision support systems may be designed within knowledge-based system environments to aid decision-makers in applying appropriate models for a particular planning problem, preparing the necessary data and analyzing output results. For this research, decision support systems are defined as computer-based systems of tools for managing data, for managing one or more models, and for providing some level of interface with the user (Turban and Watkins, 1986). Decision support systems must also possess application-specific knowledge pertinent to the problem domain (Bonczek et al., 1984).

Problem areas within the field of MSW management and planning that may be best suited to the proposed decision support approaches are discussed within this chapter. Implementation issues such as the gathering of knowledge, selecting appropriate software and the potential acceptance of the proposed decision support approaches are also addressed.

3.1 Criteria for selecting potential application areas

There are a number of factors to consider in choosing an appropriate focus area for demonstrating the potential use of knowledge-based systems to improve MSW management and planning decision-making. This research is concerned with developing a decision support system which will integrate several models within a knowledge-based system environment to assist a decision-maker facing a chosen problem. For any problem area, it is important to establish the type and availability of models for a given MSW management problem, as comprehensive mathematical models should not be constructed if appropriate models already exist and are simply not being utilized to their full potential by practitioners.

To take advantage of the capabilities of knowledge-based systems, application problem areas must be of a complexity that would require experience and judgment to work with the models, interpret the results, and integrate the results into the decision-making process. From a practical perspective, it is desired to address areas that are currently lacking in decision support tools in order to provide assistance to municipalities and communities who must ultimately deal with MSW management and planning problems.

Since the development of a prototype decision support system is only one component of this research project, the chosen problem area for a prototype system and its models should possess other characteristics. The scope of the chosen application problem should be such that a limited-scale (prototype) system demonstrates the feasibility and utility of the proposed approach for improving MSW management systems modelling. In addition, the selection of the knowledge-based system development software and the systems analysis techniques will affect the prototype decision support system development time.

3.2 Potential decision support approaches

As previously determined, systems analysis techniques have been applied to the primary problem domains related to MSW management and planning: regional solid waste management systems planning, waste generation and composition forecasting, vehicle routing and scheduling, assessing the potential for resource and energy recovery, and operating and designing facilities. In addition, the general issues of facility siting and sizing are relevant to MSW management and planning.

There are three basic methods for integrating the abilities of knowledge-based systems and mathematical models for MSW management and planning. Several distinct models addressing a specific waste management and planning issue, for example, vehicle routing, may be assembled. The goal would be to design a knowledge-based system component to provide assistance to the user in choosing and applying the most appropriate model, given the specific objective of the investigation, the accuracy desired, and the data available. The user may be offered several models based on approaches ranging from a simple, approximate estimation approach to a more comprehensive, time consuming model with greater data requirements. This coupling of knowledge-based system components and more standard models would be valid in any of the previously defined MSW management and planning problem areas, as models of varying types and complexities generally exist.

Another approach would be to simply create knowledge-based system components to interface with a single model developed to address a particular problem. Through interaction with a knowledge base, the user may be given advice regarding data preparation, model execution and output analysis. Similar applications have been described in other fields of civil engineering. This approach to combining knowledge-based systems and mathematical models would also be valid for all problem areas, particularly where models rely on less widely accepted and understood techniques such as mixed-integer linear programming or dynamic programming. The creation of such interfaces may reduce some of the complexity surrounding many of the existing systems analysis techniques, and ensure that the assumptions, limitations and appropriate uses of the resulting models are fully understood.

In addition, mathematical models from several of the predefined problem areas may be required to accomplish a specific task. Knowledge-based system components could be created to direct the course of the study, and assist with the application of the individual models. For example, several steps are necessary when planning a regional solid waste management system: design waste reduction, recycling, and/or composting programs; locate and size the necessary facilities; and allocate wastes to the facilities. These decisions are made based on waste generation and composition data and other community characteristics, as well as the availability and suitability of collection, processing, and disposal technologies. Existing optimization and simulation models created to address these tasks could be combined within a knowledge-based system environment to assist with the selection of appropriate technologies, and the development and analysis of alternative MSW management systems. As another example, landfills have received a large amount of attention and research effort as they have been a mainstay of traditional solid waste management operations. Many models exist to investigate such issues as congestion at weigh stations, liner requirements, the setting of tipping fees, and leachate production and transport. A decision support system for preliminary design of a landfill could be created using knowledge-based system components to integrate these models and assist with their execution.

Although many problem areas of MSW management and planning are appropriate for, and could benefit from, the application of knowledge-based system techniques, a thorough examination of all these areas is considered to be beyond the scope of this research. Several potential MSW management and planning problem areas will now be discussed that may benefit from the integration of knowledge-based system techniques with more conventional modelling techniques.

3.3 Potential application areas for knowledge-based systems

The suggested approaches to the development of decision support systems may be applied to long-range and short-range planning problems, and facility operational problems. Long-range planning often involves investment planning for facilities to investigate future costs, revenues and facility lifetimes. Short-term planning often involves the planning of collection routes, or the allocation of wastes to a currently developed set of facilities. Planning models may address one or more of the MSW management problem aspects: waste generation and composition, waste storage and collection, facility location and design, and waste transportation to processing facilities or landfills. Operational programs exist to aid decision-makers with the selection of collection vehicles and labour requirements, and preliminary facility design (Light, 1990). Applying these models requires varying amounts of waste management and modelling expertise, affecting the suitability of the various problem areas for application of the proposed decision support approaches. As well, for some waste management agencies, particularly those responsible for very limited systems serving small or isolated communities, the need for costly or complex decision support systems may be unwarranted. However, small-scale systems designed with an emphasis on local conditions and waste management knowledge may be of assistance to waste management engineers and planners.

The majority of waste management agencies possess programs for collecting and processing waste generation data, primarily based on weigh scale information from MSW receiving facilities. However, only minimal expertise is needed to manage such database systems, and there would be little benefit from the addition of a knowledge-based system component. In addition, many agencies may keep a database on equipment and facility records to schedule maintenance and repairs. The main difficulty for these agencies is not the complexity of the database systems but the need to continually update the information (Light, 1990). Therefore, insufficient complexity exists to suggest the need for investment in knowledge-based systems.

In general, the mathematical models designed to assist with the more complex planning and operational activities of waste management agencies vary in the level of decision support they provide. Several of the commercially available packages described by Light (1990) offer fairly extensive support for the model formulation, execution and output analysis stages. However, the usefulness and value of many of the models proposed in the MSW management literature may be augmented by including a knowledge-based system component, particularly given the lack of experience with systems analysis techniques within this domain.

Predicting waste generation rates and composition is extremely important to MSW management and planning decision-making. These values affect facility economics and environmental impacts. The problem of forecasting waste generation and composition is a concern for many planners, as they wish to avoid overdesigning or underdesigning a waste management facility. The majority of available models are based on statistical analyses which relate generation and composition to other factors such as population or the economic well-being of the community. There is little evidence to suggest that actual planning studies rely on this approach to determine current and future MSW characteristics. Rather, most communities seem to apply more general growth factors based on previous waste generation and composition data, and population trends. The results of the survey of waste management professionals indicate that they may also base their calculations on waste data collected from studies done in other communities.

The waste generation and composition forecasting models reviewed address the issues of generation at households and commercial establishments, and optimal sampling techniques for waste stream assessments to derive local estimates. This crucial MSW management problem area may benefit from the creation of knowledge-based system components designed to act as interfaces to these models, to support waste management professionals with the task of forecasting waste generation and composition, or conducting waste stream assessments. Communities may then be able to accomplish these tasks without the need for outside consultative assistance.

Another solid waste management problem is the optimal routing of collection vehicles, and the determination of labour and vehicle requirements. Optimal vehicle routing has been extensively researched outside of the realm of solid waste management, although most of the developed models have limitations which preclude their use for large systems such as municipal waste pick-up (Bodin, 1990). Several modelling approaches have been applied specifically to the problem of routing waste collection vehicles, including simulation (McCoy, 1971) and network theory (Chiplunkar et al., 1981). As a result of model limitations and complexity, many planners may rely on heuristics in the design of collection routes. Potential benefits may exist in demonstrating the use of available analytical and heuristic models to assist a waste management engineer or planner.

There are also many simulation models available to examine the optimal allocation of resources to the collection of MSW (Cardile and Verhoff, 1974; Cox, 1986). Other researchers have offered models to help assess the efficiency of a collection system (Quon et al., 1968; Truitt et al., 1969; Quon et al., 1970). The available modelling tools may also be utilized in order to improve current collection systems.

This decision-making environment could potentially benefit by the addition of knowledge-based system components to interface with individual models, to select an appropriate model for collection systems planning, or to integrate the use of several models for the design and subsequent analysis of a collection system. In addition to the development of knowledge-based system components to assist with selecting an appropriate vehicle routing model, as described in the previous section, knowledge-based system components could be developed to accompany individual models to assist with the preparation of data and the analysis of output. An ample amount of expertise related to collection systems design is in existence. Waste management expertise and collection systems modelling expertise could be combined within a knowledge-based system environment to synthesize their problem solving capabilities. The development of such decision support environments would require eliciting knowledge from human experts. This has been found to be both a difficult and time-consuming aspect of knowledge-based system development. However, more effort has taken place recently in collecting such expertise to produce handbooks and reports (Resource Integrations Systems Ltd., 1987; BioCycle, 1990). This is due to the current emphasis on creating composting and recycling programs, as separate collection systems are required if materials are separated at-source or at drop-off depots and must be transported to processing facilities.

Proper design and operation of solid waste management facilities is another problem domain requiring expertise that may be improved through the extension and support of existing modelling tools. Transfer stations are often included in a collection and disposal network in order to reduce transportation costs. Several models have been developed to aid in the optimal location of waste transfer facilities (Marks, 1969; Clark, 1973). Queuing theory may assist in designing and operating these facilities to reduce congestion (Yaffe, 1974; Hartz and Ham, 1981; Humphries, 1986). The same approaches could be extended to the design and operation of other waste receiving facilities such as mixed MSW processing facilities and EFW facilities. Knowledge-based system components could be designed as interfaces to any one of these models, or to assist with model selection or the integrated application of a series of models. For example, simulation models may produce statistical results for a collection system that have to be properly interpreted in order to make appropriate design and operational decisions. Similar to the MSW management activity of collection systems design, this area relies on the experience of operators. As a result, a substantial effort may be required in collecting and encoding expertise, as opposed to modelling the problem.

In contrast to the previously discussed waste facilities, landfills have received a great deal of scientific research attention. The same models reported for transfer station congestion may be applied to landfill weigh scale queuing problems. In addition, models are available to efficiently design and operate landfills (Christensen and Haddix, 1974), and to set tipping fees and determine optimal site life (Lund, 1990a). There are also numerous models which address the gas and leachate problems associated with this waste disposal system (Moore et al., 1982; Korfiatis, 1984; Demetracopoulos et al., 1986). The models vary in their complexity and potential uses. Of course, knowledge and experience are also important facets to the efficient management of landfill facilities. This problem area may benefit from the design of knowledge-based system components to interface with individual models, or select or manage a group of models to assist with the tasks of facility design and operation.

Potential applications also exist with respect to the operational control of MSW processing systems. An example is the control of the composting process at centralized composting facilities which relies on information regarding compost pile conditions such as temperature, odour, colour and carbon-nitrogen ratio. Some data may be collected on-line, while other data may be gathered through observation. Inexperienced managers of composting facilities may benefit from a knowledge-based system component designed to assist in deciding on the proper actions to take given the current conditions of the compost pile. Such a decision support system has recently been developed (Andrews et al., 1991). Real-time operational control is also important in the incineration of MSW. Proper control of burn time, temperature, and air addition is necessary in controlling the toxicity of the emissions. This application area holds promise, particularly since using knowledge-based systems to aid in operational control of other types of facilities has been investigated (Patry and Chapman, 1989).

The process of selecting sites for facilities to treat, process and dispose of waste products has become a very time consuming and arduous task. Certainly, many models may be used in the siting process, particularly to predict the potential impacts of waste management facilities on the natural environment. The emphasis on these issues has arisen in response to the need to conduct more intensive environmental assessments for facilities such as landfills and EFW facilities before approval is given. This area was noted by several of the waste management professionals surveyed as a troublesome problem. However, several survey respondents also mentioned that the area is extremely political, and the application of models for the actual siting process therefore has limited appeal. This problem is also addressed to a degree in the planning of MSW management systems, whereby one selects and locates facilities from a list of suitable sites previously determined in the facility siting stage. However, this area of MSW management and planning may benefit from the use of knowledge-based system techniques and decision analysis techniques to provide a framework for site selection problems. Several relevant models have already been developed (Rouhani and Kangari, 1987; Han and Kim, 1989). In addition, Schibuola and Byer (1991) demonstrate the potential for utilizing knowledge-based systems to provide information to participants in Environmental Impact Assessment reviews - which may be required for a facility siting project.

Difficulties exist for waste management engineers and planners in assessing the potential for materials and energy recovery from MSW due to uncertainty regarding the effectiveness of recovery technologies and market conditions. Models have been developed to assist with the evaluation of markets (Malina and Morgan, 1972), the investigation of resource recovery projects (Findley, 1978), and the formulation of recycling plans (Lund, 1990b). Knowledge-based system components could be developed to accompany individual models or groups of models designed to assist waste management engineers and planners with the process of assessing the feasibility and effectiveness of resource recovery alternatives.

The long-range planning of programs and facilities to deal with MSW is becoming a required planning activity in many communities. The long-range planning may reduce MSW management costs by assessing the viability of new technologies and markets, and by estimating future processing and disposal requirements and facility lives. Developing long-range plans requires the determination of program and facility requirements for managing MSW over a planning horizon of at least 20 years, based on forecasts of waste generation and composition. Generally, this involves the generation and evaluation of alternative MSW management systems. Strategic planning models provide a framework for the analysis of the cost and performance of alternative MSW management systems before community resources are applied to a specific system (Light, 1990).

The generation and evaluation of alternative solutions for a MSW management system planning problem are tasks that require expertise in many factors including available technologies, available resources and market conditions. This type of information, according to Turban (1988), is often essential for developing alternative solutions and predicting the consequences of decisions, making knowledge-based systems an apparent possibility for supporting this activity. The benefits from the introduction of knowledge-based system techniques to this problem solving environment are evident due to the large number, and the range of complexity, of mathematical models that have been developed to assist planners. Systems analysis techniques applied to long-range MSW management systems planning include optimization, simulation and decision analysis. Due to the broad scope of the problem area, benefits may be derived from any of the general decision support approaches described. Knowledge-based system components could be integrated with a single model or a series of models to assist with input data development, model execution and output analysis in connection with a planning study. The use of knowledge-based systems for planning support has been advocated in the general expert system literature due to their ability to supply planners with "the power to capture and activate knowledge" (Fiksel and Hayes-Roth, 1989). Fiksel and Hayes-Roth suggest the need to develop broad, interactive systems to support human experts at the thinking and learning stages of planning, rather than to recommend actions.

A further potential application problem area is selecting an appropriate optimization model for long-range facility planning and waste allocation. The options for optimizing a given MSW management planning problem include linear programming, dynamic programming and mixed-integer linear programming. The treatment of time as a modelling factor also varies. Static models, dynamic models with time-step-by-time-step optimization, and dynamic models with continuous optimization over time have all been developed (Wilson, 1977). In addition, simulation models have been developed to assist with strategic planning activities (Light, 1990). Considerations in selecting an appropriate model include the expected temporal variation in parameters, the objective(s) of the study and the representation of capital costs for facilities. A knowledge-based system component could be designed to assist with this selection process.

The process of strategy evaluation within optimization models has generally been conducted with the minimization of system cost as the only modelled objective (Chang et al., 1982). No examples of multi-objective optimization studies were found in the review of the MSW management and planning literature. A potential approach for considering multiple criteria in evaluating alternatives is the use of decision analysis techniques (Sobral et al., 1981; Maimone, 1985). A knowledge-based system component could be designed to assist with the selection of evaluation criteria, the estimation of values for various alternative systems, and the final comparison of alternatives. Wilson (1977), in a review of MSW management system optimization models, states that the development of methodologies to assist with the evaluation of alternatives against several criteria should be a research priority. A potential difficulty with this application area is the uncertainty that exists with respect to the prediction of the environmental and social impacts of implementing alternative MSW management systems.

Long-range MSW management systems planning was selected as the prototype application area for this research due to the complexity of the problem area, the availability of mathematical models, and the expressed need for decision support by waste management agencies. Strategy generation and evaluation activities for the proposed prototype decision support system will rely on a combination of modelling approaches including optimization and simulation. The decision support approach to be utilized is the integration of a series of models in order to accomplish the tasks of program and facility planning (as opposed to creating interfaces to an individual model or a knowledge-based system component to assist with a model selection process). This application area will be further discussed in the next chapter, following a general discussion of issues related to the implementation of the suggested decision support approaches within the domain of MSW management and planning.

3.4 Implementation issues

A common drawback of the suggested applications of the proposed decision support approaches is the indication, from the literature review and technical survey, that the majority of waste management agencies do not currently use many of the available systems analysis techniques to assist with decision-making. Thus, decision support system development projects utilizing knowledge-based system techniques would require the collection of appropriate models and modelling expertise in addition to the development of knowledge-based system components to accompany them.

This lack of experience with systems analysis and knowledge-based system techniques could lead to a problem with user acceptance. Considerable effort may be required to gain the confidence of potential users of the decision support systems. This problem may be overcome by directly involving users in the development phase, perhaps through in-house development of decision support systems. The situation will likely improve as more waste management agencies explore the use of available computer-based models (Light, 1990). In addition, to guard against the inappropriate acceptance and application of knowledge-based system results as truth, these components should be designed to supplement expertise and not to replace experts. This will require that an emphasis be placed on designing the systems to provide assistance and advice to users as opposed to providing 'the answer'.

Very few areas of waste management problem solving, from vehicle routing to facility planning, appear to have a commonly accepted approach to decision-making. This factor poses another potential stumbling block to implementing the suggested decision support approaches, namely, the gathering of waste management and planning expertise. Little work has been done to date to collect and synthesize expert knowledge. Due to the lack of practical applications of systems analysis techniques, modelling knowledge specifically related to the use of these techniques within the domain of MSW management and planning will be limited.

Another related factor is the amount of knowledge that one may assume that potential users possess. In MSW management and planning, the potential users may have varied backgrounds (from engineers to politicians), and thus will possess varied knowledge of systems analysis techniques and waste management and planning issues. If decision support systems are developed in-house, they could be tailored to the needs of the potential user community.

Post-development activities must also be considered in the waste management field as a result of the ever changing technological, political, regulatory, social and economic environments. Concerns have been raised regarding the maintenance of systems that use large amounts of domain knowledge to solve "real world problems" (Nazareth, 1989).

Knowledge encoded in a decision support system will have to be periodically updated; the system itself will then have to be subjected to verification. The difficulties related to these requirements may be lessened if the decision support systems are developed on software that is user-friendly and easy to use, and where the knowledge and solution process are made more visible. This will allow minor modifications to be readily made. Gupta and Chin (1989) warn that as knowledge-based systems become more widely used, their safety, validity and reliability will be crucial. This is a further motivation for designing decision support systems to provide assistance and advice to the user, and allowing the user to make any necessary decisions.

A requirement for any of the suggested applications of knowledge-based system techniques to improve the current modelling environments in MSW management and planning is the compatibility of the software and hardware. Decision support systems should be designed with the expected computing environments of the end-users in mind. For the majority of waste management agencies, the controlling factors may be the cost of the systems and time constraints. Light (1990) has found that most American waste management agencies are interested in microcomputer-based programs, particularly those that assist with estimating costs, if they are easy to use and cost less than $1000 U.S. The compatibility of the mathematical modelling and knowledge-based system software will affect the ease-of-use of a decision support system, and thus ultimately its extent of use.

It is expected that benefits may be derived by utilizing the explanation, user interface, and symbolic processing capabilities of knowledge-based systems to extend and support the use of mathematical models in the domain of MSW management and planning. Developing such systems will also require the collection and integration of waste management expertise, but will allow this expertise to be more widely distributed. Although decision support systems are being developed at an ever increasing rate (Turban, 1988), their acceptance and subsequent use by waste management agencies may require additional time and effort, particularly due to the current state of computer modelling in practise.

Conceptual model development will be described for the long-range planning of source separation programs and MSW management facilities to illustrate the proposed strategy for extending and supporting the use of existing mathematical models.

CHAPTER 4

CONCEPTUAL MODEL DEVELOPMENT

4.1 Description of the prototype application area

The long-range planning of MSW management systems was chosen as the prototype application area for its potential to demonstrate the benefits of combining the abilities of mathematical models and waste management expertise in a knowledge-based system framework to support decision-making. Addressing this problem requires the integrated use of a series of decision-making tools including mathematical models to solve an actual, full-scale problem. This application problem area is also of sufficient complexity, and is a field currently lacking in decision support. The planning of local or regional MSW management systems is comprised of several sub-problems.

The long-range planning of a MSW management system relies on forecasted data for waste generation and composition over the desired planning horizon. The design of downstream transfer, processing and disposal facilities may be significantly affected by inaccurate estimates of these quantities. The next phase of strategic MSW management systems planning is to gather and compile information on various technological options for treating, processing and disposing of MSW. It is important at this stage to consider, at least qualitatively, potential environmental and social impacts of implementing individual technologies. The selection of an appropriate system of programs and facilities to meet future MSW management needs will also depend on goals or policies established by the community (eg., the phasing out of incineration). The result of the examination of technologies is the generation of several alternative waste management program and facility options for further consideration. The MSW management system options generally considered in this analysis of technologies are illustrated in Figure 5. A decision support tool designed for regional or local MSW management systems planning should consider waste generation, waste reduction/re-use, composting and recycling programs, and a range of processing and disposal facility options. The chosen technologies may then be combined to form alternative integrated MSW management systems. It is then necessary to investigate facility siting, sizing and investment issues, and the allocation of waste to the facilities for each alternative system. This analysis is based on given information regarding the cost structures and operational aspects of the technologies, as well as social, environmental, technical and political objectives that must be met.

Systems analysis and knowledge-based system techniques may provide assistance when more traditional decision-making approaches are inadequate or insufficient by themselves (Han and Kim, 1989). In this particular application area, the need to plan integrated MSW management systems may require the development and use of additional tools, particularly for generating and evaluating alternative system solutions. Optimization and simulation techniques are proposed not as replacements for traditional approaches to solving multi-objective facility planning problems that have tended to rely heavily on the intuition and judgment of experts, but as added tools to support the decision-making process of human planners. A community that stands to be affected by a MSW management planning decision has interests beyond simple economics, whereas optimization models generally only explicitly consider project economics. However, when limited to identifying and examining feasible and economic alternatives for human

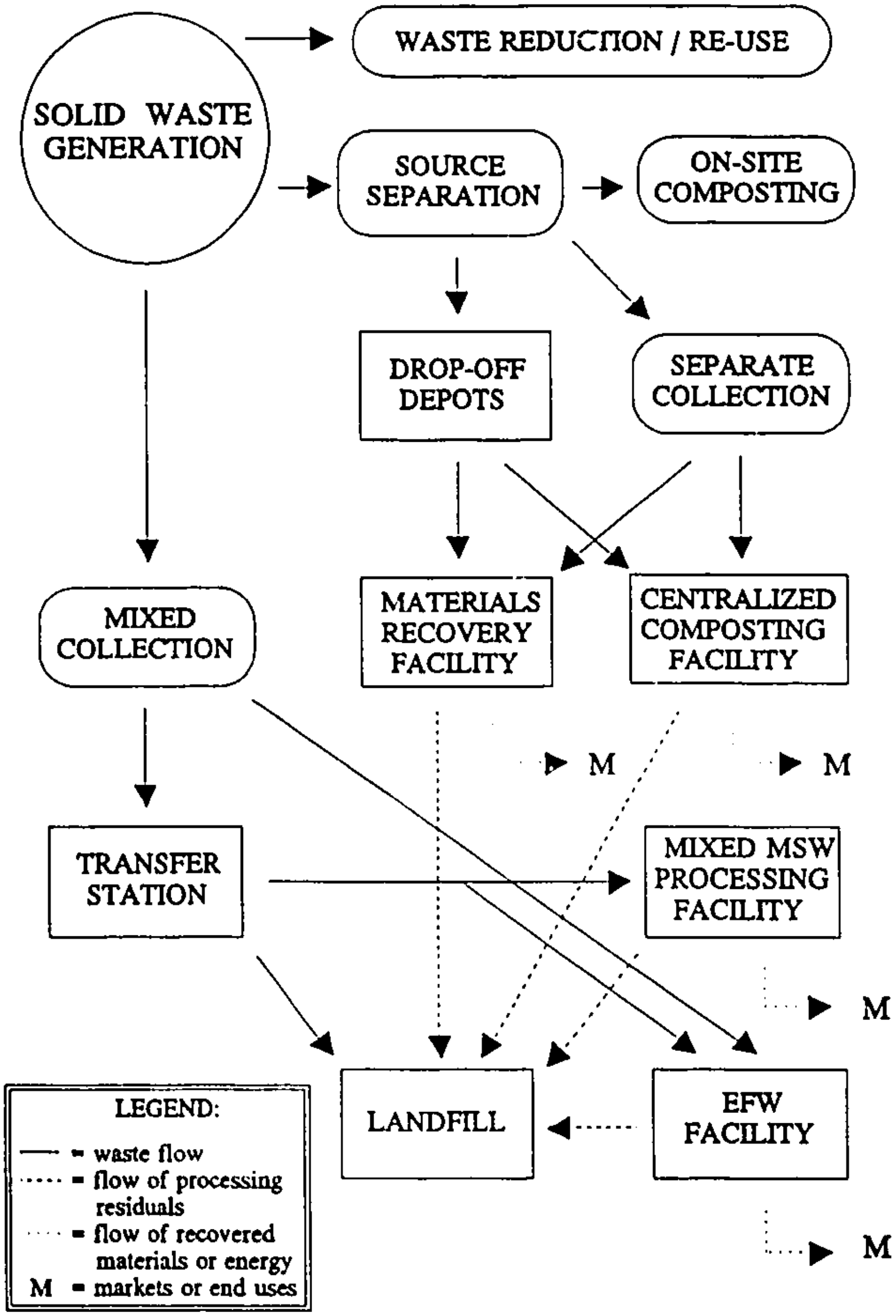

Figure 5. Flow diagram of a MSW management system
Source: adapted from Lawver et al. (1990)

planners to consider, these models may play a role in long-range MSW management systems planning.

The literature offers a multitude of models to assist in selecting and locating waste facilities from a set of existing and potential sites based on the optimal allocation of generated wastes. Fixed-charge models have been developed to address this problem, and have been modelled through the use of mixed-integer linear programming techniques (Walker, 1976; Jenkins, 1982; Gottinger, 1986). Several of the models also consider sizing and expansion issues. However, there are concerns over the solution times of such models on microcomputers if they are to solve a multi-period planning problem that considers a full range of MSW management technologies (Carlson, 1991).

It is also possible to use linear programming to model facility location/waste allocation problems. In fact, Greenberg et al. (1976) suggest the use of a linear program as a first run solution, followed by a mixed-integer linear programming analysis to fine-tune the results. This recommendation was based on difficulties encountered with fixed-charge algorithms and the added complexity of these models. Simulation may also be used to determine facility capacities, to evaluate the cost and operation of a given waste management system, or to fine-tune the results of an optimization analysis. The mathematical bases of optimization models are more complex, making them more difficult to operate and interpret, and requiring greater computational resources (Light, 1990). With the results of the optimization or simulation analysis, the relative costs of the various alternative MSW management systems may be compared. Additionally, more accurate estimates of environmental, social and political factors may also be compared based on the locations, sizes and mix of facilities suggested by the chosen model.

Another concept that may be tested through this modelling process is the development of regional versus local waste management systems, which may be particularly helpful for smaller communities that may wish to take advantage of economies of scale.

This general problem solving approach is also applicable to the design of recycling systems or composting systems that involve separate collection systems and processing facilities. The identical planning issues of facility sizing and location, facility investment timing, and waste allocation may be examined. Palmer (1975) develops a mixed-integer model to select optimal resource and energy recovery processes, and discusses the technical and political factors involved. Lund (1990*b*) develops a model to evaluate and schedule recycling measures using linear programming, after recycling options have been generated by an engineer. Generally speaking, it appears that models designed for regional solid waste management systems planning have not been adapted for use in recycling systems planning or composting systems planning.

4.2 A conceptual model of the proposed decision support system

To demonstrate the applicability of the proposed approach to extend and support the use of mathematical models in MSW management and planning, a microcomputer-based tool is proposed to assist with the preliminary planning of MSW management systems at the local or regional level. A local or regional decision-maker must decide upon facility locations, facility capacities and expansions, facility investment timing and flow routing to the facilities. The proposed planning tool, to be truly indicative of the strategic planning of MSW management systems, would guide the user through all the necessary planning steps: the estimation of waste generation and composition data; the investigation of available waste management technologies; the design of composting and recycling programs; and the estimation of operational and cost data for existing and potential waste management technologies in order to determine optimal facility sizing, timing and location, and waste allocation patterns. To accomplish these tasks, the decision support system could combine spreadsheet, optimization, and simulation models within a knowledge-based system environment. The knowledge-based system components would provide advice on the development of data for the mathematical models, execute the models and assist in the interpretation of the output. The use of this approach beyond program and facility planning may potentially benefit activities such as environmental policy making, budgetary planning and funding applications. A conceptual model of the proposed decision support system is illustrated in Figure 6.

It is also important to note that certain elements of the MSW management systems planning process are not included in the knowledge-based system modelling framework. The routing of individual curbside collection vehicles is an important and difficult task, but it is not considered within this research. In addition, a comprehensive waste generation and composition forecasting model is not included.

Potential users of the proposed decision support system are consulting engineers, waste management agencies, recycling coordinators, and municipal planners and decision-makers. The experience of these potential users varies widely with regards to both solid waste management and mathematical modelling techniques. This system is designed to assist both inexperienced and experienced MSW management engineers, scientists, planners or decision-makers. The decision support system is designed to provide inexperienced users with introductory information on waste management planning issues

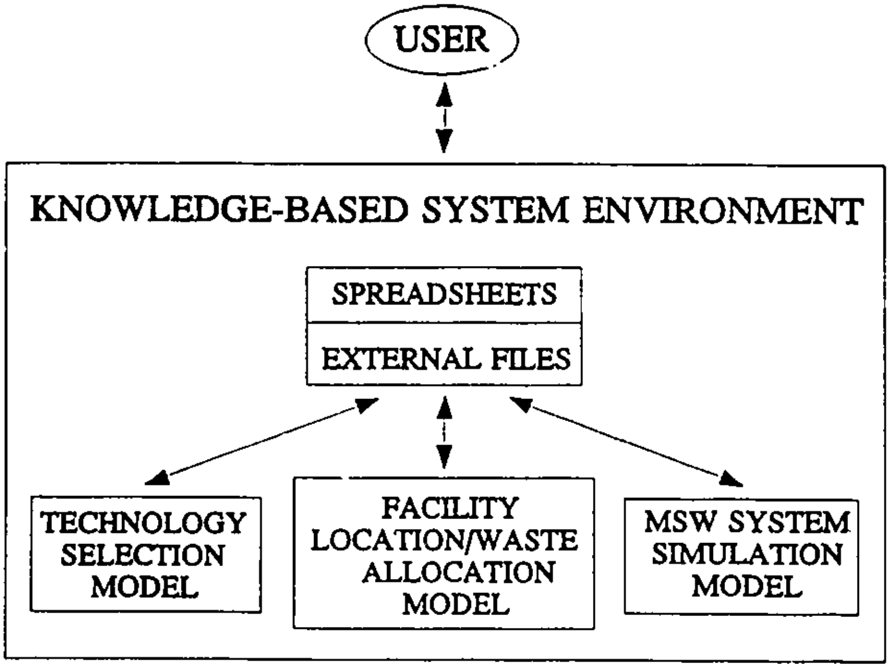

Figure 6. Conceptual model of the proposed decision support system

and the mathematical modelling components, and numerous spreadsheet models. As well, the decision support system is designed to provide more experienced users with more detailed expertise and more advanced mathematical modelling tools. With this in mind, the proposed decision support system has been made flexible enough that only certain components may be used if desired. More importantly, the structure of the decision support system should permit the knowledge-based system components to be clearly understood and thus easily modified, as there is a rapidly growing body of published material regarding waste management issues.

The elicitation of expert knowledge was not judged to be a significant factor for development of the prototype decision support system. The majority of the waste management and mathematical modelling knowledge encoded has been taken from existing waste management texts, journal articles and reports. with an emphasis on information pertinent to Canada. The chosen application area is a large-scale, complex, but timely problem which required the collection, organization and encoding of a significant amount of waste management and mathematical modelling expertise.

The analysis assumes that information is available on the current waste management system regarding waste collection, processing and disposal costs, and operational parameters. It is also assumed that prior to consultation with the facility location/waste allocation model, a preliminary investigation of potential sites for all proposed facilities has been completed. The optimization model requires information on the location and size of all sites. In addition, the decision support system assumes that a preliminary market analysis has been completed with respect to the sale of recovered energy and materials, and that data are available regarding the number and types of residential dwellings, and industrial/commercial/institutional (ICI) activities in the community or region.

The system is designed to provide assistance in program and facility planning at the preliminary planning stage. As a result, it is presumed that local estimates may not always be available for specific parameters that are requested by the developed decision support system. Emphasis has been placed on compiling and encoding advice on parameter values reported in the waste management literature to allow users to develop preliminary estimates.

In order to accomplish the task of making mathematical models more attractive to decision-makers, consideration has been given to the computing environments at most public and private waste management agencies. Most MSW management agencies have microcomputers and limited software budgets. Prototype development tools have been selected with the end-users in mind. The ideal situation would be the incorporation of spreadsheet, optimization and simulation models within an inexpensive, but effective, knowledge-based system development tool. As time permitted, the system has been made as user-friendly and flexible as possible.

The following chapters are devoted to a detailed discussion of the modelling components, and the potential benefits and limitations of the proposed decision support system for the preliminary long-range planning of MSW management systems. This discussion will be followed by a presentation of two case study applications to illustrate how the approach may be used to assist with local or regional planning studies.

CHAPTER 5

DECISION SUPPORT SYSTEM DEVELOPMENT

In this chapter, a description is provided for the components of the prototype decision support system for the preliminary long-range planning of a MSW management system. The planning procedure has been partitioned into the following major activities for discussion and modelling purposes:

- waste generation and composition forecasting;
- technology evaluation;
- source separation composting and recycling program design;
- facility cost and operational data estimation;
- facility location, sizing and investment timing, and waste allocation investigation;
- simulation of an existing or proposed MSW management system.

The general organization of the proposed decision support system is illustrated in Figure 7. In order to facilitate the description of the prototype decision support system and illustrate its full range of capabilities, the planning tool is represented as a linear system of modelling components. However, the decision support system has been designed with an emphasis on flexibility with respect to the number of programs and facility options, and to allow individual modelling components of the system to be used in isolation. Provided that initial data are supplied for waste generation and composition, and for other general parameters of the planning study (eg., community size, economic parameters, etc.), the user is not restricted to following the planning process as illustrated in Figure

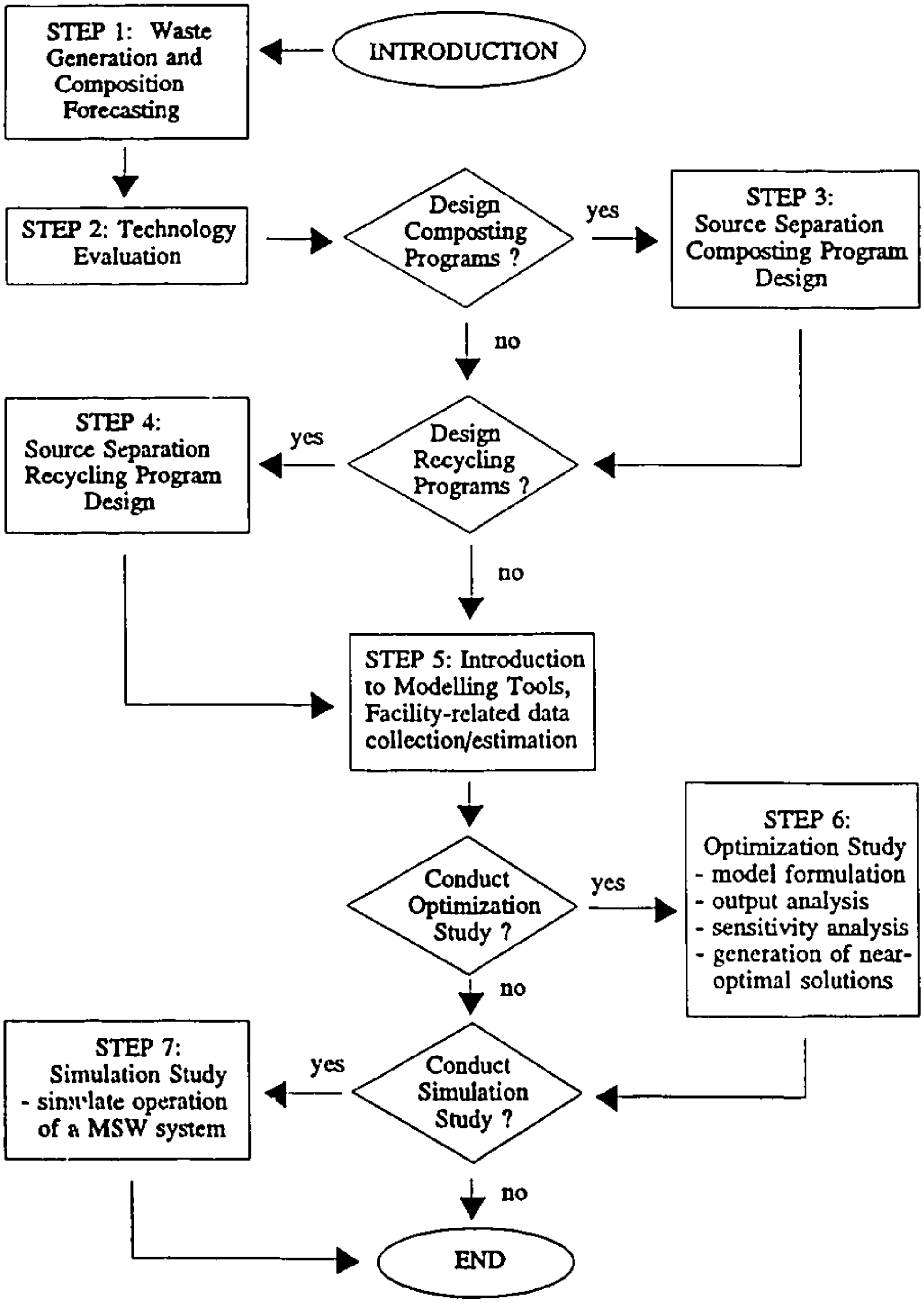

Figure 7. Flow diagram of the MSW management systems planning tool

7, and may conduct any number or combination of planning activities. The decision support system components may also be applied in an iterative manner to assist with the exploration of the effects of uncertainty due to imprecise ('fuzzy') and/or random data. Through such an investigation, the user may develop a sense of the critical model parameters (i.e., those parameters that are found to have the most significant impact on system performance or costs) and the resulting variability in subsequent calculations such as material recovery rates and facility capacities.

A planning horizon of 20 years has been assumed, as the majority of waste management planning studies have been based on a comparable planning horizon. The central purpose of this long-range planning tool is the development of system alternatives, and cost estimation for source separation composting and recycling programs, and MSW management facilities to serve a community or region. It is assumed that preliminary analyses have been performed to identify appropriate sites for potential facilities, and markets for recovered materials or energy. The approach also assumes data are available describing the costs and operation of the current MSW management system, and the number and types of residences and ICI sites.

Rather than develop a detailed prototype for one specific planning study activity, a framework has been developed for the complete planning of programs and facilities at the local or regional level. As a result, the modelling components may be restricted in the level of detail and knowledge provided. This approach was taken to better reflect actual long-range planning studies so that the potential benefits of the proposed approach to assist waste management professionals could be more readily judged. The system provides advice and recommendations based on the expertise gathered from the waste management literature, and the results obtained from the modelling tools. The user must make the final decisions regarding parameter value estimates, and program or facility options.

A list of the technical reports and other literature used as sources of waste management and mathematical modelling knowledge is included in Appendix J. Throughout the discussion of the individual modelling components, the names of knowledge bases and spreadsheet models referred to will be provided in parentheses. Listings of several knowledge bases are included in Appendices B, C and E. The author may be contacted for further details regarding the contents of the other knowledge bases and the developed spreadsheet models.

The research combines mathematical modelling and knowledge-based system techniques. Therefore, certain computational environments were required to conduct the research. The selection of the knowledge-based system and spreadsheet model development tools will be discussed prior to a discussion of the individual modelling components. The optimization solution package used in the case study applications will be discussed in the section devoted to the description of the facility planning model formulation.

5.1 Decision support system development tools selection

There are a number of important requirements for any expert system, or knowledge-based system, development tool. Ludvigsen et al. (1986) discuss the requirements of the ideal expert system development tool for civil engineering applications. These will be discussed with regards to the chosen MSW management systems planning problem. The primary consideration was the computing environments available at waste management agencies, where microcomputers are generally available, but with limited budgets for software acquisition.

The development tool had to be able to link to an outside spreadsheet (preferably Lotus 1-2-3 as it is a widely utilized program), and be able to connect to external executable programs and files. The ability to handle complex mathematics was not a requirement, as most mathematical computations were to be performed externally. Development environments such as debugging aids, editors and help facilities were desirable. The tool had to provide explanation facilities for the user. A rule-based knowledge representation was preferred to simplify the development process, and allow for more transparent and easily modified knowledge bases. The system was not expected to have a large, complex rule base, nor was it necessary for the tool to be able to induce rules from examples.

Most expert system shells provide all of the above listed requirements, and are designed for ease-of-use, although they are generally much less flexible than knowledge-based system development environments (Waterman, 1986). Levitt (1986) notes that microcomputer-based expert system shells reduce the need for the developer and decision-maker to be computer scientists. They are being extensively used by civil engineers, due to the limited time investment necessary, low cost and their ability to facilitate quick prototyping of a system (Ortolano and Perman, 1987). However, it is well documented that determining the most suitable tool for a potential use is difficult and potentially frustrating (Mackerle, 1989).

Reviews of small scale microcomputer shells usually involve the EXSYS, INSIGHT, M.1., PC PLUS, VP-Expert, Nexpert, and Expert-Ease software packages (Ludvigsen et al., 1986; Gevarter, 1987; Mackerle, 1989). These tools have all been used in civil engineering applications reported in the literature. However, Expert-Ease does not provide interfacing with other software. M.1 has many features, but is expensive and difficult to link to other software (Ludvigsen et al., 1986). Nexpert is also a mid-sized and rather costly tool that is designed for object oriented applications, and requires the user to design their own method of handling uncertainty in user responses (Mackerle, 1989).

The other tools appeared most suitable for this particular decision support approach. PC Plus has received good reviews as it offers confidence factors, and explanation, help and tracing facilities. It is also able to link to external software including Lotus 1-2-3 and dBase, and can execute external programs. PC Plus also has the capability of rule grouping into a frame representation to create a modular rule base. However, PC Plus is quite expensive and may be slow at times, especially when extensive and complicated numerical processing is required (Raeth, 1988; Adeli, 1989). EXSYS and Insight 2 also offer many of the same capabilities. However, they do not have the flexibility of frames or graphics interface that PC Plus has (Malasari, 1988; Mackerle, 1989). In comparison, VP-Expert also offers some links to external programs and spreadsheet software packages, and is a very low cost shell.

Due to the above mentioned desirable features of the VP-Expert package and this researcher's previous experience with the tool, initial work has been conducted using Version 2.1 of this expert system shell (Paperback Software, 1989). It was expected that the simplicity of the tool, its ability to chain through knowledge bases allowing for the grouping of knowledge base rules, the simple knowledge representation scheme (rules), and the limited size of individual knowledge-based system components would ease the process of updating or modifying the knowledge bases at a later time by the developer and/or end-users.

Spreadsheet models have been developed using Lotus 1-2-3 software (Lotus Development Corporation, 1989) to be compatible with end-user computing environments and to allow data transfer between these models and the knowledge-based system components.

5.2 Description of the decision support system components

The individual modelling components of the decision support system are organized and discussed according to their use with the various planning steps in developing long-range MSW management systems to serve a community or region. The general framework of the decision support system is presented in Figure 8.

Although data may be transferred to or from a Lotus 1-2-3 spreadsheet model within VP-Expert knowledge bases, without a graphical user interface control cannot be transferred to Lotus 1-2-3 during a consultation. Instead, the user must exit VP-Expert after consultation with a knowledge base which collects data for a spreadsheet model, and activate Lotus 1-2-3 to utilize the spreadsheet model. It is then necessary to exit Lotus 1-2-3 and re-enter VP-Expert to continue the consultation process. Spreadsheet models are also used to collect data for conducting optimization or simulation studies of MSW management system. The simulation program and the optimization model solver cannot

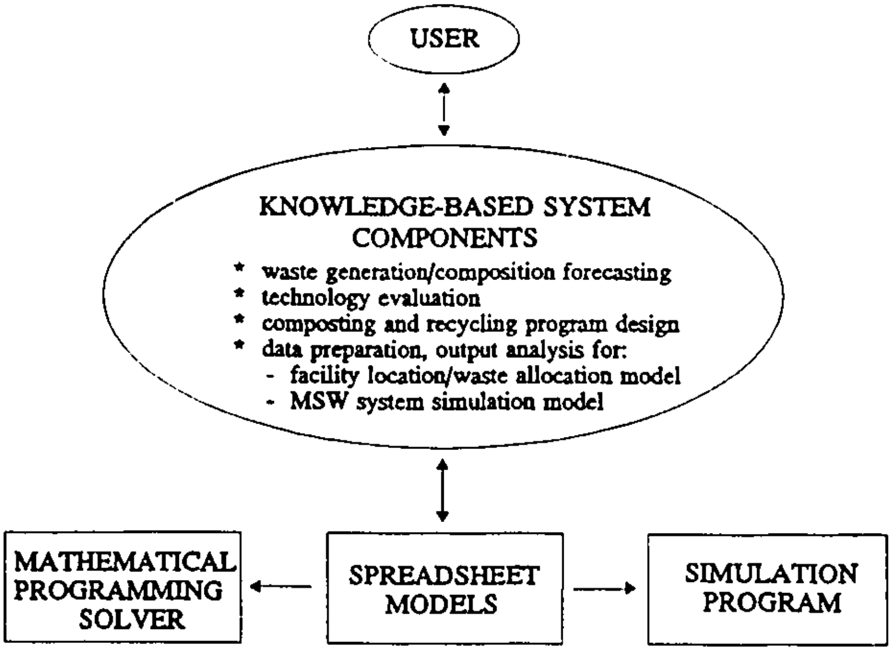

Figure 8. **Modelling component interactions in the proposed decision support system**

directly access the information regarding the planning problem contained in the spreadsheet models. The user is advised on the use of the data collected during consultations with various knowledge-based system components to prepare the necessary input for an optimization or simulation study.

5.2.1 Introduction to the decision support system

General instructions on the use of the software packages and the planning support capabilities of the decision support system are provided by an initial knowledge-based system component (INTRO.KBS). Through interaction with this knowledge base, general data are collected: economic parameters, including the prevailing interest, inflation and U.S. exchange rates (used to adjust cost and revenue estimates to current or future Canadian dollars); the current year (assumed to be year 0 of the planning horizon); community characteristics, including population and the number of single-family versus multiple-family dwellings; and average densities of waste materials. These data are saved for use by other spreadsheet and knowledge-based system modelling components.

5.2.2 Waste generation and composition forecasting

The planning of a waste management system relies on waste generation and composition data developed over the assumed 20 year planning period. The user is assisted in generating data for the residential and industrial/commercial/institutional (ICI) sectors of the community. These activities are preceded by a knowledge-based system component which explains the estimation procedure and provides information on waste forecasting considerations and the general approach of the planning tool (WASTE.KBS). This knowledge-based system component also supplies references for waste generation and composition estimation and forecasting.

Generation and composition data obtained from reported waste stream analyses are presented in a spreadsheet model for both single-family dwellings (SFDs) and multiple-family dwellings (MFDs) to aid the user who does not have local data (RES.WK1). Current waste generation and composition estimates for these residential sectors must be provided.

Percentage changes in the generation of individual, or groups of, materials over the planning period may be entered to produce waste generation forecasts over the 20 year planning horizon. These changes may account for expected population and generation growth rates, as well as for waste reduction or re-use efforts. This is a relatively simplified approach to developing waste generation and composition forecasts. Minimal assistance is provided for estimating future changes in waste generation, and no use is made of statistical techniques which relate generation and composition to community characteristics such as average income for forecasting purposes. The forecasting work is accomplished through the use of two separate spreadsheet models for the SFDs and MFDs (SFDS20.WK1 and MFDS20.WK1).

In a similar manner the user is guided through waste generation and composition forecasting for the ICI sector, following an introduction to the modelling process provided by a knowledge-based system component (ICI.KBS). Waste generation and composition estimates may be developed from average values for the ICI sector as a whole, based on local data or using the collected literature data. Assistance, through the provision of waste generation and composition data reported in the literature, is also given in producing more detailed estimates for specific institutions, commercial establishments or industries. If source separation composting and/or recycling programs are planned, the user may wish to include only specific ICI waste generators based on site-specific estimates. To simplify the forecasting process due to the scarcity of ICI related data, a single waste generation growth rate is estimated and may be applied to the entire planning horizon. A spreadsheet model has been developed for the estimation and forecasting of ICI waste generation and composition data (ICI.WK1).

A flow diagram of the representation of this initial planning stage within the prototype decision support system is supplied in Figure 9.

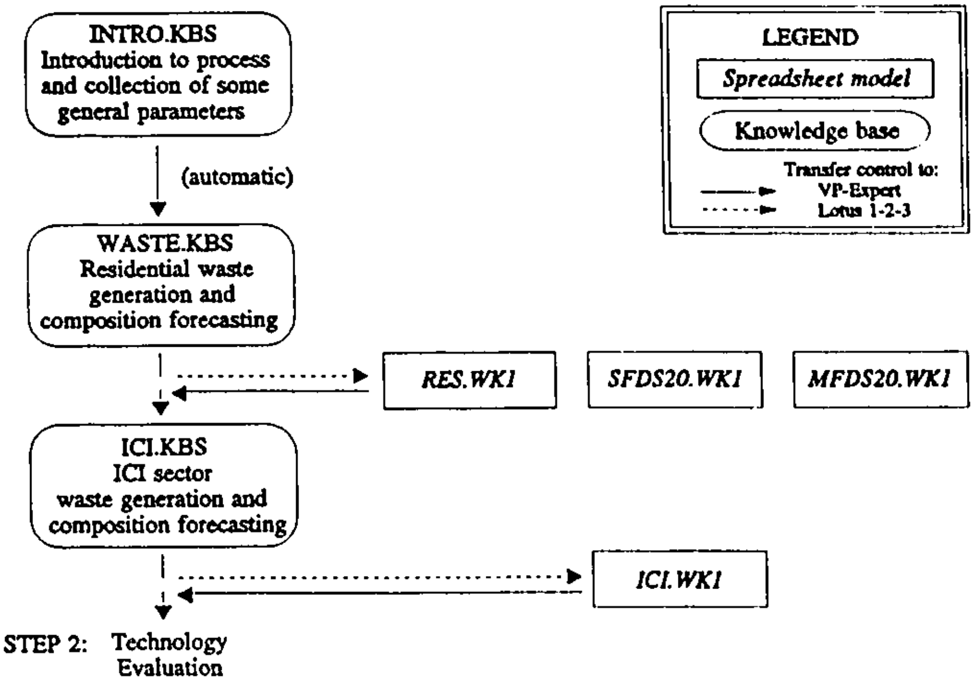

Figure 9. Flow diagram of the introductory, and waste generation and composition forecasting modelling components (STEP 1)

The primary sources for waste generation and composition data, and appropriate waste composition classifications, were two recent waste stream assessments completed on residential and commercial waste for the Ontario Ministry of the Environment (Gore & Storrie Ltd., 1991*a*; 1991*b*). The application of growth rates for forecasting waste generation within the spreadsheet models has been a commonly used approach in waste management planning studies (ACI/ADI, 1989; MacLaren Engineers, 1989).

5.2.3 The investigation of MSW management technologies

Integrated waste management relies on investigating a range of available technologies, and designing and combining appropriate technologies to complement each other and offer the flexibility to deal with future changes in the generation or composition of local waste. The planning process may continue with an investigation of the various technology choices for transferring, treating, processing and disposing of MSW. The selection of appropriate technologies depends on factors such as economics and current public sector policies, for example, the phasing out of incineration. Knowledge-based system components have been designed to provide information on the currently available waste management technologies (TECHS1.KBS and TECHS2.KBS).

Advantages and disadvantages are provided for current technological options: source separation composting and recycling programs, and processing facilities; mixed MSW processing facilities, which accept mixed MSW and process it for recovery of materials; EFW facilities, which generate energy through the combustion of MSW; transfer stations; and landfills. The advantages and disadvantages of the technologies are grouped to reflect various concerns: technical, operating, product markets, costs, societal, environmental, compatibility with other technologies, compatibility with regulations, and compatibility with waste reduction and diversion goals. Finally, a summary table is provided of the major considerations for technology evaluation illustrating a relative ranking of the technologies with respect to the evaluation criteria for comparison purposes. A flow diagram of the portion of the decision support system responsible for assisting with the technology evaluation stage is provided in Figure 10.

The majority of Solid Waste Management Master Plan studies rely primarily on a qualitative approach to the preliminary investigation and evaluation of MSW management technologies (ACI/ADI, 1989; MacLaren Engineers, 1989). The modelling components were designed to reflect this current approach to the technology evaluation

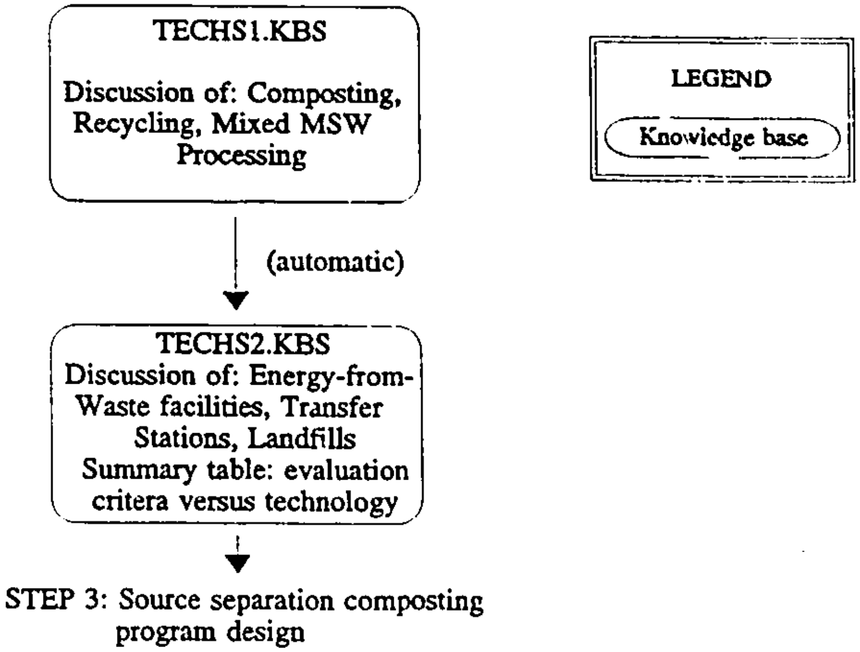

Figure 10. Flow diagram of the technology evaluation modelling components (STEP 2)

planning stage. The decision support system, unlike the consulting firms that often conduct Solid Waste Management Master Plan studies, does not recommend appropriate technologies a community or municipality should develop. Rather, it provides the user with information similar to that which consultants might gather, and offers the user modelling tools which allow a wide range of options to be explored.

5.2.4 Source separation composting and recycling program design

Municipal source separation composting and recycling systems are rapidly evolving and widely utilized MSW management technologies. This trend has taken place as governments emphasize the need to divert materials from landfills. As the number and the sophistication of programs increase, the planning of appropriate programs to meet the needs of a particular community or region becomes a more difficult task. Using knowledge-based system components interacting with spreadsheet models, the user may explore the available options for recycling systems and composting systems based on the separation of appropriate materials from mixed MSW at the point of generation for the SFD, MFD and ICI sectors. These modelling components may be used to develop new programs, or to expand existing programs (in the number of waste generators or the number of materials included). It is also possible to develop different types of programs for the various generation sectors to conduct a preliminary comparison of the potential costs and waste diversion rates.

Consideration is given to the types of programs available, equipment and labour requirements, preliminary cost estimation and program effectiveness (represented by the predicted waste diversion rates). Costs for all program components are provided within the spreadsheet models on an annual and net present value basis using the inflation, interest and exchange rates supplied by the user. A single inflationary factor is applied, without restriction, to capital and operating costs, and revenues in the calculation of the cash flows associated with source separation composting and recycling programs.

The composting program options considered are on-site (backyard) composting, curbside collection from generators and the drop-off of compostable materials by generators at specified location(s). The latter two options also require the consideration of centralized composting facility requirements.

Through consultation with a knowledge-based system component, the user is initially provided with information on the various program options and examples of existing programs (C_SOURCE.KBS). Recommendations are dispensed for appropriate programs given the type of community (rural or urban) and the existence or potential for establishing a centralized composting facility. Based on this information, the user is asked for the types of programs to be designed (or expanded) for each sector of the community. The option also exists for the user to choose not to design or expand source separation composting programs, in which case control transfers immediately to the consideration of source separation recycling systems.

If source separation composting programs are being designed or expanded, the consultation continues with an examination of centralized composting facility (CCF) requirements (C_FAC.KBS). If a nearby or existing local CCF is to receive the materials, data are collected regarding the acceptable materials and the type of composting technology used. If the materials are to be transferred to a potential (proposed) CCF site to be developed and operated by the community or region, the user is assisted in deciding what materials will be accepted and what composting technology will be used to process the materials. Technology selection recommendations are provided based on the relative availability of capital and land resources.

The consultation process may then continue with the design or expansion of composting programs. Knowledge-based system components were created to assist with the design or expansion of each type of program (on-site, drop-off and curbside), should it be requested (C_BACK.KBS, C_DROP.KBS and C_CURB.KBS). Each knowledge base may be conferred with, in turn, for the development of programs for the SFD, MFD and ICI sectors.

The user is guided through the entire process of the preliminary design of composting programs: the selection of appropriate composting units or collection containers; the evaluation and selection of an appropriate collection system, if necessary; the estimation of program costs; and the estimation of material capture rates and waste diversion rates.

The composting program knowledge-based system components collect the program design parameters: expected initial participation rate; the number of homes, complexes or sites initially eligible to participate; the intended start-up year for the program (with respect to the 20 year planning period); program advertising, administration and planning costs; and material capture rates representing the fractions of specific compostable materials present in the waste stream that are removed by the waste generators for composting. Advice and recommendations are provided to assist with the estimation of these program design parameters based on experience reported in the literature by waste management professionals.

For curbside collection programs, the user is advised on the selection of an appropriate collection system, and the estimation of collection vehicle capital and operating costs. If a collection container is to be provided, estimates are required for the expected cost and economic life of the units in order to calculate annual depreciation costs. Two methods are provided to determine the number of collection vehicles required for a program. An estimate of the average number of homes or sites a vehicle can service in one day (i.e., average route size) may be provided. Based on the frequency of collection, the number of collection days per week and the number of collection locations, the number of vehicles required is calculated for each year of a program.

It is also possible to do a more detailed analysis of vehicular requirements that explicitly considers vehicle capacity and collection time restrictions. The user must then supply estimates for the available collection time per day, the collection and travel time between individual collection locations, the round trip travel time to the processing facility, the unloading time at the processing facility and the vehicle capacity. This method also requires that the frequency of collection, the number of collection days per week and the average material density be specified.

Program design parameters are transferred from the knowledge bases to the corresponding spreadsheet models where an analysis of program costs and material removal rates may be conducted over the entire 20 year planning horizon. Separate spreadsheet models have been developed for each sector and program type (SFD_BACK.WK1, MFD_BACK.WK1, ICI_BACK.WK1, DROP.WK1, SFD_CURB.WK1, MFD_CURB.WK1 and ICI_CURB.WK1). The user may expand the scope of a program to include more homes, complexes or sites. It is also possible to use the spreadsheet models to investigate the effects of changing parameter value estimates on annual program costs and waste diversion impacts.

If a curbside collection program is to be designed or expanded and the user has requested a detailed analysis of vehicular requirements, it is necessary to utilize an additional spreadsheet model (VEH.WK1). The model is based on a previously developed model (Peavy et al., 1985). Based on the expected capture rates, or volumes of materials, at collection points, and the parameters collected through consultation with the knowledge bases, the number of vehicles required for each year of a program is calculated considering the available capacity of the collection vehicles and the time available per working day for the collection activity. With this information the capital and operating costs of the collection vehicles may be calculated. The first step is to determine the total number of minutes available for the collection activity per day (CT):

$$CT = \frac{H*(1-ORF)*60-(NT*RTT)-(NT*FT)}{NT} \qquad (1)$$

where: H = working hours per day
ORF = off-road factor (fraction of time for worker break periods, etc.)
NT = number of trips to the processing facility per day
RTT = round trip time to the facility (minutes)
FT = unloading time at the facility (minutes).

The number of pick-ups possible before making a trip to the processing facility (NPT) is calculated based on the required collection time per location (CTL), in minutes, and the available collection time per day as:

$$NPT = \frac{CT}{CTL} \qquad (2)$$

The total volume required for the collection vehicles (VOLREQ) and the number of vehicles required (NUMREQ) are then calculated as follows:

$$VOLREQ = NPT*VLL \qquad (3)$$

$$NUMREQ = \frac{NUMLOC}{(NT*NPT*ND*NW)} \qquad (4)$$

where: VLL = total volume requiring pick-up per location per collection day (m^3)
NUMLOC = number of collection locations
ND = number of days per week collection takes place
NW = number of weeks between collection periods.

The volume of materials to be collected at each location is calculated within the program design spreadsheet models (SFD_CURB.WK1, MFD_CURB.WK1 and ICI_CURB.WK1). Two possible conditions may occur. First, the volume required for the collection vehicles (VOLREQ) may exceed the given vehicle capacity, in which case the actual vehicle capacity is substituted back into equations 3 and 4 to revise the estimate of the number of vehicles required. The other possibility is that vehicle capacity is underutilized. The user specifies the desired minimum fraction of the available vehicle capacity that should be utilized. If vehicle capacity is underutilized, the number of trips made to the processing facility per day may be decreased (if it is greater than 1) and then the modelling steps are repeated. The details of the model are also presented within the spreadsheet model (VEH.WK1).

After consultation with the individual program design modules, the user may examine the Lotus 1-2-3 spreadsheet models and calculate the costs and waste diversion impacts of the programs. Following this, the user may return to VP-Expert and continue the consultation with a consideration of the processing requirements and costs for materials collected through the drop-off or curbside collection programs. If an existing or potential centralized composting facility (CCF) site has not been pre-selected to receive the materials, the consultation transfers immediately to the design of source separation recycling programs. After this stage has been completed, the user is given the opportunity to use an optimization model or a spreadsheet model to assist with the investigation of processing facility requirements. If the compostable materials collected are to be transferred to a nearby CCF, operated by another municipality or a private company, or transferred to an existing or potential site, the knowledge base gathers the information required to estimate the resulting processing costs. The tipping fee is the main cost parameter if the collected materials are transferred to a nearby CCF. For an existing, community-operated CCF a number of parameter values are requested: the facility capacity, the operating cost, the reduction in weight and volume of the input materials achieved through the composting process, the revenue generated from the sale of finished compost, the tipping fee, the potential for capacity expansion, and the estimated cost of capacity expansion. For a potential (proposed) CCF, the user is guided through the process of estimating the required design parameters mentioned above in addition to other parameters including area requirements based on the chosen composting technology, and planning and design costs. These facility related parameters are transferred to a spreadsheet model for calculation of the costs for processing the materials collected in the source separation composting programs (FAC_COMP.WK1).

A capital cost estimate is also required for the case of developing a new facility. To assist with the estimation of the capital cost, values reported in the literature were collected and are embedded within the spreadsheet model (FAC_COMP.WK1). The capital costs are inflated to current dollars and American costs are converted to the equivalent Canadian dollar costs using the inflation and exchange rates previously provided by the user. The user is guided through the use of the regression capabilities of Lotus 1-2-3 to develop an assumed linear relationship between the design capacity and the capital cost of centralized composting facilities. Based on the yearly total tonnages of materials collected through the various source separation composting programs, the user may then specify the initial capacity and any capacity expansions over the 20 year planning period. Using the linear regression parameters, the resulting capital costs of a chosen initial development and expansion pattern may be determined. The variable capital cost may also be used as an estimate for the expansion cost at an existing facility if no information is available. This representation of facility capital costs is further explained in the facility planning sections.

The general organization of the modelling components involved in the design or expansion of source separation composting programs is presented in Figure 11. A listing of the knowledge base developed for the design of drop-off composting programs (C_DROP.KBS) is provided in Appendix B.

For the collection of recyclables, the options examined are curbside or drop-off (depot) programs. The procedure followed is very similar to that previously described for the design of source separation composting programs. The user is provided with information on the various program options and asked for their selections of which programs are to be designed or expanded through interaction with a knowledge base (R_SOURCE.KBS). If source separation recycling programs are not being considered, the consultation transfers immediately to an introduction to the investigation of facility planning issues.

Drop-off or depot programs are generally used in rural areas or for the ICI sector of a community, but may complement an urban curbside collection program. This type of program may be designed for the SFD, MFD and ICI sectors (R_DROP.KBS). Curbside collection programs, most prevalent in low density residential areas, may also be designed for all sectors of the community (R_CURB.KBS). However, small ICI generators and small MFD complexes may be included in SFD curbside collection programs as well. For larger MFD complexes and ICI generators, specialized curbside

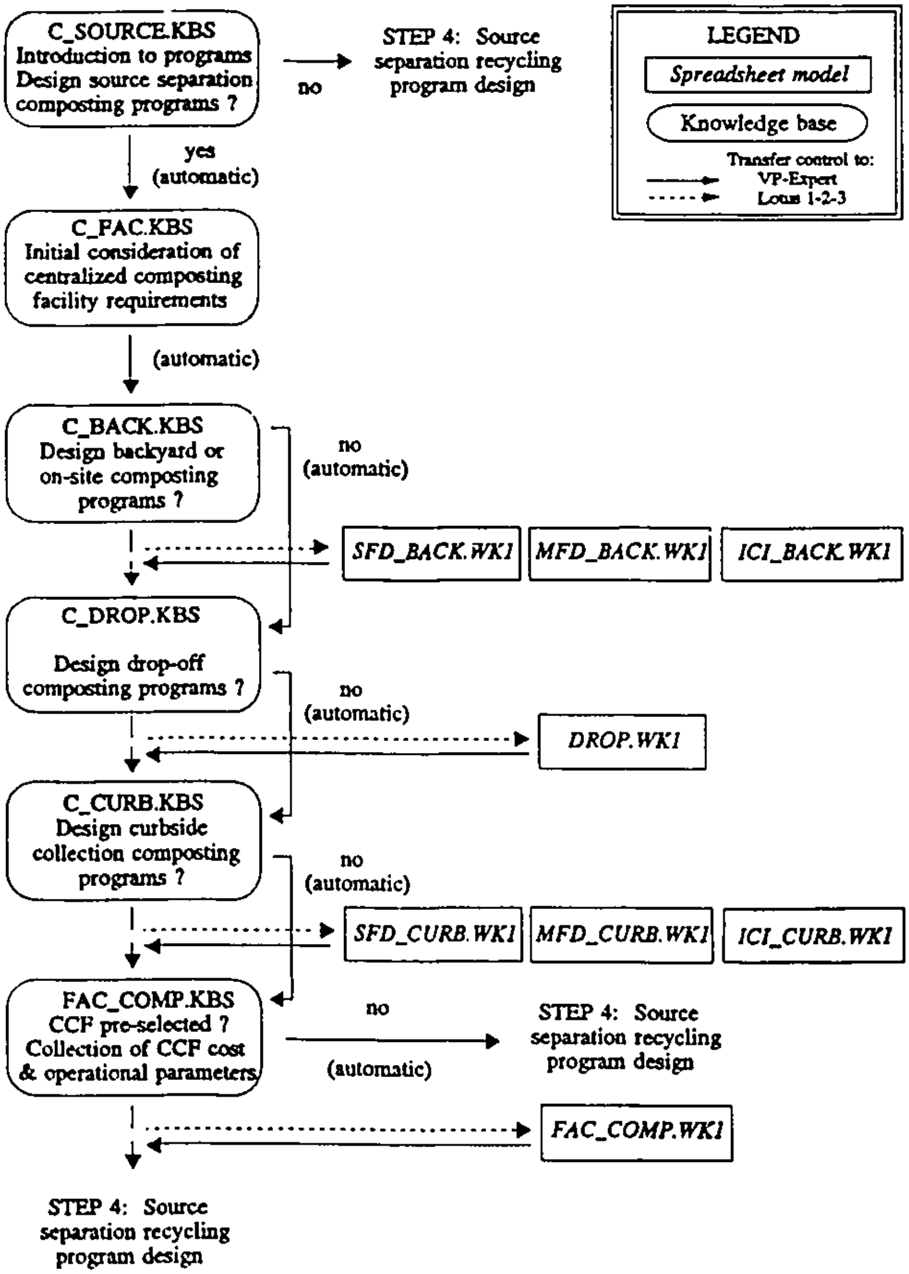

Figure 11. Flow diagram of the source separation composting program design modelling components (STEP 3)

programs which rely on the use of depots may be designed (R_DEPOT.KBS). The analysis of costs and material recovery rates is conducted in the corresponding spreadsheet models (R_DROP.WK1, R_CURB.WK1 and R_DEPOT.WK1).

Within the knowledge bases, information is provided regarding materials suitable for recovery through recycling, along with information on potential revenues for recovered materials. A determination of the costs of drop-off (depot) or curbside programs are assessed with the assistance of the spreadsheet models. For drop-off (depot) and curbside recycling programs, a collection system must also be designed, as previously described for curbside composting programs. After the design of the programs, a knowledge base assists with the assessment of the resulting processing costs if an externally operated materials recovery facility (MRF) or a local existing or potential site will receive the materials (FAC_REC.KBS). Otherwise, if a site has not been pre-selected from the available existing and potential sites, the consultation continues with the next planning stage, the analysis of facility location/waste allocation planning issues.

The general organization of the modelling components involved in the design or expansion of source separation recycling programs is presented in Figure 12.

The costing methodology developed by Smith (1989) has formed the basis for the source separation composting and recycling program design modelling components. Smith demonstrates the validity of the costing methodology using a case study application - the design and costing of a curbside recycling program for an Ontario community. This work was also a major source for the advice encoded in the decision support system regarding program parameter values.

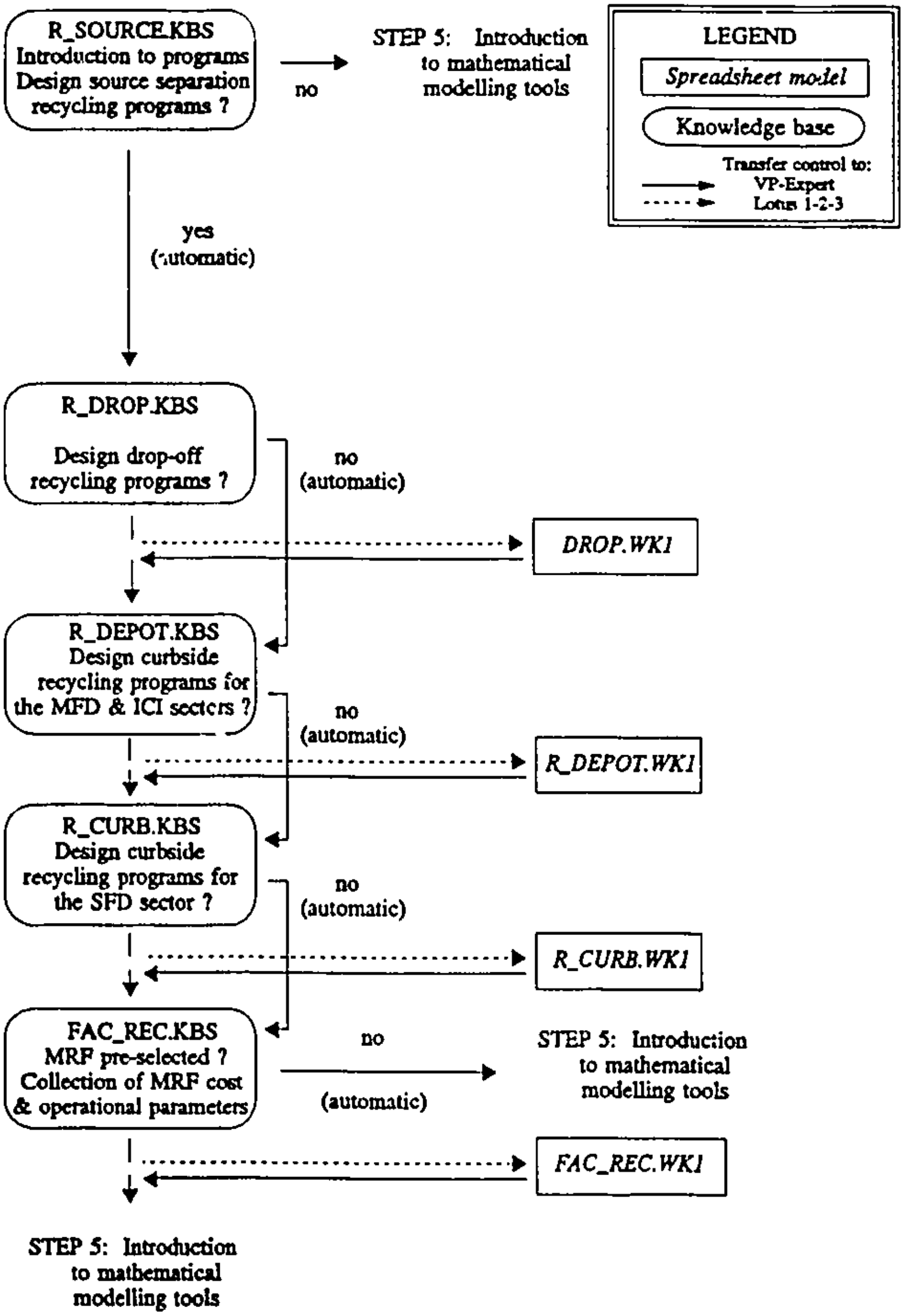

Figure 12. Flow diagram of the source separation recycling program design modelling components (STEP 4)

5.2.5 Introduction to the facility planning modelling components

After consideration is given to the design of source separation composting and recycling systems, the user is introduced to several modelling techniques (spreadsheets, optimization and simulation) that may be used to investigate facility planning issues for a preliminary local or regional MSW management system planning study. Introductory information is supplied regarding the modelling options and their potential uses in generating and evaluating alternative MSW management systems. The mathematical formulations and data requirements of the optimization and simulation modelling approaches are described.

The study of facility planning issues, such as investigating facility locations and waste assignments, may be conducted for a source separation composting system or a source separation recycling system in isolation, as these systems generally have their own dedicated collection and processing systems. Alternatively, after considering the impacts of source separation composting and recycling programs, a MSW management system may be investigated to manage the remaining residual waste stream. In addition, rather than pursuing a detailed design of composting and recycling programs and facilities, the user has the option of preparing cost and operational data for these technologies and thus investigating an integrated MSW management system to manage the entire waste stream. In this manner, the user may explore facility selection and location, facility investment timing, facility sizing, and waste allocation issues with respect to managing recyclables, compostables, processing residuals, and/or the entire MSW stream.

A recommendation is provided regarding the appropriateness of conducting an optimization study given the number of technological options and facility sites being considered. The user may decide that the scope of their MSW management system planning problem does not warrant an optimization study; in which case the facility spreadsheet models may be used to size and cost facilities given an assumed pattern of yearly waste or material allocations.

The introduction to the modelling tools for investigating facility planning issues is supplied through interaction with a knowledge base (MILP.KBS). The user may return to this knowledge base after completion of any of the modelling steps, such as the preparation of data for a model or model output analysis, to decide on the next step for the facility planning study.

To investigate facility related planning issues using either the spreadsheet models or an optimization modelling approach, certain cost and operational parameters are required for each of the technological options being examined or being considered for inclusion in a MSW management system. In the following section, the use of a set of knowledge bases and spreadsheet models to estimate the required facility related modelling parameters will be described. This is followed by a description of the optimization and simulation modelling approaches.

5.2.6 The estimation of facility cost and operational parameters

After an indication of the type of system planning problem being investigated, cost and operational parameter estimates are required for the relevant existing and potential facility sites. A brief introduction is provided, through consultation with a knowledge base, for the estimation and collection of the facility related modelling parameters (F_INTRO.KBS). The analysis then proceeds to an examination of MSW management technologies the user deems appropriate for the system planning problem indicated, in order to develop the necessary cost and operational parameters required for the facility location/waste allocation models. This is done through consultation with individual knowledge bases created to examine specific technologies (FAC_CCF.KBS, FAC_MRF.KBS, FAC_MSW.KBS, FAC_EFW.KBS, FAC_TS.KBS and FAC_LF.KBS).

For existing facilities, several cost and operational parameters are requested: the current capacity; the potential for capacity expansion and an estimate for the cost of expansion if it is possible; the current operating cost and tipping fee; the fraction of the input stream that is recovered as materials and/or energy, and the revenue generated from the sale of the recovered materials and/or energy; the number of operating days per year; and the fraction of the facility design capacity utilized for normal operation.

For any potential facility sites being considered, estimates are also required for the necessary cost related modelling parameters. To assist the user in developing the necessary data to explore facility planning issues using the spreadsheet or optimization modelling tools, estimates reported in the technical literature are provided for many of the parameters. The user must supply the chosen estimates for the planning and approvals cost per facility, the design and engineering cost per facility, the operating cost, the tipping fee and the construction or capital cost. The operating cost is represented as a linear or variable cost dependent on the waste loading to the facility.

For the development of capital cost estimates, a listing of reported values for existing and proposed facilities is provided during the consultations with the facility related knowledge bases. These values have also been transferred to the corresponding facility spreadsheet models to permit the development of capital cost curves of design capacity versus capital cost. The information provided for the literature estimates includes the type of facility, the specific technology utilized, the capital cost, the design capacity and other important factors such as whether the facility is existing or proposed. The user may decide which data to consider in a capital cost curve estimation process. Using the regression analysis capabilities of Lotus 1-2-3, capital costs may then be represented by a fixed cost, independent of the initial capacity of the facility, and a linear cost (or variable cost) dependent on the design capacity of the facility.

The variable capital cost is also used to represent the linear capacity expansion cost. The variable cost may also serve as a preliminary estimate for the expansion cost of an existing facility if no local information is available. This simplification causes the cost of any expansion to the initial design capacity of a facility to be independent of the present capacity, and to result in no additional fixed costs. This does not wholly represent reality if the expansion of a facility will incur significant approvals or design costs.

In addition, the assumption of linearity in the development of the capital cost curves results in no economies of scale being represented for capacity development beyond the fixed cost. Rhyner and Wenger (1986) found no economies of scale exist for large or complex EFW facilities; however, the limited number of previous studies (completed in the 1970's to early 1980's) addressing the estimation of scaling factors for MSW management facilities indicate the existence of economies of scale.

In addition to the cost related data for all potential facilities being examined, estimates must be supplied for the available area at all potential sites. The acquisition of this land may be included as a variable capital cost. The available land area is also required to estimate the maximum capacity of a facility that could be constructed on the site. An estimate is also required for a factor that relates the area requirements to the capacity of a facility. Again, technical literature estimates are provided for guidance.

All of the costing information collected through consultation with the knowledge bases is transferred to the corresponding facility spreadsheet models (FAC_CCF.WK1, FAC_MRF.WK1, FAC_MSW.WK1, FAC_EFW.WK1, FAC_TS.WK1 and FAC_LF.WK1).

Parameters are also required that reflect other operational considerations for potential facility sites being considered in a particular MSW management system planning study: the maximum capacity of a facility based on technical, political or economic constraints; the minimum capacity before a proposed facility would be built; the expected materials and/or energy recovery, as a fraction of the input, and the predicted revenues from the sale of these commodities; the earliest year from the current year a potential facility site may be operational; and the maximum number of potential sites that may be developed over the available planning horizon. These parameter estimates are also transferred to the corresponding facility related spreadsheet models.

After cost and operational parameter estimates have been provided for all of the facilities that are being considered for a particular MSW management system planning problem, the user may examine the individual spreadsheet models and perform a capital cost curve estimation procedure for any potential facility types. The spreadsheet models may also be used to conduct a cost analysis for a particular site, whether it is an existing or proposed (potential) facility site. Yearly waste or material allocation estimates to the site must be provided. Based on these assignments, the spreadsheet model calculates the resulting annual costs and revenues. An additional spreadsheet model may be consulted to assist with the development of yearly waste or material allocation estimates (WASTE.WK1). This spreadsheet model assists with the transfer of data from the previously completed waste generation and composition forecasting spreadsheet models. It also assists with the transfer of total yearly material recovery estimates from the source separation composting and recycling program design spreadsheet models to determine processing facility requirements for a compostable or recyclable materials stream, or for a system to manage the residual waste stream.

Thus, if an optimization study is not requested due to the limited number of facility sites and/or technologies being considered, the user still has access to modelling tools to assist with the development of cost estimates based on a predetermined pattern of waste or material allocation. The facility planning spreadsheet models may also be used in isolation of the knowledge bases by directly entering parameter estimates. For the consideration of a system to manage source separated materials without an optimization study, the user is directed back to the spreadsheet models created to accompany the program design knowledge bases to estimate material allocations and processing costs (FAC_COMP.WK1, and FAC_REC.WK1).

An illustration of the organization of the modelling components involved in the process of collecting facility related data is provided in Figure 13. A listing of one of the facility related knowledge bases (FAC_EFW.KBS) is provided in Appendix C.

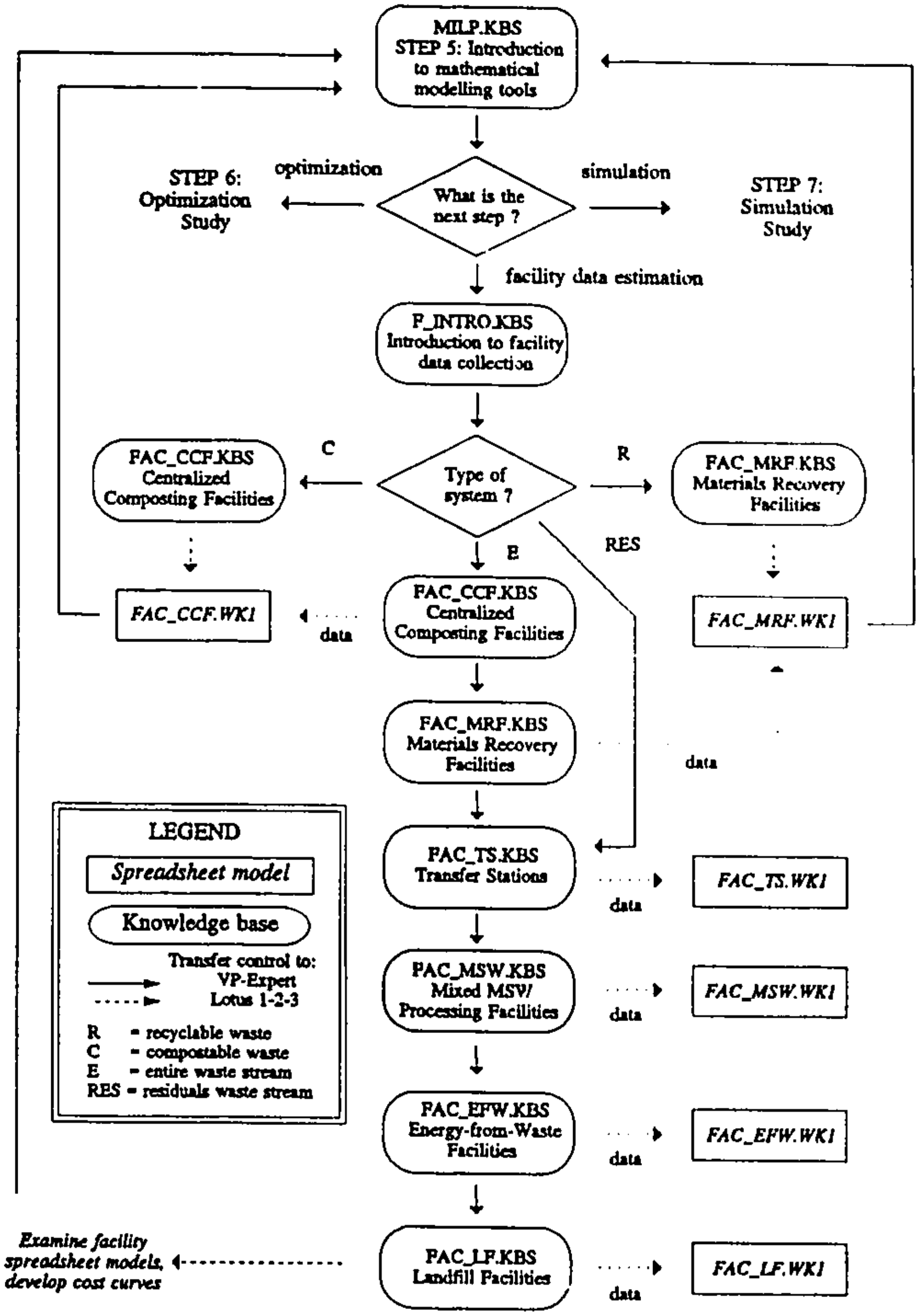

Figure 13. Flow diagram of the modelling components responsible for the collection of facility cost and operational data (STEP 5)

5.2.7 Facility planning using an optimization model

Optimization techniques have been widely proposed in the water resources and waste management literature as a means of developing and evaluating alternatives for long-range systems planning (Brill, 1979; Wilson, 1981). Wilson (1981) summarizes that the problem is, given an expected pattern of waste generation, to investigate the types of facilities that should be built, together with their location, capacity, implementation, and waste allocation patterns over the desired planning horizon, based on the objective of minimizing total system costs.

Problems such as facility planning in which the objectives of the study may be unclear, conflicting or difficult to quantify require less formal approaches to resolving conflicts and arriving at compromise solutions. Optimization models may be used in such situations to produce a set of feasible and economic MSW management system solutions which can then be examined for their non-economic implications. The role of optimization models in facility planning is thus limited and should be directed at the generation and economic evaluation of alternatives (Brill, 1979).

The literature offers a multitude of models that may be used to investigate the MSW management planning issues of facility sizing, timing and location, given information on potential and existing sites and capacities, waste generation and composition data for the waste generation source areas, and the cost functions for the transportation, processing and disposal of waste subject to constraints such as capacity or budgetary limitations.

Based on the results of the literature review, a widely utilized approach for modelling facility planning problems is through the use of linear or mixed-integer linear programming techniques to minimize total system costs. These optimization techniques generally reduce the transportation, capital and operating costs, and revenues incurred over the planning horizon to their net present value for comparison purposes (Wilson, 1981).

In order to provide flexibility in the decision support system, the basis for the optimization study is the use of a mixed-integer linear programming (MILP) model formulation for facility location, timing and sizing, and waste allocation. This allows the user the flexibility of developing an MILP or a linear programming (LP) model formulation for a facility planning problem. The general MILP facility planning model formulation described in the prototype decision support system is based on the previous work of several researchers (Kuhner and Heiler, 1973; Kuhner and Harrington, 1975; Jenkins, 1979).

Knowledge-based system modelling components and spreadsheet models have been created to assist the user in developing an LP or MILP model formulation for a given facility planning problem. An MILP model formulation is required if potential (proposed) sites for transfer and/or processing facilities are being considered and the capital cost curves for any of these facilities have been modelled with a fixed cost (other than 0), or if potential landfill sites are being considered. Integer decision variables must be included in the model formulation to ensure that fixed capital costs are incurred only if a potential site is to be used during the planning time horizon. In the case of landfill facilities, the integer variables will ensure that when a potential landfill site is to be opened the maximum available capacity is developed.

Several extensions to the basic MILP MSW management systems planning model formulations suggested in the literature were required to make the approach more generally applicable to current facility planning, as the previous models focused on the transportation, processing and disposal of mixed MSW only. The previous optimization studies were, thus, limited to the consideration of the utilization of transfer stations, incinerators or EFW facilities, mixed MSW processing facilities and landfills. The facility planning components of the prototype decision support system also had to be flexible enough to be used in the planning of systems to manage source separated compostable or recyclable materials in isolation of the residuals management system. In addition, these components had to be flexible enough to be used in the planning of a more highly integrated system to manage the entire MSW stream considering the collection, transportation and processing of source separated materials in addition to the previously stated options for managing a mixed MSW stream.

The basic MILP model formulation could be quite easily adapted for use in facility planning for processing compostable materials or recyclable materials collected in drop-off (depot) or curbside programs. In these situations, the optimization modelling approach could assist in the investigation of facility location/waste allocation issues with respect to materials recovery facilities (MRFs) required to process source separated recyclables or centralized composting facilities (CCFs) required to process source separated organics, and the allocation of recovered materials to the available facilities. Transportation costs would then reflect the cost associated with the transport of source separated materials in the composting or recycling collection vehicles from the drop-off depots or collection areas to a processing facility. The cost of disposing of residuals could then be included as an additional facility operating cost, or optimal allocation of residuals to predetermined landfill sites may be investigated.

For planning a system of facilities to manage mixed MSW in addition to managing source separated materials through the use of MRFs or CCFs, several changes were made to the basic model formulations suggested in the previous MILP facility planning studies. Transportation costs would be different for the flows of materials destined for MRFs or CCFs as compared to flows of mixed MSW destined for transfer stations, mixed MSW processing facilities, EFW facilities and landfills. For the previously identified MILP studies investigating the management of a mixed MSW stream, this differentiation was unnecessary as the collection costs were the same regardless of where the waste was to be transported. In order to allow consideration of the impacts of the relative magnitude of source separation program collection costs versus standard mixed MSW (garbage) collection costs on the solution to an integrated planning problem, collection costs were included in the objective function of the model, in units of $/tonne, as a linear function of the flow of materials or waste to the applicable MSW management facilities. Composting and recycling collection cost estimates may be developed with the assistance of the source separation program planning knowledge base(s).

In addition, the user may wish to restrict capacity development and expansion to discrete values which requires integer variables to ensure only one discrete level of capacity is developed at a potential facility or added to an existing facility during any time period. This extension to the basic model formulation was included to better reflect the general practise with respect to facility construction. Otherwise, the model will allocate different quantities of waste to a given facility and, thus, base costs on the full utilization of facilities of different capacities in different time periods (which more realistically represents varying usage of the design capacity of a single facility at that site); the optimal solution may then not be the true least-cost solution but may also not be a practical or even implementable solution (Wilson, 1977). For example, modular EFW facilities are constructed and expanded in units of standard capacity. The general model formulation presented in Appendix D allows the user to specify discrete capacity levels for the development and expansion of potential and existing facilities.

As well, the general optimization approach may be used to handle less complicated LP model formulations for situations where potential facility capital cost curves were not modelled using a fixed cost and landfill sites have been predetermined for use, or where all facility sites that are to be developed over the planning period have been predetermined. If facilities already exist or will definitely be developed on the sites, the need for integer variables is eliminated, reducing the problem to an LP model formulation. The optimization model is then used to select rather than locate MSW management facilities, and to investigate waste allocation and capacity expansion patterns. An MILP model formulation would still be required if discretization of expansion capacities is desired. A description of the optimization modelling approach and data requirements are provided through consultation with two knowledge bases mentioned in the previous section (MILP.KBS and F_INTRO.KBS).

After the user has developed the necessary facility related cost and operational parameters for a specific MSW management system planning problem, an additional knowledge base may be consulted to assist with the preparation of the mathematical statements to represent the objective function and the constraints on the system

(INPUT.KBS). The advice encoded was derived from several sources including Jenkins (1979) and Wilson (1981). The assumption is made that a standard solution package is to be used. This modelling component provides advice regarding model formulation steps; it does not prepare an input file for use with standard mathematical programming software, nor does it display the actual mathematical representation of the model. The user is directed to a hard copy of the optimization model formulation (included in Appendix D) which assists with model formulation using data collected through the consultation process. A brief description of the additional modelling considerations addressed by this knowledge base follows.

Costs for transporting waste from waste source areas to facilities and between facilities must reflect the type of vehicle used, labour requirements, operation and maintenance costs, fuel costs, insurance, the amount of waste transported and the distance travelled. The optimization modelling approach assumes that the capacities of all transportation routes are boundless. Transportation costs are represented in units of $/tonne/km. This has traditionally been the method of describing this cost component for modelling purposes as it allows the model to be computationally tractable by assuming proportionality to distance and the amount of waste transported (Gottinger, 1991). There is, however, a lack of information on appropriate values for transportation costs for the various collection vehicles and transfer trailers. The knowledge base provides assistance in developing transportation cost parameters by providing values reported in the literature. A matrix of round trip transportation distances between all waste source area centroids and existing and potential facilities, and between facilities must also be developed to calculate the transportation costs, in $/tonne units, associated with the assignment of flows between the centroids of waste source areas and facilities.

A community or region may be subdivided into smaller waste generation source areas, particularly if it covers a large geographical area, to better represent the average distance from the centroid of a waste source area to all existing and potential facility sites. If the user is considering the planning of a system of processing facilities to receive source separated materials collected through a drop-off (depot) program, individual depots or groups of drop-off depots could represent the waste source area centroids. Using population figures for the subdivided waste source areas, flows of waste or source separated materials may be calculated with the assistance of a spreadsheet model (WASTE.KBS). The LP or MILP model determines the optimal, least-cost, routing scheme.

The suggested model is dynamic, i.e., multi-period, to account for temporal changes in waste generation rates and waste composition. Waste flows or flows of source separated materials are then required for the chosen time period divisions over the 20 year planning horizon. The use of time increments of 1 year or more is needed to ensure the model is computationally feasible, and is sufficient given the time frame for planning and developing facilities. MILP models tend to require higher computational resources, and solution times may be unacceptable if a multi-period problem with a large set of options is proposed (Jenkins, 1980). The user is advised on the selection of an appropriate number of modelling time periods.

Due to the higher level of mathematics used in MILP models, they are inherently more difficult for inexperienced users to understand and operate (Light, 1990). As a result, knowledge bases were developed to assist in the formulation of the model, but more importantly to assist with analyzing the model outputs and conducting post-optimality tests.

Due to the fact that these optimization models are deterministic and waste management and planning data are generally uncertain, parameter variability effects should be explored. The probabilities of such important factors as waste generation rates and costs are generally unknown; leaving sensitivity analysis as the main means of gaining insights into the effects of uncertainty (Lund, 1990*b*). Wilson (1981) notes that the exploration of model sensitivity may focus attention on the degree of accuracy desired for system parameters, and is of practical importance when relatively new options are being considered. Using the advice provided in a knowledge base, the user may analyze the output from standard mathematical programming software, including the interpretation of the sensitivity analysis results generally provided (SENSE.KBS). In the case of an MILP model formulation, these results cannot be used to derive information regarding the sensitivity of the optimal solution to changes in the values of cost coefficients or constraining parameters (Wilson, 1981). The user is advised on sensitivity tests that may be conducted by adjusting parameters and re-running the model. The advice encoded in this knowledge base was primarily derived from Jenkins (1979) and Wilson (1981).

Several researchers have noted that optimization models developed for public sector planning problems are not particularly useful if they are confined to the generation of a single 'optimal' solution. Optimization models are generally restricted to the minimization of costs. Many objectives relating to the environmental, social and political impacts of decisions are not modelled. Therefore, researchers warn that the best solution may lie within the inferior region of an optimized planning problem. These models should be used to generate planning alternatives and facilitate their evaluation on the basis of cost (Brill, 1979; Chang et al., 1982; Harrington and Gidley, 1985).

The user is provided with advice on methods available to generate near-optimal solutions for a previously optimized MSW management system planning problem through consultation with a knowledge base (NEAR_OPT.KBS). The suggested methods of generating these alternatives using the original, optimal LP or MILP model formulation have been researched in the area of water resources management planning. The information provided in the knowledge base is derived mainly from three sources: Brill (1979), Chang et al. (1982), and Harrington and Gidley (1985). The techniques require adjusting the original (optimized) model formulation to generate solutions that are different with respect to facility development, usage and waste allocations patterns, but that have costs within a specified range of the optimal (least-cost) solution. Alternative systems may then be compared on the basis of costs, in addition to the consideration of unmodelled social, political, environmental and technical considerations.

The organization of the optimization modelling components of the prototype decision support system is displayed in Figure 14. Appendix D contains the general MILP model formulation developed for use in facility planning optimization studies, and Appendix E contains a listing of one of the knowledge bases (NEAR_OPT.KBS).

An important consideration for developing and demonstrating the modelling components associated with conducting an optimization study for facility planning was the selection of an appropriate solver for the mathematical programming module. For the prototype decision support system, an MILP solution package was needed. The

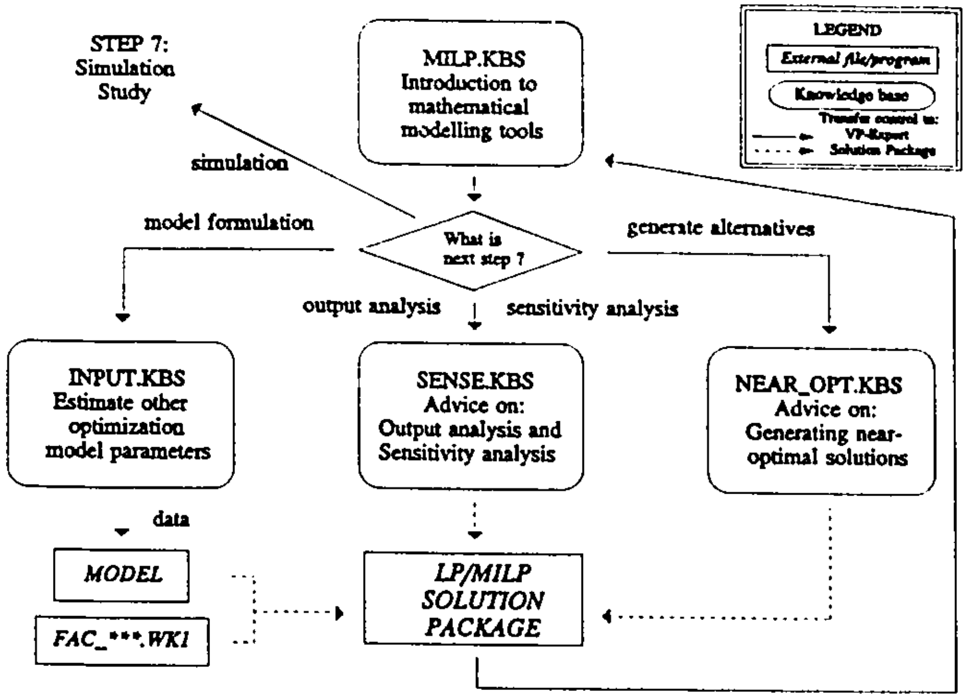

Figure 14. Flow diagram of the optimization modelling components for facility planning (STEP 6)

solver had to allow for a substantial number of variables and constraints, and preferably be able to access spreadsheet models. The solver had to be available for use on microcomputers, preferably IBM PC compatible systems, as this is a standard computing environment available to most waste management professionals (Light, 1990).

In a recent article by Llewellyn and Sharda (1990), linear programming software is reviewed. Some of these tools may also be used for solving mixed-integer linear programs. From this review, several packages met the above mentioned criteria:

- GAMS (General Algebraic Modelling System);
- LINDO (Linear, Interactive and Discrete);
- MILP88 (Mixed-Integer Linear Programming).

The MILP88 package was the preferred candidate as it is able to read Lotus 1-2-3 spreadsheets, and has a relatively low cost compared to the other packages. The LINDO package offers an add-on package that also allows for communication with Lotus 1-2-3 spreadsheets. The computational speed of MILP solution packages is affected by the number of variables and constraints, particularly the number of integer variables. Their comparative capabilities and computational speeds were not fully known.

5.2.8 The simulation of a MSW management system

The final option in the program and facility planning decision support system is the examination of the effect of uncertainty and temporal variation in waste generation on the overall economics and efficiency of a MSW management system, to provide another means of evaluating and comparing alternatives. Wilson (1981) advises of the importance of this step, as waste generation and composition may change considerably over the planning horizon. Simulation may aid in the examination of the effects of changes in parameters on the performance of the system, particularly when it is infeasible to experiment with the full-scale system. It also facilitates scenario studies, a form of sensitivity analysis, in which alternative systems may be compared (Lawver et al., 1990). Brill (1979) suggests that for public sector planning studies, an optimization model could be used to identify preliminary plans while simulation may be more appropriate to more closely examine these plans or minor modifications to these plans. The previously optimal system solution would have to be re-evaluated for more significant or critical system modifications.

The review of the literature indicated the prevalence of the use of simulation techniques to explore all the problem areas of MSW management and planning. Light (1990) describes several commercially available MSW management systems planning models that rely on simulation as a method of evaluating alternatives.

With simulation, a MSW management system is specified - waste or source separated material flow values, flow assignments for waste or source separated materials (compostables or recyclables), and operational parameters (facility capacities, costs, etc.) - and the effects of uncertainty in waste generation data on the operation and cost of the specified MSW management system may be examined. A mathematical model is used, in this application, to provide a simulated time history of the cost and operation of a given MSW management system over a given time period. A discrete, deterministic simulation model has been developed in FORTRAN to further evaluate the MSW management system(s) suggested by the MILP optimization model for finer time increments. However, any MSW management system may be specified and simulated. The time increment and time horizon for the simulation study may be chosen based on the waste generation data available. The user may simulate an isolated system for managing source separated compostable or recyclable materials, a MSW management system to handle the residuals remaining after source separation impacts are estimated, or a MSW management system to handle the entire MSW stream.

The user may simulate a MSW management system given a forecasted series of waste (unsegregated MSW or residuals) or source separated material flows, or a synthetic waste series generated from the stochastic variation exhibited by a historical waste series for each of the waste source areas in the study region. The annual waste generation forecasts stored in the waste generation and composition spreadsheet models may be used in conjunction with the data stored in the source separation program design spreadsheet models to forecast periodic waste flows (unsegregated MSW or residuals) given the estimates regarding the effect of the seasonal yard waste component. The user is advised on the steps required to produce a yearly or a periodic waste flow series assuming two 6-month generation periods, or to produce a yearly source separated material flow series. The MSW management system derived from an optimization modelling study using time increments of more than one year may thus be simulated for finer time increments. This simulation option of using a forecasted waste or source separated material flow series is appropriate for users who do not have access to historical periodic waste flow data, or for users who wish to do an annual analysis of a proposed, optimal or near-optimal MSW management system. The spreadsheet models associated with the forecasting of waste generation and source separation program design facilitate the development of alternative waste (unsegregated MSW or residuals) and source separated material flow data. The user may change waste generation or program parameter assumptions to derive alternate waste or source separated material flow series.

If a historical series of monthly or weekly waste flows is available for the waste source areas of the study region, monthly or weekly synthetic waste flow data may be generated based on the seasonal fluctuations exhibited in the historical series. In order to model the variability of waste generation data for a simulation study, an assumption must be made regarding the probabilities related to waste generation rate forecasts. The probabilities associated with specific values of uncertain MSW management data such as waste generation rates and costs are generally not known (Lund, 1990*b*). Arey (1991) notes a general absence of literature related to the determination of a probability distribution for waste generation data sets and proposes the fitting of mixed distribution functions to waste generation data. Due to the deficiency in research on appropriate distribution function assumptions for waste generation data, the randomness exhibited in periodic waste flow data is modelled with an arbitrary distribution to conform with a sample set of historical observations for normalized waste flows.

For each year of the historical data, the periodic waste flows are normalized using the calculated yearly mean in order to relate the periodic variations that may be expected from the yearly mean value. A cumulative distribution function (CDF) is derived from the variability from the mean exhibited by the entire set of normalized historical waste flows. Synthetic waste flow values are generated based on an assumed random deviation from the previously forecasted yearly waste generation averages adjusted for the simulation time period. The random component is generated using a uniformly distributed random number and the periodic variability from the mean represented in the CDF. With the assistance of the waste generation forecasting and program design spreadsheet models, the user may also develop several yearly waste or source separated material flow series to serve as the basis for forecasting the periodic waste flow values, by altering parameter assumptions.

The user must specify the number of waste source areas and the number of facilities to be modelled. For the waste source areas, information must be supplied in an external file including the waste generation rate for each period of the study, the fraction of the waste stream that will be transferred to specific facilities in each time period (i.e., the waste assignments), and the associated collection and transportation costs. The user must also specify cost and operational data for all the facilities in the MSW management system. The assumption is made that these data are available for time increments of one or more years over the same time horizon as the waste flow series. Data must be supplied for each facility: the waste assignments to the other facilities in the system; the available capacity during each time period; material and energy recovery, as a fraction of the input, and expected revenues, if any; the operating cost; and a back-up facility that will receive any waste or source separated material flows assigned in a specific period that exceed the available capacity.

The model simulates the operation of the given MSW management system for the specified time periods and calculates facility costs, and waste and/or source separated material flows. The model output is a complete time history of the system costs and facility usage patterns.

This simulation model represents a simplified view of the operational and economic behaviour of a MSW management system. The value of this modelling approach is to provide a means of deriving further information regarding a MSW management system planning problem in order to make better long-range planning decisions. The user may investigate the effects of varying the waste (unsegregated MSW or residuals) or source separated material flows and thus inputs to the facilities in an existing or proposed MSW management system, due to the uncertainty that exists in waste generation and composition data. This methodology may also assist with the investigation of the potential impacts of assumptions regarding waste reduction, waste re-use and/or source separation composting and recycling programs on an existing or proposed MSW management system. Additional uncertainty exists in forecasting waste flows due to the assumptions regarding population growth rates, and the seasonal variability of waste generation rates. The simulation model may also be used to conduct sensitivity tests on other significant model parameters for an existing or proposed MSW management system. Based on the results of a simulation study, the user may wish to re-examine a previously optimal (least-cost) system solution to determine the effects of changing particular system parameters.

The user is assisted in developing model inputs and analyzing the output of the simulation model through interaction with a knowledge base (SIM.KBS) and the accompanying documentation (which includes a more detailed explanation of the program, and the input and output files). Suggestions are provided with regards to potential model runs that may be investigated to account for assumptions made in the forecasting of waste generation and composition data, and the estimation of other significant cost and operational parameters. In addition, the modelling components designed to assist with waste generation and composition forecasting and source separation program planning may be used to create several hypothetical waste flow series. An additional spreadsheet model has been designed to assist the user in collecting and analyzing the waste and source separated material forecasts from these decision support system components to develop a flow series for use as input to the simulation model (WASTE.WK1).

A listing of the simulation program (SIM.FOR), developed in FORTRAN, and accompanying documentation is provided in Appendix F. A flow diagram of the simulation modelling components of the prototype decision support system is illustrated in Figure 15.

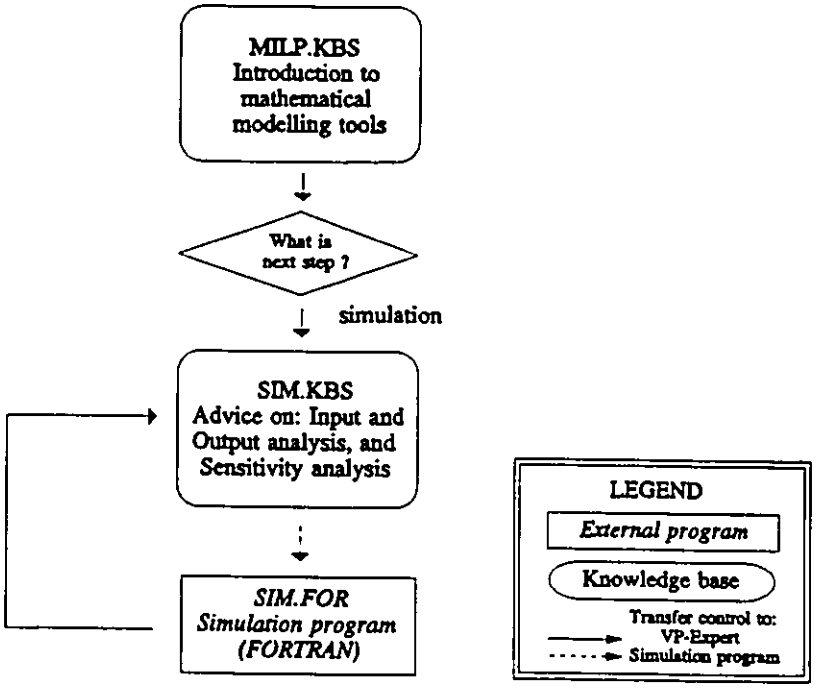

Figure 15. Flow diagram of the simulation modelling components (STEP 7)

In the following chapter, the evaluation of the prototype decision support system will be discussed including an examination of the validity, potential benefits and limitations of the current system.

CHAPTER 6

DECISION SUPPORT SYSTEM EVALUATION

6.1 Verification and validation of the modelling components

Mathematical models are verified by ensuring the mathematical equations and the solution procedure are correctly represented, and that the model correctly implements its specifications (O'Keefe et al., 1987). A mathematical model may be verified incrementally: first, by eliminating programming errors to ensure the structure and logic are complete, correct and consistent; and, secondly, by using the input data and results from a similar type of study relying on a different estimation technique.

Validation is the process of substantiating that a model is sufficiently accurate for the intended use, and ensuring that the intended use is within its domain of applicability. It is often established through successful application of the model to several different situations, to the same situation over time, or to the same process at different sites (Patry and Chapman, 1989). Other than comparing the outputs of a model to experiments conducted on the real system or to historical data, the main method of validating a model is to affirm it through expert reactions. In addition to how well a model represents the behaviour of the real system, a model's validity is also related to usefulness, usability and cost considerations (Landry et al., 1983; O'Keefe et al., 1987).

Unfortunately, there was minimal reference to the issues of model verification and validation in the MSW management and planning literature reviewed for this research. In the majority of the research studies reported, the mathematical model was demonstrated on a hypothetical problem. The discussion that follows will address the methods used to verify and validate the individual modelling components of the prototype decision support system. The issues of representativeness, accuracy, and potential usefulness and usability with respect to validating the individual modelling components will be emphasized. Following this discussion, the evaluation of the general decision support approach demonstrated in the prototype decision support system will be further explored.

The difficulty in verifying and validating mathematical models in the domain of MSW management and planning arises from a general lack of consistent, high quality data, and the difficulties posed by the changing political, social, technical, regulatory and economic environments. There are very few studies which may be used to validate many of the modelling approaches due to their lack of use in practise. This is particularly true for long-range planning models. Jenkins (1979) notes the limited quantity of published material on planning studies as many studies are conducted by consulting firms who often do not choose to publish the modelling approach utilized. Further impediments to model validation arise due to the inability to experiment with full-scale MSW management systems and the relatively recent emphasis on long-range program and facility planning for MSW management. The short history of long-range planning studies leads to a deficiency in historical data that may be used to test model validity.

As the intention of this research is not to introduce new mathematical models but to develop an improved modelling environment, the validation of the suggested decision support approaches is of primary importance. This validation process may be accomplished through the solicitation of opinions from waste management professionals, also referred to as face validation (Landry et al., 1983). For the most part, the mathematical modelling components included in the system are based on models previously developed by other researchers. The existence of previous studies is an indication that the proposed modelling approaches included in the prototype decision support system are sufficiently accurate for their intended uses within the domain of MSW management and planning. However, earnest attempts were made to verify that these modelling approaches are correctly represented, and to validate that the adapted mathematical models, and the spreadsheet models and knowledge bases designed for this particular application are sufficiently accurate for their intended uses.

A time horizon of 20 years is assumed as the basis for program and facility planning, based on the approach reported to be taken in MSW management planning studies (Ministry of the Environment, 1992), and to reflect the general useful life of MSW management facilities (Jenkins, 1979).

The costing methodology utilized in the spreadsheet models created for the composting and recycling program design components is adapted from an approach developed by Smith (1989). Smith demonstrates the validity of this approach with an actual case study application. Using program parameters supplied by Smith for the design of a curbside recycling program for the case study community, the same final program costs were approximately reproduced with the use of the spreadsheet models. In addition, hand calculations were performed to verify that the spreadsheet formulas were correct.

A final method used to verify the calculations performed by the program design spreadsheet models and validate their usage was to compare estimated program costs (based on parameter values reported for existing programs) to reported program costs.

Program parameters reported in the technical literature are also presented within the spreadsheet models themselves to provide additional information to an end-user and a means of judging the validity of the parameter estimates and the resulting calculations. In the majority of the tests performed, program implementation and operating costs estimated by the spreadsheet models were approximately equivalent to, or higher than, the reported values. The differences between the model predictions and the literature values may be explained by the varied accounting practises used in reporting composting and recycling program costs. In addition to regionally varying material revenues and equipment costs, identical cost components are not always included. For example, the values obtained for an on-site (backyard) composting program designed for single-family dwellings produced final program costs twice as high as those reported in the technical literature. There was no indication, however, as to whether the depreciation of the composting units was considered, i.e., whether the need to replace the units at the end of their economic lives was accounted for. In addition, annual program operating costs may or may not have deducted revenues from the sale of recovered recyclables or compost, and may or may not have included the avoided disposal costs (i.e., what it would have cost to landfill these materials if they had not been recovered). The current spreadsheet models do not consider the avoided waste disposal costs as a form of revenue to be deducted from the annual operating costs of the programs.

The spreadsheet models created to assist with the estimation of facility capital and operating costs were designed based on the costing methodology developed by Smith (1989), and the basic model parameter requirements of the MILP optimization model.

Similar means were used to verify the mathematical equations in these spreadsheet models, using hand calculations and comparisons to reported values.

The addition of knowledge-based system components provides additional means to ensure that the developed spreadsheet models are sufficiently accurate for their intended uses. The spreadsheet models' cost and waste diversion rate predictions rely on the parameter estimates, assuming the models have been verified. The user is assisted in estimating the required modelling parameters through the provision of a collection of values reported in the technical literature for existing and proposed programs and facilities.

The approach of utilizing linear programming (LP) or mixed-integer linear programming (MILP) techniques to model MSW management systems planning problems has been demonstrated through the previous work of numerous researchers including Kuhner and Harrington (1975), Greenberg et al. (1976) and Jenkins (1979). Jenkins (1982) also refers to examples where these optimization techniques were used in planning studies for several Canadian communities. Greenberg et al. (1976) applied their static planning model to a currently operating system to determine if the model would suggest the development of the current system, assuming it had been applied in the planning stages. Jenkins (1982) was able to obtain the necessary data to sufficiently validate the MILP MSW management systems planning model used in a planning study for Toronto, Ontario. Jenkins also suggests that an alternative method of validating planning models is to compare the output results to those obtained by another planning model of the same type for the same problem, preferably for which the previous model has been validated. A model designed for planning MSW management systems was applied to the problem of hazardous waste management systems planning because it was readily available, well-documented, and "had a useful track record" (Peirce and Davidson, 1982).

This research does not involve a new or unique formulation for MSW management systems planning problems. However, certain modifications were made to the basic MILP model formulations suggested by previous researchers to make the formulation more applicable to a variety of MSW management systems planning problems.

The validity of using optimization techniques to produce useful information for MSW management planning studies relies heavily on the quality of the input data. As it is impossible to accurately forecast many of the model parameters, particularly costs, the results of an optimization study will vary from the actual behaviour of the MSW management system. The degree to which the predicted and actual scenarios vary depends on the accuracy of the estimates and predictions for the model parameters. The purpose of model validation is to ensure that a model is sufficiently accurate for its intended use. Several approaches were taken to verify and validate the optimization modelling component of the decision support system.

In order to verify the mathematical formulation for the optimization modelling of facility planning problems (detailed in Appendix D), test case studies were conducted based on the inputs and model outputs for a hypothetical problem and for the facility planning problem described in Chapter 8 to ensure the completeness and correctness of the formulation.

Sensitivity analysis and simulation have been proposed as additional means by which a planning model may be validated through the examination of model parameter uncertainty (Brill, 1979; Lund, 1990*b*). The validity of optimization approaches may also be extended by utilizing techniques to generate alternative and near-optimal solutions as opposed to employing optimization models to predict a single optimal plan (Kuhner and Harrington, 1975; Rogers and Fiering, 1986). Jenkins (1979) and Wilson (1981) warn that it is usually not valid, and may be dangerously misleading, to assume the 'optimal' solution generated by an optimization planning model based on minimizing costs will be truly indicative of the behaviour of the real system.

In an attempt to improve the acceptability and usefulness of the results of an optimization study, the user of the decision support system is given advice on the use of sensitivity analysis to examine the effects of uncertainty. Assistance is also provided for the generation of near-optimal solutions to allow alternative systems with costs near that of the optimal (least-cost) system to be examined and compared. A decision-maker may then be more confident about the results of an optimization study. Emphasis is placed on cautioning the user that the optimization model should not be viewed as an accurate method of predicting the future behaviour of a MSW management system nor should model outputs alone be used as the basis for long-range decisions. In this way, an attempt is made to indicate the domain in which this modelling approach is of sufficient accuracy to be valid and useful. The optimization component is presented to the user as a means of providing additional information by assisting with the generation and evaluation of alternative solutions to long-range facility planning problems.

The knowledge-based system components developed to accompany the optimization model provide the user with recommendations on model parameter values based on values reported in the waste management literature, and thus improve the potential accuracy and usefulness of the approach. The user is also assisted in developing a model formulation and analyzing outputs for a given facility planning problem.

The simulation model developed for the prototype decision support system performs calculations on system costs and waste allocations based on a MSW management system description supplied by the user to provide a further means of exploring the effects of uncertainty. All cost components and relationships between generation points and facilities in an existing or proposed MSW management system must be described, including the assignment of waste flows to facilities. The model was verified by using the original material flows and the resulting MSW management system proposed by the optimization model for the facility planning case study application (for the identical time increment and planning horizon), and ensuring that the total present value system costs were identical. This component is also accompanied by a knowledge base which describes the simulation model and its appropriate uses.

Although strict experimental and operational validation of the mathematical modelling components was not feasible, the proposed modelling components of the decision support system may improve on current methods of generating and evaluating alternative long-term strategies. The models offer assistance and a framework for generating and evaluating planning alternatives.

In order to improve the validity of all the mathematical models with respect to data accuracy, appropriateness and availability, knowledge derived from the current waste management literature has been encoded. The validity of all of the mathematical modelling approaches will improve as more waste management and mathematical modelling knowledge is added to the knowledge bases. Developing and maintaining knowledge bases also requires verification and validation activities.

Nazareth (1989) reports a general view of verification of expert systems as being the process of demonstrating that the knowledge base is consistent, complete and correct. In order to demonstrate the logical correctness of the knowledge bases in the prototype decision support system, checks were made to eliminate errors in the rule-bases which could lead to poor system performance as suggested by Nazareth. Verification of the knowledge bases was a fairly straightforward task given the use of a rule-based representation of knowledge, and their limited problem scope and size. The knowledge bases are restricted to dealing with one type of program, facility, or modelling stage. Individual knowledge bases generally contain approximately 10 to 50 rules.

The logical correctness of the various knowledge bases was verified by exhaustive testing of rule sets wherever feasible. For large rule sets where exhaustive testing was not feasible, test cases were run to detect and remove errors from the rule bases. Despite these attempts, typographical errors may remain whereby knowledge taken from the available literature has been incorrectly encoded. In addition, the knowledge encoded with respect to certain elements of the program and facility planning components may be limited at this initial stage in the development of the decision support system. These gaps in the knowledge bases may affect system performance as inexperienced waste management engineers or planners may make inappropriate decisions regarding model parameter estimates (Nazareth, 1989).

Validation of expert systems has been directed towards evaluating the performance of the system as compared to test case results obtained from domain experts to determine if the experts' problem solving knowledge is accurately represented (O'Leary et al., 1990). The difficulty with expert system validation has been the infeasibility for large problem domains of exhaustive testing of all possible problem scenarios (Nazareth, 1989).

For the knowledge-based system components, the task of model validation was somewhat eased due to the fact that these components were designed to provide advice as opposed to make decisions: to supplement expert judgment, not to supplant it (Wilson, 1981). The user is responsible for the ultimate selection of appropriate program and facility parameters based on the information and recommendations provided. Therefore, it was not necessary, as with most expert system applications to date, to ensure that the system was making expert-level decisions. In addition, the knowledge contained in the system was derived from literature sources as opposed to eliciting knowledge from human experts. The latter approach requires additional attention be paid to confirming that knowledge transferred to the model developers through communication with the expert(s) has been accurately represented.

Maintenance of the current knowledge bases as system expansion occurs will require additional verification and validation of the components. The methods applied in the development stage should also be feasible for long-term maintenance of the knowledge-based system components of the decision support system, providing the problem scope and size of the rule bases remain relatively small. The advantages of validating model subsystems has been recognized with respect to expert system development due to the less complex and more manageable size of subsystems and, thus, the localization of errors which eases error detection (O'Keefe et al., 1987).

6.2 Decision support system validation

The need for a set of modelling tools to assist with the development, evaluation and elaboration of alternative solutions to public sector planning problems has been suggested by Brill (1979). This approach for providing decision support to waste management engineers and planners has also been supported by numerous other researchers and waste management professionals (Clark and Gillean, 1981; Wilson, 1981; Light, 1990). Fiksel and Hayes-Roth (1989) support the application of knowledge-based system techniques to planning activities in general if they are designed to provide advice as opposed to recommend courses of action. Therefore, there is evidence to suggest that the proposed decision support approach for preliminary program and facility planning in MSW management and planning is valid, in theory.

As previously described, the validity of a model must also be concerned with its usefulness, useability and cost of the system if it is intended to have a role in assisting and improving decision-making for a public sector planning problem (Clapham, 1987). This operational validity of the prototype decision support system, and thus to a degree the validity of the proposed decision support approaches to the entire domain of MSW management and planning, may best be judged by knowledgeable waste management engineers and planners. Experts determine if the developer's view of the problem domain, represented by the decision support system, contains all relevant problem elements and is "sufficiently well structured that a credible solution may be derived" (O'Leary et al., 1990).

Face validation, or expert validation, may be the only recourse for long-range waste management planning models due to the lack of practical model applications and the data shortages within this application domain. Ludvigsen and Dupont (1988) state that "decision support systems are generally judged not on their conclusions but rather their ability to improve human performance via a human-computer synergism". Demonstrating usefulness and useability were important considerations of this research given that the suggested decision support approaches, based on an integration of knowledge-based system and systems analysis techniques, have not been applied in the field of MSW management and planning.

Several knowledgeable waste management professionals were consulted to determine the reasonableness, accuracy and usefulness of the prototype decision support system for long-range MSW program and facility planning. During a meeting generally lasting several hours, the waste management professionals were provided first with a verbal description of the planning tool, followed by a demonstration and examination of several knowledge-based system components and spreadsheet models. The names and contact addresses of the waste management professionals consulted may be found in Appendix G.

The responses indicated that the prototype decision support system is a valid approach for providing mathematical modelling and waste management planning support to local or regional waste management engineers and planners. The organization of the prototype planning tool was judged to be logical and reasonably accurate, particularly as the necessary program and facility planning phases are broken down into a series of more manageable parameter estimation and modelling steps. This characteristic of the planning tool was attractive to the practitioners as a waste management engineer or planner could be guided through a complex process with the decision support system providing assistance as needed. The input parameter requirements were deemed reasonable.

The knowledge-based system components were considered to be useful and user-friendly additions to the mathematical models due to their provision of information and/or recommendations regarding required parameters or actions. The waste generation and composition forecasting components were particularly appealing to one waste management engineer as smaller communities seldom have the resources to undertake complete waste stream assessments. One expert indicated that the prototype decision support system would provide waste management engineers and planners with the tools to develop approximate estimates of program and facility costs, and the ability to refine these estimates as data became available. The prototype planning tool was also recognized for its benefits in permitting the analysis of various alternative programs or MSW management systems. The knowledge contained in the system would also facilitate comparisons to programs or facilities operated by other communities.

The collection and organization of waste management expertise and data reported in the waste management literature was considered to be a definite benefit to the proposed decision support system, and would improve the chances of such systems being utilized in actual planning or operations studies. The projected cost of the system (approximately $600 assuming compatible spreadsheet software is available) was viewed as reasonable.

Although the benefits of the optimization and simulation components were recognized, some potential users may be unfamiliar with these techniques and may require additional assistance in correctly utilizing these models. The experts also recognized that updating of the knowledge bases would be required as more information became available, as the effectiveness of the planning tool to assist with actual decision-making is dependent on the quality of the available information. The waste management professionals also had first hand knowledge of the variability in program and facility accounting and data reporting practises of waste management agencies; these inconsistencies affect the validity of the data encoded in the system, particularly the cost related data. One waste management professional was uncomfortable with the perceived need to "guess" at certain modelling parameters due to limited encoded knowledge, and also the lack of explanation as to why a certain parameter was being requested. These concerns could be addressed in future development stages through the incorporation of explanation clauses to the rule bases, and through the expansion of the current knowledge bases. However, the practising professionals consulted acknowledged that having the decision support system actually decide on parameter values is probably not appropriate in this application area.

The experts also made several recommendations for future additions to the current prototype decision support system: the consideration of avoided disposal costs due to the diversion of waste from landfills; the consideration of the effects of a user-pay collection system (whereby waste generators are charged a fee for a collection service) on waste characteristics and costs; a more detailed explanation of the steps required in identifying, sizing and pricing markets for recovered materials and energy due to the fluctuating nature and importance of these revenues; a clearer distinction made with respect to the type of community (rural or urban, population size) for which program or facility planning parameters are quoted; and a summary of all the parameters collected for individual programs or facilities, perhaps provided within accompanying documentation.

These recommendations arise from the recognition that program and facility planning data may be highly dependent on factors such as the geographical location and size of a community or region. Finally, one waste management engineer recognized the benefits from the use of spreadsheet models, but felt that the development of source separation programs within some communities may be too advanced for the developed preliminary planning modelling components and may require additional tools to assist with more refined or detailed program design.

The face validation procedure indicates that additional development work is desired before the system is used in actual planning situations. However, the overall consensus appears to be that the suggested decision support approach for the preliminary planning of MSW programs and facilities is valid due to its acceptable degree of accuracy in representing this problem domain, and its usefulness and useability.

The ultimate validity of the proposed decision support approaches (combining knowledge-based systems with more traditional mathematical models) demonstrated in the prototype decision support system may only be fully established with more extensive field testing. However, the prototype decision support system appears to be of sufficient validity to warrant the continuation of its development and to indicate that similar systems may be well received by practising waste management professionals.

6.3 Benefits of the prototype decision support system

Planning is essential to assure adequate long-range capacity will exist for MSW management, although it has been referred to as a maligned practise (Hickman, 1991). Levinson (1990) suggests that opposition to MSW management systems would be reduced if they were designed to be more flexible to the incorporation of new technologies as they become available. To include this flexibility requires the creation of integrated systems that do not rely on one technology only, and the development of planning tools to assist in investigating alternative integrated systems under varying conditions. Systems analysis techniques provide an organized framework in which to conduct an exploration of the most suitable methods of dealing with MSW and the long-range provision of adequate facilities (Wilson, 1981). The effects of different objectives or alternative courses of action may be examined in a systematic and, as far as is possible, in a fair manner (Wilson, 1981). The prototype decision support system developed for this research facilitates the generation and examination of alternatives for program and facility planning problems.

Light (1990) has indicated that such planning models accomplish several objectives: they provide a useful training tool for waste management engineers and planners; they identify the major cost and performance parameters; they demonstrate the need for reliable data collection on the local level; and they indicate the system's sensitivity to parameter changes which focuses data collection efforts. The ultimate benefits of their use are the maximization of service and the avoidance of unnecessary costs. More sophisticated planning could also indirectly improve the public image of waste management (Light, 1990). The proposed decision support system accomplishes all of the above mentioned tasks.

The prototype decision support system is designed to illustrate the benefits of combining the capabilities of knowledge-based system techniques and mathematical modelling tools to provide a more flexible and powerful environment in which to conduct preliminary long-range planning studies. Communities conducting preliminary planning of their MSW management systems may capitalize on the experience reported by others and avoid problems with lengthy or costly investigations. Due to the extensive body of knowledge contained in the system, preliminary analyses may be conducted even if local waste management information is limited. The prototype decision support system also illustrates a method of creating a standardized approach for long-range MSW management systems planning.

The knowledge-based system components contain operational expertise reported in the literature, and a collection of cost estimates for various waste management technologies as derived from an extensive review of academic and trade journals, textbooks and reports. Thus, waste management professionals are assisted in determining the operational and cost elements that are necessary to carry out a preliminary planning study for a local or regional MSW management system, or to investigate one component of a system. The gathering and encoding of knowledge for the various modelling components has also indicated areas where available knowledge is limited, particularly with respect to facility costs. Although the costing information encoded may become obsolete in the future if drastic changes occur in the economic, political, regulatory or social environments, the decision support system permits the economic comparison of current waste management technologies, with the capability of being updated to reflect new information.

Spreadsheets are a widely understood and utilized modelling tool. The prototype system contains numerous spreadsheet models to conduct program and facility cost analyses, where data may be easily viewed and modified, and reports or graphs may be easily produced.

The planning tool assists with the principal steps required to accomplish preliminary long-range, or strategic, planning of source separation composting and recycling programs. It allows the user to investigate a large number of program options, which may ultimately reduce planning costs and improve decision-making. The user is advised on appropriate programs or technologies based on expertise reported in the technical literature. The program planning components may be used to design new programs, or expand existing ones with respect to the number of sites serviced or the number of materials collected. The user may thus determine the costs and effectiveness (waste diversion rates) of program decisions such as including an additional material or the chosen type of collection system (eg., curbside versus drop-off).

Both inexperienced and experienced users may benefit from the mathematical modelling knowledge contained in the prototype decision support system. The planning tool supports and extends the use of optimization models to investigate alternative MSW management systems as it can be used to provide the user with near-optimal systems for proposed scenarios, and to evaluate systems as it provides the user with advice on the use of sensitivity analysis. The simulation component permits waste management engineers and planners to examine the impacts of various assumptions and constraints: different waste generation growth patterns; community waste reduction, re-use and recycling assumptions or goals; fluctuating markets for recovered materials and energy; or, regulatory restrictions on system economics and operational reliability or resiliency (Lawver et al., 1990). The modelling approaches allow the examination of the robustness of a MSW management system solution with respect to the modelling assumptions and unavoidable uncertainty in the data.

Potential users of the proposed decision support system are consulting engineers, waste reduction and recycling coordinators, and municipal decision-makers. The planning tool contains introductory information regarding MSW management systems and the mathematical modelling tools, supplied through interaction with several knowledge-based system components, and includes spreadsheet models which may benefit less experienced users. More experienced users may benefit from the provision of additional expertise (or opinions) and several more advanced modelling tools which may be used to expand the scope of a study to reduce the effect of personal bias regarding acceptable planning solutions. The suggested decision support approaches to MSW management and planning, demonstrated in the prototype planning tool, assist waste management engineers and planners in making their own decisions using their own skill and judgment.

The prototype decision support system could also assist local or regional waste management agencies and politicians in gaining a better understanding of the problem area, the techniques available for generating and investigating MSW management systems, and the formulation and application of mathematical models. The additional expertise and planning support provided by the prototype decision support system may make it possible for waste management agencies to conduct planning activities currently handled by outside, often expensive, consultants; or, at a minimum, municipal planners and decision-makers may be better equipped to evaluate the adequacy of the analysis and recommendations provided by consultants.

Waste management engineers and planners may examine different MSW management systems within a highly interactive and knowledge-intensive, yet structured environment. Thus, they are assisted in creating long-range cost-effective plans that meet local objectives and constraints. Waste management engineers and planners may also use the planning tool to conduct preliminary feasibility studies or assess budgets, to validate the results of other types of planning studies, or to better focus their site investigation efforts (which may be particularly helpful given the enormous costs of the facility approval process). In addition, the individual modelling components may be utilized in isolation of the entire system if desired (providing initial data are supplied for waste and general study characteristics). Due to the uncertainty involved in the estimation of system parameters, the planning tool components may also be applied in an iterative process to explore a range of values for important parameters (to account for imprecise or 'fuzzy' data, and random or stochastic data) and determine the potential impacts on subsequent planning stages and decisions. The components of the planning tool can, thus, be utilized to perform sensitivity analysis and scenario studies.

A generally applicable decision support system such as the one proposed could be used in different locations, and at different time periods (provided the knowledge bases are updated if significant changes occur in the MSW management and planning field). The option exists to expand the system to include new technological options, or updated program or facility related data in a relatively simple manner. The prototype system was designed to allow knowledge bases to be clearly understood and thus easily modified or updated. The ease of user understanding and modification of the knowledge bases was a major consideration in choosing to use a rule-based representation of knowledge. An additional characteristic of the organization of the prototype decision support system that will facilitate changes to the knowledge bases or organization of the components is the modularity of the system. All knowledge bases are reasonably small with respect to their scope and rule base. As well, due to the modular rule-based structure of the decision support system, the task of transferring the existing knowledge-based system components to software that allows for more direct transferring of control and communication with mathematical modelling tools would be a manageable task.

The prototype planning tool is easy to use with its menus and interactive data input. The development tools were also chosen for their practicality with respect to cost. Assuming a waste management agency has Lotus 1-2-3, or a compatible spreadsheet model (VP-Planner or Symphony), the total cost of the required software would be approximately $600.

6.4 Decision support system limitations and potential extensions

Wilson (1981) states that a model which covers all aspects of MSW management planning would be "hopelessly complicated". The prototype decision support system developed to assist with preliminary MSW management systems planning has several limitations which may be important considerations for future development stages. Some of these limitations may be easily removed, others not so easily as a change in development tools may be required. The discussion will begin with an examination of several, more easily correctable, decision support system limitations, followed by an examination of more severe limitations. Finally, issues relating to the updating of the knowledge bases for this, and any other potential, decision support system for MSW management and planning applications are briefly addressed.

One of the simplifications made in the calculation of expenditures for programs or facilities is the application of a single inflationary factor to all cost components: capital, operation and maintenance, and revenues. To better reflect the effects of inflation on buildings, equipment, labour and revenues from the sale of end products, the use of several different inflationary factors may be more appropriate. Advice could be added to the introductory knowledge base (INTRO.KBS) to assist with the estimation of appropriate inflationary factors. For example, Statistics Canada produces several indices that reflect the trends in such costs. The spreadsheet models would have to be slightly altered as well.

The design of hazardous waste collection and disposal programs for small generators such as households was not considered within the current preliminary planning tool. The management of hazardous waste is becoming an increasingly more important problem. Modelling components, similar to those constructed to assist in the design or expansion of composting and recycling programs, could be developed and easily integrated into the current system as municipal hazardous waste management expertise and experiences expand.

Currently, the user is provided with a restricted number of selections for the specific materials that may be included in a composting or recycling program. While the list of acceptable materials reflects current technological and market conditions, the range of material choices for inclusion in a source separation program may be readily expanded.

Information has been included in the prototype system regarding materials and energy that may be recovered from MSW, and potential revenues that may be expected from the sale of recovered materials and energy based on values reported in the waste management literature. However, due to the relative instability and regional nature of these markets, current local market conditions would have to be assessed, and the information contained in the planning tool would have to be revised and perhaps regularly updated. The prototype decision support system does not currently provide assistance to the user on conducting a local market analysis.

The knowledge currently encoded in the components associated with the optimization model is fairly restricted. Jenkins (1979), in a study of the application of MILP for optimal facility location planning, experienced difficulties with solution times for large MSW management systems planning problems. Jenkins also suggests methods that may be used to help control the MILP search technique. It would be of benefit to the user to have access to this expertise.

Technological innovations are continuing in the field of waste management. While the facility planning components of the prototype decision support system allow the investigation of numerous options for collecting, transporting, processing and disposing of waste, information on currently emerging technologies could be integrated into the appropriate knowledge bases.

The knowledge encoded in the prototype knowledge bases is only a small fraction of the waste management and mathematical modelling expertise collected through a review of research reports and the technical literature. Although the use of mathematical models in the field of MSW management and planning is limited, planning studies and experts exist that could be consulted to provide additional knowledge. The acquisition of knowledge from experts has been identified as a very time consuming task. Thomas et al. (1990) warn of the challenges of knowledge acquisition for MSW management planning expert systems, particularly as it requires the cooperation of municipalities, planners and private industry. Regardless, there is ample information available in static sources such as texts and articles that could be added to the current knowledge bases. With the current emphasis on conducting Solid Waste Management Master Plan studies, many government agencies are producing materials to assist waste management engineers and planners with program and facility planning activities.

Jenkins (1982) reports on the results of a planning study for developing a solid waste management system for Toronto, Ontario using an MILP model formulation. Additional programs were developed that accept raw data regarding a MSW management system planning problem, that assist in checking the consistency of the data to eliminate input errors, and that prepare output reports and details of the solution in a form more understandable to a waste management engineer or planner. Future consideration should be given to combining the facility planning approach suggested in this research with the thorough work done by Jenkins (1979; 1982) in the area of MSW management systems planning using MILP techniques. This would improve the components of the prototype decision support system connected with the use and analysis of LP or MILP techniques for MSW management systems planning studies.

The objective of the current system with respect to facility planning has been the generation and evaluation of alternative MSW management systems. However, the evaluation has been limited primarily to a consideration of economics. The literature review identified several approaches which facilitate the evaluation of alternative facility sites, technologies or MSW management systems considering other, less quantifiable, factors. The use of knowledge-based systems to assist with site selection has been proposed for other problem domains (Rouhani and Kangari, 1987; Han and Kim, 1989). In addition, there have been numerous applications of decision analysis techniques to the problem of comparing alternative MSW management solutions with respect to multiple criteria (Sobral et al., 1981; Maimone, 1985). Other studies have applied utility theory to multi-criteria evaluation problems (Collins and Glysson, 1980). Multi-criteria evaluations and suitability analysis using overlay or constraint mapping are being conducted by consulting firms for the selection and evaluation of landfill sites (Lane and McDonald, 1983; Han and Kim, 1989; MacLaren Engineers, 1989). These approaches merit further investigation, particularly as the technical survey indicated an interest, on the part of practitioners, for a more objective approach to the evaluation and comparison of technologies and facility sites. The decision support system could then be expanded to assist with the use and integration of the numerical analyses, heuristic analyses and expert opinions required to adequately explore facility planning problems (Rouhani and Kangari, 1987).

The prototype decision support system does not allow for flexibility with respect to the planning horizon, i.e., it cannot be any longer than 20 years. Allowing this flexibility would require many changes to the current spreadsheet models.

The modelling approaches used in the planning tool to conduct program and facility planning studies are very data intensive, so a decision-maker must be cautious of the results of the various models. In addition, the knowledge-based system components do not make decisions, they only provide recommendations; the user is ultimately responsible for estimating the important planning parameters.

The software packages used for the prototype decision support system provided several limitations to development. The development phase was conducted using a 386SX (16 MHz) microcomputer. VP-Expert performs limited mathematical functions, and is slow in performing calculations. In addition, the transfer of data from the knowledge bases to spreadsheet models was a sluggish process, and added significantly to knowledge base consultation times. Although VP-Expert permits the transfer of data to Lotus 1-2-3 spreadsheets, to update the spreadsheet models and perform calculations it is necessary to exit VP-Expert and transfer control to Lotus 1-2-3. More compatibility with spreadsheet models is possible with VP-Planner spreadsheet software. These problems may also be reduced or eliminated through the use of a graphical user interface, or more compatible mathematical modelling and expert system development tools that facilitate the transfer of data between software packages. It would be beneficial to user acceptance if complete software linkage was possible, and the user could run the mathematical models within the knowledge-based system environment.

The previous comments on the limitations of the current prototype decision support system for preliminary long-range MSW management program and facility planning raise the issue of the potential expandability of the system. The knowledge contained within knowledge-based decision support systems must be updated to ensure that the most current and correct expertise is available to a decision-maker. This issue is particularly important in the field of MSW management and planning due to the constantly changing economic, technological, political and regulatory environments.

Thomas et al. (1990) warn that an expert system to design a detailed waste management system would not be practical. Due to the scope of the demonstration application, it was not possible to create a full-scale working system. As with the majority of knowledge-based system applications, further work will be necessary to develop a deliverable system, by improving the user interface, incorporating the knowledge of current experts to improve the efficiency and accuracy of the system, and improving the communication and integration of the various modelling components. The understanding and application of knowledge acquisition techniques will be an issue when considering the future development of this system or projects of a similar nature due to the necessity to encode a greater amount of human expertise. The prototype knowledge bases could also be improved through the addition of clauses to the rules which identify why certain parameters are being requested, and which deal with the situation in which a parameter value is unknown.

Two case study applications of the model will be discussed in the following two chapters. These case studies were chosen to demonstrate the two major capabilities of the decision support system - providing assistance with preliminary long-range source separation composting and recycling program planning, and MSW facility planning.

CHAPTER 7

APPLICATION OF THE PLANNING SUPPORT APPROACH: PROGRAM PLANNING

The community of Selkirk, Manitoba, formed the basis of a case study application used to demonstrate the source separation composting and recycling program planning capabilities of the prototype decision support system.

Selkirk, Manitoba, is a community of approximately 10,000 people located in southern Manitoba, along the Red River. Curbside waste (garbage) collection is provided by a private waste collection agency. This same collection agency has also been responsible for a voluntary, bi-weekly curbside recycling program to collect glass bottles, metal cans, plastic pop bottles and newspaper. Recyclables are collected one day per week with approximately 90 tonnes of materials collected in 1992. The materials are taken to a regional processing facility located within Selkirk, and are subsequently marketed to several brokers and processors within Manitoba. In 1992, the Town of Selkirk was also considering the establishment of a composting program, with centralized composting potentially taking place at the current landfill site. All remaining waste is taken to the existing landfill for disposal. Based on current composting and recycling activities, the following source separation program options were explored using the program planning components of the prototype decision support system:

- on-site (backyard) composting of organics;
- centralized composting at the landfill site through the use of both drop-off and curbside collection programs operated by the Town of Selkirk;

- curbside collection of recyclables by the Town of Selkirk;
- and, collection of recyclables by the Town of Selkirk through the establishment of a system of drop-off depots.

According to the Public Works Department, in 1992 Selkirk had a population of 9815 with approximately 2814 single-family dwellings (SFDs), 763 apartment suites and 294 commercial establishments. Due to the limited amount of information available regarding waste tonnages, waste stream assessment information contained in the waste forecasting spreadsheet models (RES.WK1 and ICI.WK1) was utilized to develop waste generation and composition estimates. Forecasting was not performed; program costs and waste diversion rates were determined only for the initial operating year of the proposed programs. Total waste generation rates for the various sectors of the community are presented in Table 2.

Table 2. Summary of the estimates for the waste generation parameters for the program planning case study

initial population	9815
waste generation rate for the SFD sector	2950 tonnes/year
waste generation rate for the MFD sector	600 tonnes/year
waste generation rate for the ICI sector	2000 tonnes/year

Following the waste forecasting stage, the program planning knowledge bases were consulted to design alternative composting and recycling programs. The program planning spreadsheet models were then used to estimate the costs and effectiveness of the proposed programs. Recycling programs were designed to collect only the materials currently accepted by the regional processing facility for the Town of Selkirk.

Information regarding the operation and the effectiveness of the current curbside recycling program was provided by the regional processor. The main parameters assumed in this case study are included in Appendix H. The choice of many of the parameters was based on the information available through consultation with the program planning knowledge-based system components. The costs and waste diversion rates calculated for the program planning case study reflect the costs for the initial operating year without considering future changes to the programs.

The initiation of an on-site (backyard) composting program, assuming composters are distributed free-of-charge to SFD residents, would require a start-up cost of approximately $60000 (primarily for the purchase of the composters). Estimated annual costs of $9500 and annual expected waste diversion of 145 tonnes would represent a program cost of $65/tonne of waste diverted. Reported values for Ontario programs are in the range of $20/tonne, but it appears that container depreciation (i.e., the need to replace the units at the end of their useful lives) is not accounted for in these estimates. Depreciation represents 65% of the annual costs of the proposed program to service Selkirk. Similarly, a program for the households of the multi-family dwellings (MFDs) would have a start-up cost of approximately $10000 and a yearly cost of $1800, with a diversion rate of 18 tonnes per year. These estimates are based on the assumption of a conservative 40% participation rate. Ontario programs distributing free composters have reported participation rates in the neighbourhood of 75%. By adjusting this parameter to 75% in the spreadsheet models, the effect of the participation rate assumption may be easily evaluated. For the SFD program, the annual cost rises to $20000 with 365 tonnes per year recovered resulting in a cost of $55 per tonne of waste diverted from the landfill. For the MFD program, the annual program cost rises to $5000, and the waste diverted increases to 54 tonnes per year. The overall effect on the per tonne cost is limited due to the fact that an increase in the depreciation costs is balanced by an increase in waste diversion rates. For both programs, an administrative cost was included to ensure all potential cost components were considered. It is not clear if an administrative cost has been included in values reported in the technical literature.

Preliminary design of a drop-off composting program was also considered. If a participation rate of 25% is assumed based on values reported in the literature, approximately 71 tonnes per year of yard waste would be composted. The program would have an estimated annual cost of $4000 or $55 per tonne, with the assumed administrative cost of $3000 per year representing approximately 75% of this cost. If no administrative costs are included, the program cost drops to $15 per tonne of waste diverted. These program costs would be in addition to the costs required to establish and operate a centralized composting facility to receive and process the materials. For the Selkirk case study, a facility may be established at the current landfill site at an estimated cost of $10000 for site preparation and equipment based on the use of low technology windrow composting. Operating costs were estimated at $2200 per year with the result being an added program cost of $30 per tonne of waste diverted. The preliminary estimates of the facility related costs provided by the Public Works Department of the Town of Selkirk were $5000 for site preparation and $1200 per year for operating costs.

For comparison purposes, a weekly curbside yard waste collection program was considered for servicing the residential and commercial sectors of the community. Bagged materials would be collected in a dump truck by a two-person crew. Assuming a participation rate of 90% would result in approximately 300 tonnes of waste being diverted from the landfill. The annual cost of such a program was estimated to be $73000. The main start-up cost would be the purchase of two collection vehicles (approximately $160000), if required. The resulting annual program cost would then be $245 per tonne of waste diverted. Once again, there would be the added facility related costs for composting the recovered materials. The yearly cost per tonne of $30 for processing the materials is essentially identical to the processing cost estimated for the proposed drop-off program. Due to the larger amount of materials to be processed, the facility capital cost was estimated to be $30000 while the annual operating cost was estimated to be $9000.

The costs and waste diversion rate estimates for the source separation composting program options explored to service Selkirk are summarized in Table 3. The results of the analysis demonstrate the relative costs of establishing and operating composting programs, and their resulting impacts on the waste stream destined for the landfill. The on-site composting program, based on the free distribution of composters, would be the lowest cost alternative on a $/tonne of waste diverted basis. The drop-off composting program would have lower program start-up and operating costs even after considering the need for a centralized processing facility, due to the fact that materials are assumed to be dropped off at the facility (i.e., no collection system would be required) and composting units would be distributed free-of-charge for the on-site composting program. Expected waste diversion impacts for drop-off programs may be much lower than for on-site programs. Drop-off programs have reported participation rates in the range of 10% to 30%, while on-site (backyard) composting programs have reported rates in the range of 30% to 80%. The initiation of a curbside collection program for yard waste would be prohibitively expensive for a community of this size at an estimated $245/tonne, particularly as a centralized facility would also be required. The waste diversion rates could be significantly higher with a curbside program, but based on the participation rates being experienced for several Ontario on-site composting programs (in the range of 75% to 80%), the resulting waste diversion rates may be comparable.

Table 3. **Summary of the estimated costs and waste diversion rates for the source separation composting program options**

PROGRAM	WASTE DIVERSION (tonnes/year)	ANNUAL COST ($/year)	PROGRAM COST ($/tonne)
residential, on-site	163	$11300	$70
residential and ICI, drop-off	71	$4000 $2200 (processing)	$55 $30 (processing)
residential and ICI, curbside	300	$73000 $9000 (processing)	$245 $30 (processing)

The agency operating the curbside recycling program charged the Town of Selkirk a flat fee of $1000 per month or approximately $125 per tonne of waste diverted for 1992. For comparison purposes, a weekly program, similar to the current 'Blue Box' curbside recycling programs operating in Ontario, was designed to service the residential sectors of the community. Assuming a 90% participation rate and that materials are collected using a stake truck and a two-person crew, approximately 335 tonnes per year of materials would be diverted from the landfill at an estimated annual cost of $66000. The program start-up cost was estimated to be in the range of $70000. If a specialized recycling collection vehicle requiring only one operator is used the cost decreases from $195/tonne to $170/tonne. Reported costs for similar Ontario programs are in the range of $100 to $170 per tonne, however there is no indication if administrative costs are included. The estimated annual costs are approximately five times greater than the cost that the current operator is charging the town. For a program similar to the existing one, where bagged collection occurs bi-weekly, one day per week (requiring only part-time workers), costs are reduced to $150 per tonne and the waste diversion rate is reduced to 115 tonnes per year (due to decreased participation). This program option had an annual cost of $17000 as compared to the current $12000 per year charged by the collection agency. The estimated annual cost, however, includes an annual administrative cost of $3000.

An investigation of the establishment of a drop-off (depot) program for collecting recyclable materials was also conducted. Assuming a participation rate of 25%, approximately 98 tonnes per year of waste would be diverted from the landfill at an annual cost of $70000. An estimated program start-up cost of $90000 would be required for the purchase of the drop-off depots and one collection vehicle. However, the collection vehicle is only needed one day a week. With an adjustment made to the operation and maintenance costs, the program cost decreases from $715 to $175 per tonne of waste diverted and the annual cost is reduced to $17000.

The results of the preliminary design of drop-off and curbside recycling programs to service Selkirk, Manitoba, are summarized in Table 4. The drop-off recycling program, as compared to a weekly curbside collection program, would achieve significantly lower waste diversion rates (98 tonnes per year as compared to 335 tonnes per year), and would require part-time workers as opposed to creating full-time positions. The drop-off program would, however, require significantly lower capital and operating costs as a collection vehicle and crew would only be required one day per week. A trade-off relationship is demonstrated in this case study between the annual expenditures for the alternative voluntary recycling programs and the expected waste diversion rates, resulting in comparable operating costs on a $/tonne of waste diverted basis. However, operating a bi-weekly curbside recycling program similar to the program currently operating in Selkirk would achieve approximately the same waste diversion rates as the drop-off program with a marginally lower annual operating cost.

Table 4. Summary of the estimated costs and waste diversion rates for the source separation recycling program options

PROGRAM	WASTE DIVERSION (tonnes/year)	ANNUAL COST ($/year)	PROGRAM COST ($/tonne)
residential, drop-off	98	$17000	$175
residential, curbside (weekly, using Blue Boxes)	335	$66000	$195
residential, curbside (bi-weekly, using bags)	115	$17000	$150

The investigation into the preliminary design of source separation composting and recycling programs for Selkirk, Manitoba, required approximately two days to complete. This included consultation with the knowledge bases, examination of the spreadsheet models, and adjustment of the model parameters to account for different program options and design parameter assumptions. This analysis, however, was based on the application of reported waste generation and composition figures for Ontario communities to Selkirk, Manitoba, and assumed the current markets for recovered recyclable materials would accept increased amounts of materials.

The case study application demonstrates the ease with which a preliminary investigation of the commonly used source separation composting and recycling programs may be accomplished despite a limited amount of locally available data. Using the waste management expertise available in the knowledge bases and the spreadsheet models designed to calculate program costs and waste diversion rates, various collection options and program parameter assumptions may be readily explored and compared. After an initial consultation with the program planning modelling components, the program parameters may be changed within the spreadsheet models with the impacts on the costs and effectiveness (waste diversion rates) of the programs automatically adjusted. Thus, a sensitivity analysis may be performed to determine the effects of changing the assumptions regarding important program parameters. The program costs generated for the case study were generally reflective of the costs reported in the technical literature. A summary of the input data and results of this case study are provided in Appendix H.

CHAPTER 8

APPLICATION OF THE PLANNING SUPPORT APPROACH: FACILITY PLANNING

In order to demonstrate the application of the prototype decision support system to facility planning studies, a case study was conducted based on the current recycling situation in the community of Winnipeg, Manitoba. A preliminary study of a recyclable materials management system is described.

Winnipeg is the capital city of Manitoba, and is located at the junction of the Red and Assiniboine Rivers in southern Manitoba. The 1991 census reported a population of 616,786 for the City of Winnipeg (Statistics Canada, 1992). Although the population of Winnipeg has experienced sharp increases and decreases in the late 1970's and early 1980's, respectively, the population is showing signs of stabilization. A recent study predicted an annual population growth of 4500 persons/year from 1988 to 2011 (Manitoba Bureau of Statistics, 1989). Therefore, a population growth rate of 0.7%/year was assumed over the 20 year planning study time horizon of 1991 to 2011.

Currently, Winnipeg does not operate any incineration facilities or transfer stations. Consistent with many communities in western Canada, Winnipeg relies almost exclusively on the use of landfills for managing its MSW. Following a 1982 landfill siting study, the 40-year, 50 million m^3, Brady Road landfill site was proposed to replace the Summit Road landfill facility. A drop-off program for centralized leaf and garden waste composting has recently begun. Materials are accepted at nine drop-off locations. For the fall of 1992, 200 tonnes or 4500 m^3 of compostable materials were expected to be collected for composting. Composting takes place at the Summit Road landfill site using minimal technology, windrow composting that requires 2 to 3 years for the entire process to be completed. There is ample land area available for expanding the centralized composting facility.

Recycling activities are primarily privately operated, and include a combination of drop-off depot collection (using approximately 30 depots) and voluntary curbside collection programs. The City of Winnipeg recently provided funding for the establishment of 5 drop-off depots that would be used to collect materials for processing at an existing privately-operated materials recovery facility (MRF). The City of Winnipeg, thus far, has tended to surrender the planning and operation of recycling programs and facilities to the private sector. However, many different companies are actively involved in the collection and processing of recyclables, with little in the way of coordination of efforts, or centralized collection or dissemination of information regarding the effectiveness of their efforts. Therefore, it was very difficult to determine the waste diversion rates, collection and processing costs, and other important data associated with the current system for managing recyclables. Due to the present situation with respect to recycling in the City of Winnipeg, a planning study was conducted to investigate processing facility requirements if the City of Winnipeg were to instigate a widespread, municipally-operated or municipally-funded drop-off recycling program or curbside recycling program. Information regarding current waste management practises in the City of Winnipeg was provided by a waste management engineer with the Waterworks, Waste and Disposal Department.

The initial step in the investigation was the use of the waste generation and composition forecasting models to develop estimates for waste generation over the 20 year planning horizon. The basic data required with respect to population and dwelling types within the City of Winnipeg were obtained from several sources (Manitoba Bureau of Statistics, 1989; Statistics Canada, 1992). Waste generation and composition forecasts were determined for the residential and ICI sectors. The approximate base estimates for waste generation parameters for the various sectors are presented in Table 5, with a more detailed listing provided in Appendix I.

Table 5. Summary of the estimates for the primary waste generation parameters for the facility planning case study

initial population	616,786
initial waste generation rate for the SFD sector	257000 tonnes/year
initial waste generation rate for the MFD sector	57000 tonnes/year
initial waste generation rate for the ICI sector	257000 tonnes/year
initial waste generation rate for public works	72000 tonnes/year

The source separation recycling program design components of the decision support system were utilized to design two alternative voluntary recycling programs to service the residential sectors; one program was designed based on the use of drop-off depots, and the other program was designed based on the curbside collection of recyclables. This estimation process was required in order to forecast the total material tonnages that would require processing within a system of MRFs. The programs were assumed to expand over time to include more materials, and to include more residences due to the expected growth in the population. However, the curbside program was assumed to initiate with a pilot scale program. A summary of the main program parameters for the drop-off and curbside collection alternatives are summarized in Tables 6 and 7, respectively. The ranges listed for several of the program parameters indicate their values in the start-up year and final year (year 20) of the planning period. A listing of the base input parameter values estimated for the two collection program alternatives has been included in Appendix I.

Table 6. Summary of the proposed drop-off depot collection program for recovery of source separated recyclable materials

Source separation recycling:	drop-off program with depot collection to service residential sector
participation rate	25%
depot capital cost, capacity	\$4250, 10 m^3
number of depots required	160 (start-up) to 265 (year 20)
collection vehicle, capital cost, capacity	roll-off truck, \$90000/vehicle, 30.5 m^3
number of vehicles required	4 to 6
start-up cost	\$1.5 million
total waste diversion rate	10000 to 14000 tonnes/year
annual cost	\$500000/year to \$700000/year
annual cost per tonne of waste diverted	\$50/tonne
total present value program cost over the 20 year planning period	**\$8.7 million**

Table 7. **Summary of the proposed curbside collection program for recovery of source separated recyclable materials**

Source separation recycling:	weekly, curbside program to service residential sector (not including large MFD complexes)
participation rate	85%
collection vehicle, capital cost, capacity	closed-body vehicle, \$75000/vehicle, 21 m^3
number of vehicles required	11 to 45
start-up cost	\$4.0 million
total waste diversion rate	9000 to 48000 tonnes/year
annual cost	\$1 million/year to \$3 million/year
annual cost per tonne of waste diverted	\$110/tonne (start-up) to \$65/tonne
total present value program cost over the 20 year planning period	\$35.4 million

It was assumed that the material recovery (waste diversion) rates predicted for the drop-off recycling program could be managed using three existing facilities. Due to the higher forecasted material recovery rates for the curbside collection program, the development of at least one additional facility would be required, as no expansions were assumed possible at the existing MRFs. Three potential facility locations were assumed with two of the potential sites being located in proximity to the current landfill sites.

The City of Winnipeg was subdivided into 12 waste generation source areas based on the 1991 census tracts (Statistics Canada, 1992). The total forecasted recyclable material recovery rates were allocated to the waste source areas based on relative population and expected growth rates. The complete listing of the recyclable material recovery rates for the optimization study time periods are presented in Appendix I. The relative locations of the facility sites and the waste generation source areas are illustrated in Figure 16. The sites of the three existing and three potential MRFs are represented in Figure 16 with solid and hollow circles, respectively. The waste source areas and facility sites are also indexed.

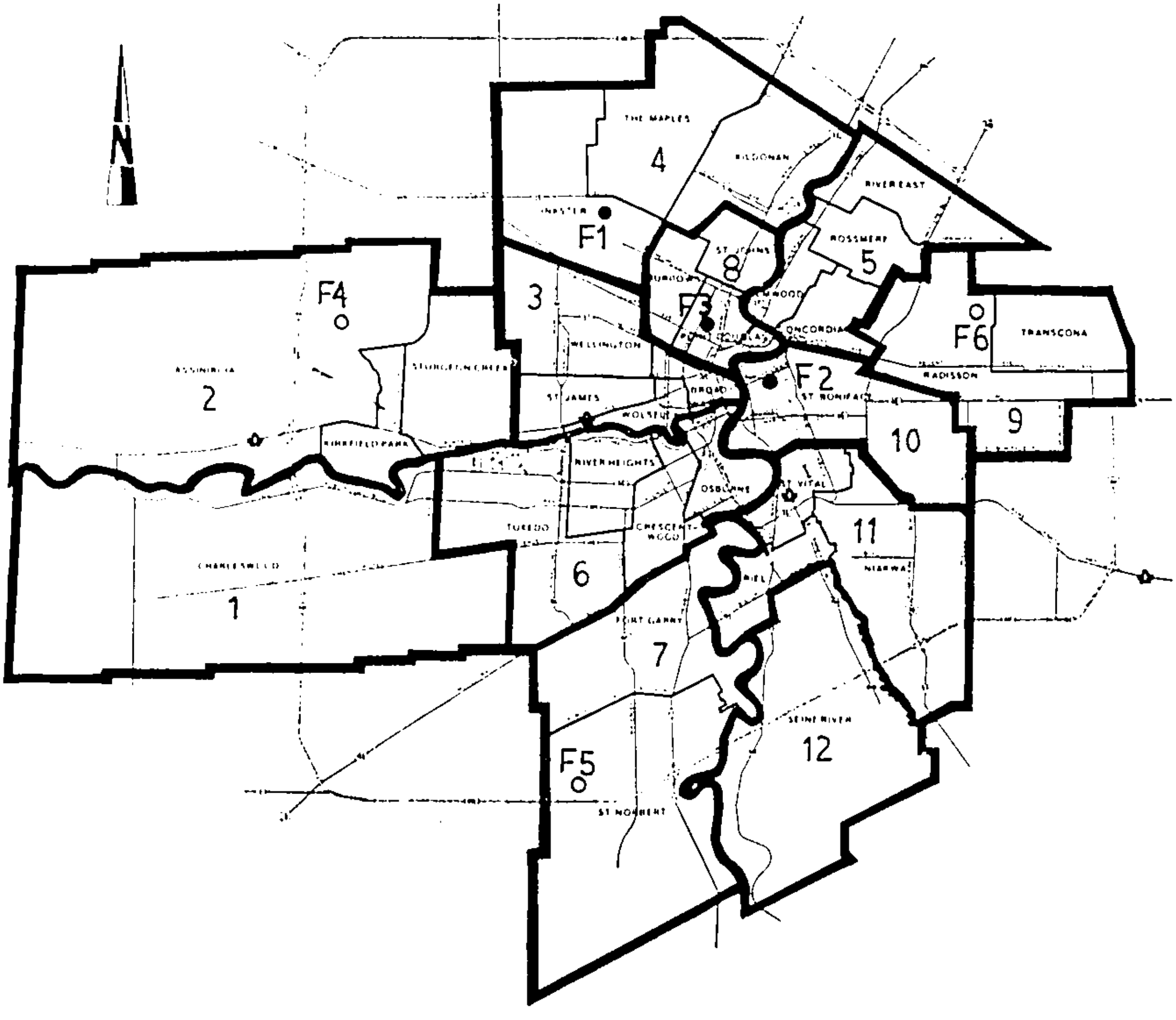

Figure 16. Map of the case study area illustrating the facility locations and waste source area divisions
Source: adapted from Elections Manitoba (1990)

An optimization study was conducted for the series of forecasted material recovery rates developed for the drop-off and curbside collection options. The MILP solver package MILP88 (Version 7.11) (Eastern Software Products, Inc., 1988) was used for the case study. Waste allocation and facility selection/location issues were investigated in consultation with the facility planning components of the prototype decision support system.

The materials recovered through the drop-off program over the 20 year planning horizon were assumed to be managed using the three existing MRFs. This system planning problem reduced to an optimization of flow allocation and required only an LP model formulation. Total material flow values were developed for each of the 12 waste source areas for each year of the 20 year planning horizon. Estimates for the collection cost and the expected revenue from the sale of recovered materials associated with the flows of recyclable materials, applicable to all the MRFs, were developed using the results from the source separation program design stage. Facility operating costs were approximated using information in the facility related data estimation knowledge base developed for MRFs (FAC_MRF.KBS). Transportation, or linehaul, costs were estimated through consultation with a knowledge base (INPUT.KBS); transportation distances between facility sites and waste source areas were estimated from a City of Winnipeg map. The remaining model parameters (the residuals disposal cost and facility capacities) were assumed based partially on information provided by several waste management professionals involved in the operation of the current Winnipeg MSW management system. A listing of the model parameters assumed for the optimization of the drop-off recycling program processing system is provided in Appendix I.

The model formulation for the optimization study of the drop-off recycling program processing system was developed with the assistance of the optimization modelling components of the prototype decision support system. The solution package also provided reports summarizing the post-optimality (sensitivity) analysis information.

The optimal present value system cost was determined to be $6.3 million which includes the costs of collecting, transporting and processing the materials. In the optimal solution, facility one is allocated materials such that it continually operates at full capacity. As total material flows exceed the available capacity of facility one, flows are next assigned to facility two. By year 20 of the planning horizon, materials from eight of the 12 waste source areas (WSAs) (WSA = 1, 2, 3, 4, 6, 7, 8, 9) are allocated in their entirety to facility one, the majority of materials from three of the waste source areas are allocated to facility two (WSA = 10, 11, 12), and materials from two of the waste source areas are allocated to facility three (WSA = 5, 10). These results may be explained due to the difference in operating costs assumed for the facilities and haul transportation distances, as all other cost parameters were identical.

LP post-optimality analyses indicate the reduced costs associated with the cost coefficients in the objective function (which indicate the amount a cost coefficient may decrease before the given flow assignment would become financially desirable), the dual variables or shadow prices associated with the capacity constraints (which indicate the decrease in the system cost if the capacity of a facility is increased by one unit), and the ranges over which the cost coefficients and the right-hand-side values for constraints (representing the maximum facility capacities in each time period) may be changed without affecting the optimal basis of the solution (Lund, 1990*b*). The output from the sensitivity analysis was interpreted with the assistance of a knowledge base (SENSE.KBS).

The lowest reduced costs associated with the flow allocation decision variables indicate the most financially desirable alternative assignments for the flows of materials. For example, in the first year of the optimization study, the lowest reduced costs are associated with flows from waste source areas 10, 11 and 12 to facility two. Once facility one reaches its capacity, excess flows for these system links are assigned to facility two. Facility one has the lowest operating cost, but once its capacity is reached the flows of materials originating from distant waste source areas are allocated to the next closest alternative facility. The dual variables indicate that facility three never reaches its capacity so there is no benefit to adding small amounts of capacity. Capacity increases would be most beneficial at facility one. The cost coefficient and facility capacity ranges provided by the sensitivity analysis also illustrate the tendency for materials to be allocated to facility one, as some degree of variability may occur in these estimates without affecting the flow assignments. However, the ranges for these model parameters are relatively small (8 to 12% of the estimated values) indicating that many near-optimal solutions, or sets of flow allocations, may exist.

An investigation of a processing system for the forecasted flows of recyclable materials from the proposed curbside recycling program was also conducted. In this case, only existing facility one was included in the system (due to the very limited sizes and processing capabilities of the other two existing facilities), along with the three proposed sites for new MRFs. Potential facility capital costs were estimated using a fixed and a variable cost; capacity development and expansions were limited to discrete units of capacity. Thus, an MILP model formulation was required. The remaining model parameters were estimated in a similar manner to the drop-off program processing system problem previously described. The 20 year time horizon was modelled in five 4-year time periods. In order to ensure sufficient capacity was developed within the system, the maximum predicted flows of recyclable materials in each time period were utilized as the basis for aggregating the yearly data. A listing of the model parameters assumed for the optimization of the curbside program processing system is included in Appendix I.

The optimal present value system cost was determined to be \$43.2 million, which includes the costs of facility construction and expansion, and the costs of collecting, transporting and processing the recyclable materials. In addition to requiring the full use of the operating capacity of facility one, the solution calls for the development of facility six in period one at 50 tonnes/day and a subsequent expansion of this facility by 50 tonnes/day in the second time period, and the development of facilities four and five in the second time period at 50 tonnes/day each. The available capacities of facilities five and six are fully utilized, and the capacity of facility four is gradually utilized over time (assuming a design capacity utilization factor of 0.8 to determine the normal operating capacity). In general, facility one is assigned recyclable materials from three waste source areas (WSA = 3, 4, 6), facility four is assigned materials from three waste source areas (WSA = 1, 2, 3), facility five is assigned materials from two waste source areas (WSA = 6, 7), while facility six is assigned materials from six waste source areas (WSA = 5, 6, 9, 10, 11, 12).

Using the methods for generating near-optimal solutions described in several water resources research papers (Brill, 1979; Chang et al., 1982; Harrington and Gidley, 1985) and summarized in a knowledge base (NEAR_OPT.KBS), several alternative solutions were produced with total system costs within 5% of the optimal (least-cost) solution. Three near-optimal solutions were generated which involved varying facility location, sizing and timing of investment patterns, and waste allocations. The existence of near-optimal solutions indicated the general flexibility of the assumed system of facilities for managing the recyclables collected through the proposed curbside program. As maximum capacity limitations were not imposed on the sites due to the availability of land, one near-optimal solution required the development and expansion of only one of the proposed facility sites. The near-optimal systems solutions also provided excess capacity within the system (while still producing costs within 5% of the optimal) as there was no direct driving force for the reformulated model to produce minimal cost alternatives. The ability to produce several near-optimal solutions to this planning problem with excess capacity and with different facility usage and waste allocation patterns revealed that the capital and transportation costs are less significant cost components of the assumed recyclables management system. This conclusion arises from the assumption that the operating and collection costs would be the same at all of the potential facility sites. The capital investments required for the alternative systems represent approximately 12% of the total system costs.

Conducting a simulation study of the optimal system for the same time periods as the optimization study provided a means of verifying the optimization modelling approach. The total present value system cost calculated by the simulation model was within 0.1% of the optimal solution.

The simulation model was also used to evaluate the proposed optimal recyclable materials management system for the curbside collection program under yearly time increments. This allowed the examination of the variability in material flows and system costs within the optimization time period increments. The total present value system cost based on an annual analysis of the system was calculated to be $39.2 million. The difference in the total present value system costs calculated through the two mathematical models may be attributed primarily to the effects of discounting on a yearly basis in the simulation model. The output from the simulation model indicates the significance of the collection and facility operation cost components on the total system cost as compared to the required capital investments and transportation costs. The simulation study was conducted using the FORTRAN simulation model (SIM.FOR) with the assistance of the accompanying knowledge base (SIM.KBS).

The case study results were reviewed by a City of Winnipeg waste management engineer, and were found to compare favourably to estimates previously determined for waste generation and composition, and for the potential costs and waste diversion impacts of a city-wide recyclable materials management system.

This case study has demonstrated the extensive and flexible nature of the facility planning components of the prototype decision support system. As well as assisting with the investigation of facility location, sizing, development and expansion issues, the optimization and simulation modelling components may be used to generate alternative solutions to a planning problem and perform sensitivity analyses. This application also served to demonstrate the full range of capabilities of the prototype decision support system, from the forecasting of waste generation and composition data to the use of simulation modelling for facility planning.

The results of the facility planning study for Winnipeg are presented in Appendix I, and include a summary of the optimal and near-optimal recyclable materials management system solutions and the results of the simulation studies.

CHAPTER 9

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

An investigation into the use of systems analysis techniques within the domain of municipal solid waste (MSW) management and planning was conducted for this research, with the objectives of determining the current availability and use of existing mathematical models, and proposing an approach for supporting and extending the use of mathematical models by practising waste management professionals.

Three general approaches were suggested for the integration of the waste management knowledge found in the literature and possessed by waste management professionals, and the existing systems analysis techniques applied in mathematical models within the domain of MSW management and planning. Decision support systems based on the use of knowledge-based system techniques could be developed to interface with individual mathematical models, assist with model selection, or manage a series of models required to investigate a MSW management or planning activity.

Based on the results of an extensive literature review and a survey of waste management professionals, suitable problem areas within the domain of MSW management and planning were proposed for the application of the decision support approaches based on the integrated use of mathematical models and knowledge-based system techniques.

To date, the majority of MSW management planning studies have relied on the integrative abilities of experienced planners or external consultants, although the methods used may not have been generally rigorous or detailed. The suggested decision support approaches may extend and support the use of systems analysis techniques in practise, while allowing end-users to make decisions using their own skill and judgment.

This research was also an attempt to address what numerous studies and inquiries have identified as the most significant deterrent to implementing MSW management projects: the perceived complexity of the planning process. A prototype decision support system has been designed to identify the activities and decisions required to conduct preliminary planning studies for MSW management systems. The prototype decision support system contains components related to the major planning activities: waste forecasting; source separation composting and recycling program design; facility sizing, location and investment timing, and waste allocation; and systems analysis using simulation. Any of these components may also be used in isolation, providing a flexible framework for MSW management and planning. The various components may also be applied in an iterative manner to determine the effects of uncertainty in model parameters and assumptions on the outputs from subsequent planning stages.

9.2 Conclusions

1) An extensive literature review identified numerous mathematical models developed for MSW management and planning based on the application of systems analysis techniques. The emphasis of these previous studies has been on model formulation, as opposed to issues such as useability and data requirements.

2) Research, to date, has not dealt effectively with identifying the extent of application of mathematical models and the perceived deficiencies in current solid

waste management and planning procedures, nor have knowledge-based systems been applied to help narrow the gap between waste management professionals and mathematical models.

3) A technical survey indicated that available mathematical models for MSW management and planning are not widely utilized in practise, particularly within municipal or regional waste management agencies.

4) Waste management engineers and planners require additional tools to assist in the examination of MSW management system options, particularly as the knowledge and technological options in this field continue to expand.

5) There is both a need for, and an interest in, a useful, practical (with respect to data requirements and cost) and reasonably objective form of decision support system for use at the local or regional MSW management decision-making levels.

6) Ample opportunity exists to apply the suggested decision support approaches for the integration of systems analysis and knowledge-based system techniques to support the use of mathematical models in MSW management and planning practise.

7) The prototype decision support system demonstrates the potential benefits and limitations of the suggested approaches for decision support in the MSW management and planning field. The use of the system yielded useful and reasonable results for two case study applications. The prototype system was considered to be a reasonable, useful and useable planning tool by several waste management professionals.

8) A significant amount of waste management and planning expertise has been collected, organized and encoded for the development of the prototype decision support system. The knowledge contained within the current knowledge-based system components and the list of technical references are in and of themselves an important contribution of this research.

9) Based on the opinions expressed by several practising waste management professionals, the integration of knowledge-based systems and mathematical models appears to be a suitable method of providing decision-making support to waste management professionals.

9.3 Recommendations

1) Further research should be conducted to identify the potential impediments to the practical application of the existing systems analysis techniques within waste management and planning agencies. The domain of MSW management and planning may benefit from a more concerted effort on the part of mathematical modellers to provide more extensive decision support to facilitate model applications in actual MSW management or planning situations.

2) Other applications of the suggested decision support approaches for the integration of knowledge-based systems with existing mathematical models should be explored within the domain of MSW management and planning. Knowledge-based system components may be developed to assist with model integration or model selection, or to assist with the use of an individual mathematical model. Suitable application areas identified for future study may include waste generation

and composition forecasting, collection vehicle routing, landfill design and the operation of waste receiving facilities.

3) Due to the constantly changing decision-making environment in MSW management and planning, it is recommended that future decision support systems be designed to be modular, and to represent knowledge in a form that would permit end-users to understand, and thus readily update, the system. Alternative software packages should be considered that allow more efficient data transfer between the modelling components of decision support systems.

REFERENCES

Abert, J.G., and Vancil, R.M. (1977). "A Graphical Approach to Determine the Economics of Recovering Resources from Municipal Solid Waste." *Conservation and Recycling*, **1**(3-4): 299-314.

Adeli, H. (1989). "Software Review: Personal Consultant Plus." *Microcomputers in Civil Engineering*, **4**: 243-244.

ACI/ADI (1989). Westmorland/Albert Region Waste Management Alternatives -Final Report. Prepared for the Westmorland/Albert Solid Waste Provisional Committee, Province of New Brunswick.

Ali Khan, M.Z. (1984). "Optimization of Refuse Storage Systems." *Civil Engineering*, **1**(3): 145-150.

Ali Khan, M.Z., and Burney, F.A. (1989). "Forecasting Solid Waste Composition - An Important Consideration in Resource Recovery and Recycling." *Resources, Conservation and Recycling*, 3(1): 1-17.

Andrews, B.H., Ecker, J., and White, R.M. (1991). "Composting: Computing the Right Recipe." *Civil Engineering (ASCE)*, 55(6): 55-56.

Arey, M-J. (1991). "Fitting Statistical Distributions to Unaltered Solid Waste Generation Data and Development of Sizing Methodologies for Solid Waste Receiving Facilities." unpublished Master of Engineering Thesis, McMaster University, Hamilton, Ontario.

Baetz, B.W. (1988). "Capacity Planning for Production Facilities and Alternative Facilities with Consumable Capacity: Application to Waste Management Systems." unpublished Ph.D. Dissertation, Duke University, Durham, North Carolina.

Baetz, B.W. (1990). "Optimization/Simulation Modeling for Waste Management Capacity Planning." *J. of Urban Planning and Development*, **116**(2): 59-79.

Baetz, B.W., and Byer, P.H. (1989). "Moisture Control During Landfill Operation." *Waste Management and Research*, 7(3): 259-275.

Baetz, B.W., Pas, E.I., and Neebe, A.W. (1989*a*). "Trash Management: Sizing and Timing Decisions for Incineration and Landfill Facilities." *Interfaces*, **19**(6): 52-61.

Baetz, B.W., Pas, E.I., and Vesilind, P.A. (1989*b*). "Planning Hazardous Waste Reduction and Treatment Strategies: An Optimization Approach." *Waste Management and Research*, 7(2): 153-163.

Baffaut, C., and Delleur, J.W. (1989). "Expert System for Calibrating SWMM." *J. of Water Resources Planning and Management*, 115(3): 278-298.

Balachandran, M., and Gero, J.S. (1987). "Use of Knowledge in Selection and Control of Optimization Algorithms." *Engineering Optimization*, 12(2): 163-173.

Behncke, P. (1989). "REGRESSOR: An Expert System for Data Regression Models." Working Paper, McMaster University, Hamilton, Ontario.

Beltrami, E.J., and Bodin, L.D. (1974). "Networks and Vehicle Routing for Municipal Waste Collection." *Networks*, 4(1): 65-94.

Bertolini, G.E. (1987). "Household Refuse: Recovery or Disposal? Research for a New Economic Optimum." *Conservation and Recycling*, 10(4): 321-330.

BioCycle (1990). The BioCycle Guide to Collecting, Processing and Marketing Recyclables. The JG Press Inc., Emmaus, Pennsylvania.

Bishop, A.B., and Narayanan, R. (1979). "Combined Management of Air, Water and Solid Wastes." *J. of Environmental Management*, 9(2): 103-121.

Bobrow, D., Mittal, S., and Stefik, M. (1986). "Expert Systems: Perils and Promise." *Communications of the ACM*, 29(9): 880-893.

Bodin, L.D. (1990). "Twenty Years of Routing and Scheduling." *Operations Research*, 38(4): 571-579.

Bodner, R.M., Cassell, A., and Andros, P.J. (1970). "Optimal Routing of Refuse Collection Vehicles." *J. of the Sanitary Engineering Division (ASCE)*, 96(SA4): 893-904.

Bonczek, R.H., Holsapple, C.W., and Whinston, A.B. (1984). "Developments in Decision Support Systems." *Advances in Computers*, 23: 144-175.

Boose, J.H. (1986). Expertise Transfer for Expert System Design. Elsevier Science Publishers, New York.

Brill, E.D. Jr. (1979). "The Use of Optimization Models in Public-Sector Planning." *Management Science*, 25(5): 413-422.

Buchnea, A. (1983). "A Systems Modeling Approach to Evaluating Low-Level Waste Disposal Systems." *Trans. of the American Nuclear Society*, 44: 88-89.

Cardile, R.P., and Verhoff, F.H. (1974). "Economical Refuse Truck Size Determination." *J. of the Environmental Engineering Division (ASCE)*, 100(EE3): 679-697.

Carlson, R.L. (1991). Second Opinion: Solid Waste Disposal Model. Product and Model Overviews - private communication.

Chang, S-Y., Brill, E.D. Jr., and Hopkins, L.D. (1982). "Use of Mathematical Models to Generate Alternative Solutions to Water Resources Planning Problems." *Water Resources Research*, **18**(1): 58-64.

Chapman, R.E., and Yakowitz, H. (1984). "Evaluating the Risks of Solid Waste Management Programs: A Suggested Approach." *Resources and Conservation*, **11**(2): 77-94.

Chen, K., Mathes, J.C., Jarboe, K., and Wolfe, J. (1979). "Value Oriented Social Decision Analysis: Enhancing Mutual Understanding to Resolve Public Policy Issues." *IEEE Trans. on Systems, Man, and Cybernetics*, 9(9): 567-580.

Chertow, M.R. (1989). Garbage Solutions: A Public Official's Guide to Recycling and Alternative Solid Waste Management Technologies. National Resource Recovery Association, The United States Conference of Mayors, Washington, D.C.

Chikte, S.D., and Levis, A.H. (1976). "A Dynamic Simulation Model of Urban Litter Generation." *IEEE Trans. on Systems, Man, and Cybernetics*, **6**(5): 374-377.

Chiplunkar, A.V., Mehndiratta, S.L., and Khanna, P. (1981). "Optimization of Refuse Collection Systems." *J. of the Environmental Engineering Division (ASCE)*, **107**(EE6): 1203-1210.

Christensen, H.L., and Haddix, G.F. (1974). "A Model for Sanitary Landfill Management and Design." *Computers & Operations Research*, **1**(2): 275-281.

Clapham, W.B. Jr. (1987). "RECYCLE: A Computerized Planning Tool to Improve Municipal Solid Waste Management." *Ohio J. of Science*, **86**(5): 189-199.

Clark, R.M. (1973). "Solid Waste: Management and Models." in Models for Environmental Pollution Control. R.A. Deininger (ed.), Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, pp. 269-305.

Clark, R.M., and Gillean, J.I. (1974). "Systems Analysis and Solid Waste Planning." *J. of the Environmental Engineering Division (ASCE)*, 100(EE1): 7-24.

Clark, R.M., and Gillean, J.I. (1981). Resource Recovery Planning and Management. Ann Arbor Science Publishers, Ann Arbor, Michigan.

Clark, R.M., and Helms, B.P. (1970). "Decentralized Solid Waste Collection Facilities." *J. of the Sanitary Engineering Division (ASCE)*, **96**: 1035-1943.

Clark, R.M., and Helms, B.P. (1972). "Fleet Selection for Solid Waste Collection Systems." *J. of the Sanitary Engineering Division (ASCE)*, 98(SA1): 71-78.

Clark, R.M., Grupenhoff, B.L., Garland, G.A., and Klee, A.J. (1971). "Cost of Residential Solid Waste Collection." *J. of the Sanitary Engineering Division (ASCE)*, 97(SA5): 563-568.

Clayton, K.C. (1976). "A Planning Model for Regional Solid Waste Management Systems." unpublished Ph.D. Dissertation, Purdue University, West Lafayette, Indiana.

Clifford, J.S., Laughton, M.A., McRoberts, T.S., and Slee, P.V. (1978). "LP Modelling in the Paper Industry as an Aid to Recycling Decisions." *Conservation and Recycling*, 2(2): 97-109.

Cohn, L.F., Harris, R.A., and Bowlby, W. (1988). "Knowledge Acquisition for Domain Experts." *J. of Computing in Civil Engineering (ASCE)*, 2(2): 107-120.

Collins, J.P. (1974). "The Development of a Solid Waste Environmental Evaluation Procedure." unpublished Ph.D. Dissertation, the University of Michigan, Ann Arbor.

Collins, J.P., and Glysson, E.A. (1980). "Multiattribute Theory and Environmental Decisions." *J. of the Environmental Engineering Division (ASCE)*, 106(EE4): 815-830.

Coombs, M., and Alty, J. (1984). "Expert Systems: An Alternative Paradigm." in Development in Expert Systems. M.J. Coombs (ed.), Academic Press, Toronto.

Cox, J. (1986). "Waste Collection and Disposal." in Microcomputers for Local Government Planning & Management. P.W. Newton and M.A.P. Taylor (ed.), Hargreen Publishing Company, Victoria, Australia.

D'Ambrosio, B. (1985). "Expert Systems - Myth or Reality ?." *Byte*, 10(1): 275-282.

DeGeare, T.V. Jr., and Ongerth, J.E. (1971). "Empirical Analysis of Commercial Solid Waste Generation." *J. of the Sanitary Engineering Division (ASCE)*, 97(SA6): 843-850.

Demetracopoulos, A.C., Korfiatis, G.P., Bourodimos, E.L., and Nawy, E.G. (1984). "Modeling for Design of Landfill Bottom Liners." *J. of Environmental Engineering (ASCE)*, 110(6): 1084-1098.

Demetracopoulos, A.C., Sehayek, L., and Erdogan, H.. (1986). "Modeling Leachate Production from Municipal Landfills." *J. of Environmental Engineering (ASCE)*, 112(5): 849-866.

Eastern Software Products, Inc. (1988). Mixed-Integer Linear Programming for the IBM PC, MILP88, Version 7.11: User's Manual. Eastern Software Products, Inc., Alexandria, Virginia.

Elections Manitoba (1990). Statement of Votes. Report of the Chief Electoral Officer.

Environmental Protection Agency (1989). Decision-Makers Guide to Solid Waste Management. Solid Waste and Emergency Response, EPA/530-SW-89-072, Washington, D.C.

Esmaili, H. (1972). "Facility Selection and Haul Optimization Model." *J. of the Sanitary Engineering Division (ASCE)*, 98(SA6): 1005-1020.

Fayegh, D., and Russell, S.O. (1986). "An Expert System for Flood Estimation", in Expert Systems in Civil Engineering. C. Kostem and M. Maher (ed.), ASCE Publication, New York, pp. 174-181.

Felago, R.T., and Stoller, P.J. (1979). Resource Recovery Management Model. The Mitre Corporation, Metrek Division, Bedford, Massachusetts.

Fenves, S.J., Maher, M.L., and Sriram, D. (1984). "Expert Systems: C.E. Potential." *Civil Engineering*, 54(10): 44-47.

Findikaki, I.T. (1986). "An Expert System for Site Selection", in Knowledge-based Systems in Civil Engineering. C. Kostem and M. Maher (ed.), ASCE Publication, New York, pp. 182-192.

Findley, C.E. (1978). "A Methodology for Evaluating the Potential Materials and Energy Recovery from Municipal Solid Waste." unpublished Ph.D. Dissertation, University of Washington, Seattle.

Fiksel, J., and Hayes-Roth, F. (1989). "Knowledge Systems for Planning Support." *IEEE Expert*, 4(3): 16-23.

Forgie, D.J.L., and Byer, P.H. (1984). "Modelling the Cost-Effectiveness of Sanitary Landfill Leachate Control Systems." *Civil Engineering Systems*, 1(9): 261-269.

Fuertes, L.A., Hudson, J.F., and Marks, D.H. (1974). "Solid Waste Management: Equity Trade-Off Models." *J. of the Urban Planning and Development Division (ASCE)*, 100(UP2): 155-171.

Gebhardt, K., and Jankowski, J. (1987). "Preliminary Landfill Siting and Related Analysis Using Simple Modeling Techniques." *Engineering Geology*, 23(3-4): 291-306.

Gevarter, W.B. (1987). "The Nature and Evaluation of Commercial Expert System Building Tools." *Computer*, 20(5): 24-41.

Gibson, J.A. (1976). "A Review of Recent Extensions of Linear Economic Models to Regional Environmental Quality Analysis." *J. of Environmental Systems*, 6(2): 147-172.

Glassey, C.G., and Gupta, V.K. (1974). "A Linear Programming Analysis of Paper Recycling." *Management Science*, **21**(4): 392-408.

Gore & Storrie Limited (1991*a*). Residential Waste Composition Study: Volume I of the Ontario Waste Composition Study. Prepared for the Waste Management Branch, Ontario Ministry of the Environment, Queen's Printer for Ontario, PIBS 1415.

Gore & Storrie Limited (1991*b*). Commercial Waste Composition Study: Volume II of the Ontario Waste Composition Study. Prepared for the Waste Management Branch, Ontario Ministry of the Environment, Queen's Printer for Ontario, PIBS 1608.

Gottinger, H.W. (1986). "A Computational Model for Solid Waste Management with Applications." *Applied Mathematical Modelling*, 10(5): 330-338.

Gottinger, H.W. (1991). Economic Models and Applications of Solid Waste Management. Gordon and Breach Science Publishers, New York.

Greenberg, M., Caruana, J., and Krugman, B. (1976). "Solid-Waste Management: A Test of Alternative Strategies Using Optimization Techniques." *Environment and Planning A*, 8(5): 587-597.

Grossman, D., Hudson, J.F., and Marks, D.H. (1974). "Waste Generation Models for Solid Waste Collection." *J. of the Environmental Engineering Division (ASCE)*, 100(EE6): 1219-1230.

Gupta, Y.P., and Chin, D.C.W. (1989). "Expert Systems and their Applications in Production and Operations Management." *Computers & Operations Research*, **17**(6): 535-543.

Guruswamy, L.D. (1985). "Waste Management Planning." *J. of Environmental Management*, **21**(1): 69-84.

Han, S-Y., and Kim, T.J. (1989). "An Application of Expert systems in Urban Planning: Site Selection and Analysis." *Computers, Environment & Urban Systems*, **13**(4): 243-254.

Harrington, J.J., and Gidley, J.S. (1985). "The Variability of Alternative Decisions in a Water Resources Planning Problem." *Water Resources Research*, **21**(12): 1831-1840.

Hartz, K.E., and Ham, R.K. (1981). "Determining the Optimum Number of Receiving Bays for a Solid Waste Facility." *Conservation and Recycling*, **4**(1): 39-46.

Hasit, Y., and Warner, D.B. (1981). "Regional Solid Waste Planning with WRAP." *J. of the Environmental Engineering Division (ASCE)*, 107(EE3): 511-526.

Haynes, L. (1981). "A Systems Approach to Solid Waste Management Planning." *Conservation and Recycling*, 4(2): 67-78.

Hekimian, K.K. (1972). "A Systems Engineering Approach to Environmental Quality Management with Emphasis on Solid Waste Management." unpublished Ph.D. Dissertation, University of Southern California, Los Angeles.

Helms, B.P., and Clark, R.M. (1971). "Selecting Solid Waste Disposal Facilities." *J. of the Sanitary Engineering Division (ASCE)*, 97(SA4): 443-451.

Hickman, L. (1991). "Capacity and Interstate Transport: Partners in Crime." *Municipal Solid Waste News (SWANA)*, 13(3): 1-2.

Huang, Y.W., Shenoi, S., Mathews, A.P., Lai, F.S., and Fan, L.T. (1986). "Fault Diagnosis of Hazardous Waste Incineration." in Expert Systems in Civil Engineering. C. Kostem and M. Maher (ed.), ASCE Publication, New York, pp. 145-158.

Humphries, M.P. (1986). "Modelling Congestion at Refuse Reception Installations." *Waste Management and Research*, 4(3): 279-291.

Jenkins, A.L. (1979). "Optimal Location of Facilities for Recycling Municipal Solid Waste in Southern Ontario." unpublished Ph.D. Dissertation, University of Toronto, Toronto, Ontario.

Jenkins, L. (1980). The Ontario Waste Management Systems Model. Ontario Ministry of the Environment.

Jenkins, L. (1982). "Developing a Solid Waste Management Model for Toronto." *INFOR*, 20(3): 237-247.

Jennings, A.A., and Sholar, R.L. (1984). "Hazardous Waste Disposal Network Analysis." *J. of Environmental Engineering (ASCE)*, 110(2): 325-342.

Kahalas, H., and Leininger, W.E. (1979). "A Stochastic Decision Model for Returnable Containers." *J. of Environmental Management*, 8(2): 163-171.

Kahn, G., Nowlan, S., and McDermott, J. (1985). "Strategies for Knowledge Acquisition", *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 7(5): 511-522.

Kampmann, E.C. (1975). "Planning for Solid Wastes Management: Post-Collection Alternatives." unpublished Ph.D. Dissertation, University of California, Berkeley.

Kawamura, K. (1984). "Specifications for Interactive Environmental Management." *IEEE Trans. on Systems, Man, and Cybernetics*, 14(4): 654-658.

Khan, A.M. (1987). "Solid-Waste Disposal with Intermediate Transfer Stations: An Application of the Fixed-Charge Location Problem." *J. of the Operational Research Society*, 38(1): 31-37.

Klee, A.J. (1970). "DISCUS - A Solid-Waste Management Game." *IEEE Trans. on Geoscience Electronics*, 8(3): 125-129.

Klee, A.J. (1989). "d-SSYS, a Computer Model for the Evaluation of Competing Alternatives." *Hazardous Waste & Hazardous Materials*, 6(3): 297-314.

Klee, A.J., and Carruth, D. (1970). "Sample Weights in Solid Waste Composition Studies." *J. of the Sanitary Engineering Division (ASCE)*, 96(SA4): 945-954.

Korfiatis, G.P. (1984). "Modeling the Moisture Transport Through Solid Waste Landfills." unpublished Ph.D. Dissertation, Rutgers University, Piscataway, New Jersey.

Kostem, C.N. (1986). "Design of an Expert System for the Rating of Multibeam Highway Bridges." in Knowledge-based Systems in Civil Engineering. C. Kostem and M. Maher (ed.), ASCE Publication, New York, pp. 87-95.

Kuhner, J., and Harrington, J.J. (1975). "Mathematical Models for Developing Regional Solid Waste Management Policies." *Engineering Optimization*, 1(4): 237-256.

Kuhner, J., and Heiler, B. (1973) "Regional Planning Models for Solid Waste Management." in Models for Environmental Pollution Control. R.A. Deininger (ed.), Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, pp.327-357.

Landry, M., Malouin, J-L., and Oral, M. (1983). "Model Validation in Operations Research." *Eur. J. of Operational Research*, 14: 207-220.

Lane, W.N., and McDonald, R.R. (1983). "Land Suitability Analysis: Landfill Siting." *J. of Urban Planning and Development (ASCE)*, 109(1): 50-61.

Lang, R.J. (1989). "Modeling the Movement of Trace Gases in Municipal Solid Waste Landfills." unpublished Ph.D. Dissertation, University of California, Davis.

Law, K.H., Zimmie, T.F., and Chapman, D.R. (1986). "An Expert System for Inactive Hazardous Waste Sites." in Knowledge-based Systems in Civil Engineering. C. Kostem and M. Maher (ed.), ASCE Publication, New York, pp. 159-173.

Lawver, R., Lund, J.R., and Tchobanoglous, G. (1990). "GIGO - A Solid Waste Management Model for Municipalities." in Proceedings of the Sixth International Conference on Solid Waste Management and Technology. Philadelphia, Pennsylvania.

Leech, D.J., Etemad, F., Williams, D.B., and Williams, H.J. (1985). "The Computer as a Tool for Predicting the Financial Implications of Future Municipal Waste Disposal and Recycling Projects." *Inst. of Mechanical Engineers Conf. Publications*, C82/85: 133-141.

Lennon, G., Mikroudis, G., Rumbagh, D., and Tanen, S. (1988). "A Parameter Estimation Expert System for the USGS Modular Groundwater Model." in Computing in Civil Engineering: Microcomputers to Supercomputers. K.M. Will (ed.), ASCE Publication, New York, pp. 664-673.

Levinson, A. (1990). "A System for Managing Solid Waste." *J. of Resource Management and Technology*, 18(1): 17-20.

Levitt, R.E. (1986). "Howsafe: A Microcomputer-Based Expert System to Evaluate the Safety of a Construction Firm." in Knowledge-based Systems in Civil Engineering. C.N. Kostem and M.L. Maher (ed.), ASCE Publication, New York, pp. 55-66.

Lidgren, K. (1986). "The Economics of Recycling - A Matter of Life or Death for the Resource Recovery Sector in the 1980s and 1990s." *Resources and Conservation*, 12(3-4): 175-192.

Light, G.L. (1990). "Microcomputer Software in Municipal Solid Waste Management: A Review of Programs and Issues for Developing Countries." Water and Sanitation Paper Series (DP No.6), UNDP-World Bank Water and Sanitation Program, Washington, D.C.

Llewellyn, J., and Sharda, R (1990). "Linear Programming Software for Personal Computers: 1990 Survey." *OR/MS Today*, Oct., 1990: 35-47.

Lohani, B.N., and Ko, S.M. (1988). "Optimal Sampling of Domestic Solid Waste." *J. of Environmental Engineering (ASCE)*, 114(6): 1479-1483.

Lotus Development Corporation (1989). Lotus 1-2-3, Release 3. Lotus Development Corporation, Cambridge, Massachusetts.

Ludvigsen, P.J., and Dupont, R.R. (1988). "Formal Evaluation of the Expert System DEMOTOX", *J. of Computing in Civil Engineering (ASCE)*, 2(4): 398-412.

Ludvigsen, P.J., Grenney, W.J., Dyreson, D., and Ferrara, J.M. (1986). "Knowledge-based systems Tools for Civil Engineering Applications." in Expert Systems in Civil Engineering. C.N. Kostem and M.L. Maher (ed.), ASCE Publication, New York, pp. 18-29.

Lund, J.R. (1990*a*). "Pricing Solid- and Hazardous-Waste Landfill Capacity." *J. of Urban Planning and Development (ASCE)*, 116(1): 17-33.

Lund, J.R. (1990*b*). "Least-Cost Scheduling of Solid Waste Recycling." *J. of Environmental Engineering (ASCE)*, 116(1): 182-197.

Mackerle, J. (1989). "A Review of Expert System Development Tools." *Engineering Computations*, 6(1): 2-17.

MacLaren, J.W., and Sexsmith, D.P. (1970). "A Systems Engineering Approach to Urban Solid Waste Collection and Disposal." in Man and His Environment. Proceedings of the 1st Banff Conf. on Pollution, V.1, University of Calgary, pp. 177-184.

MacLaren Engineers (1989). Waste Management Master Plan Study. Draft Report to The Municipalities of Dufferin County.

Maimone, M. (1985). "An Application of Multi-criteria Evaluation in Assessing Municipal Solid Waste Treatment and Disposal Systems." *Waste Management and Research*, 3(3): 217-231.

Malasari, S. (1988). "PC Plus + Lotus 123." in Microcomputer Knowledge-Based Expert Systems in Civil Engineering. H. Adeli (ed.), ASCE Publication, New York, pp. 79-87.

Malina, J.F., and Morgan, W.T. (1972). "Refuse, Reclamation, and Recycle." *J. of the Sanitary Engineering Division (ASCE)*, 98(SA6): 819-831.

Manitoba Bureau of Statistics (1989). "Manitoba Population Projections: 1988-2011." MBS 88-1.

Marks, D.H. (1969). "Facility Location and Routing Models in Solid Waste Collection Systems." unpublished Ph.D. Dissertation, The Johns Hopkins University, Baltimore, Maryland.

Marks, D.H., ReVelle, C.S, and Liebman, J.C. (1970). "Mathematical Models of Location: A Review." *J. of the Urban Planning and Development Division (ASCE)*, 96(UP1): 81-93.

Maser, K.R. (1986). "Applications of Automated Interpretation to Sensor Data." in Expert Systems in Civil Engineering. C. Kostem and M. Maher (ed.), ASCE Publication, New York, pp. 224-238.

McCoy, P.T. (1971). "A Simulation Model for Planning and Management of Solid Waste Collection Systems." unpublished Ph.D. Dissertation, Texas A&M University, College Station.

McLeod, N.B., and Park, Y.M. (1982). "RAWSYM - Radioactive Waste Management System." *Trans. of the American Nuclear Society*, **41**: 84-85.

Meenan, P.M. (1974). "A Decision-Making Structure and Computer Simulation Approach for Analysing Solid Waste Management Systems." unpublished Ph.D. Dissertation, Union College.

Mikroudis, G.K. (1987). "GEOTOX: A Knowledge-Based Surrogate Consultant for Evaluating Waste Disposal Sites." unpublished Ph.D. Dissertation, Lehigh University, Bethlehem, Pennsylvania.

Milke, M.W., and Aceves, F.J. (1989). "Systems Analysis of Recycling in the Distrito Federal of Mexico." *Resources, Conservation and Recycling*, 2(3): 171-197.

Miller, D.M., and Craig, R.J. (1977). "Systems Analysis of Refuse Disposal Alternatives." *J. of the Environmental Engineering Division (ASCE)*, 103(EE5): 935-948.

Ministry of the Environment (1992). The Ontario Environmental Assessment Act as it relates to Waste Management Planning. Environmental Assessment Branch.

Moore, C.A., Rai, I.S., and Lynch, J. (1982). "Computer Design of Landfill Methane Migration Control." *J. of the Environmental Engineering Division (ASCE)*, 108(EE1): 89-106.

Musa, E., and Ho, G.E. (1981). "Optimum Sample Size in Refuse Analysis." *J. of the Environmental Engineering Division (ASCE)*, 107(EE6): 1247-1259.

Nazareth, D.L. (1989). "Issues in the Verification of Knowledge in Rule-based Systems." *Int. J. of Man-Machine Studies*, 30: 255-271.

O'Keefe, R.M., Balci, O., and Smith, E.P. (1987). "Validating Expert System Performance." *IEEE Expert*, 2(4): 81-89.

O'Leary, T.J., Goul, M., Moffitt, K.E, and Radwan, A.E. (1990). "Validating Expert Systems." *IEEE Expert*, 5(3): 51-58.

Ogbudinkpa, R.N. (1978). "Optimum Recycling of Aluminum Beverage Cans: An Empirical Approach." *J. of Environmental Systems*, 7(4): 343-353.

Ortolano, L., and Perman, C.D. (1987). "Software for Expert System Development." *J. of Computing in Civil Engineering (ASCE)*, 1(4): 225-240.

Ortolano, L., and Steinemann, A.C. (1987). "New Expert Systems in Environmental Engineering." *J. of Computing in Civil Engineering (ASCE)*, 1(4): 298-302.

Ostro, B.D. (1976). "Land Use and Urban Solid Waste Disposal." unpublished Ph.D. Dissertation, Brown University, Providence, Rhode Island.

Ouano, E.A.R. (1983). "Hauling Distance and Transfer Station Location." *J. of Environmental Engineering (ASCE)*, 109(6): 1429-1433.

Ouano, E.A.R., and Frankel, R.J. (1976). "Decision Criteria in Solid Waste Collection." *J. of the Environmental Engineering Division (ASCE)*, 102(EE3): 645-655.

Palmer, D.G. (1975). "Economic Planning for Resource and Energy Recovery from Municipal Solid Waste by Mathematical Programming Models." unpublished Ph.D. Dissertation, Syracuse University, Syracuse, New York.

Palmer, R.N., and Tull, R.M. (1987). "Expert Systems for Drought Management Planning." *J. of Computing in Civil Engineering (ASCE)*, 1(4): 284-297.

Panagiotakopoulos, D. (1972). "Environmental Absorption Possibility Frontier: A Network Model for Waste Management." unpublished Ph.D. Dissertation, Cornell University, Ithaca, New York.

Panagiotakopoulos, D. (1975*a*). "A Multi-objective Framework for Environmental Management Using Goal Programming." *J. of Environmental Systems*, 5(2): 133-147.

Panagiotakopoulos, D. (1975*b*). "An Optimization Model for Balancing Economic-Environmental Systems." *Canadian J. of Civil Engineering*, 2(1): 1-9.

Paperback Software (1989). VP-Expert: Rule-Based Expert System Development Tool. Paperback Software International, Berkeley, California.

Patry, G.G., and Chapman, D. (1989). Dynamic Modeling and Expert Systems in Wastewater Engineering. Lewis Publishers Inc., Michigan.

Peavy, H.S., Rowe, D.R., and Tchobanoglous, G. (1985). Environmental Engineering. McGraw-Hill Book Company, Toronto.

Peirce, J.J., and Davidson, G.M. (1982). "Linear Programming in Hazardous Waste Management." *J. of the Environmental Engineering Division (ASCE)*, 108(EE5): 1014-1026.

Petak, W.J. (1980). "Environmental Planning and Management: The Need for an Integrative Perspective." *Environmental Management*, 4(4): 287-295.

Petak, W.J. (1981). "Environmental Management: A Systems Approach." *Environmental Management*, 5(3): 213-224.

Petrovic, W.M. (1976). "An Economic Analysis of Municipal Solid Waste Collection." unpublished Ph.D. Dissertation, Indiana University, Bloomington.

Quon, J.E., Tanaka, M., and Charnes, A. (1968). "Refuse Quantities and Frequency of Service." *J. of the Sanitary Engineering Division (ASCE)*, 94(SA2): 403-420.

Quon, J.E., Tanaka, M., and Wersan, S.J. (1969). "Simulation Model of Refuse Collection Policies." *J. of the Sanitary Engineering Division (ASCE)*, 95(SA3): 575-592.

Quon, J.E., Martens, R.R., and Tanaka, M. (1970). "Efficiency of Refuse Collection Crews." *J. of the Sanitary Engineering Division (ASCE)*, 96(SA2): 437-453.

Raeth, P.G. (1988). "Two PC-Based Expert System Shells for the First-Time Developer." *Computer*, 21(11): 73-81.

Rao, D.N. (1975). "A Dynamic Model for Optimal Planning of Regional Solid Waste Management." unpublished Ph.D. Dissertation, Clarkson College of Technology, Potsdam, New York.

Resource Integration Systems Ltd. (1987). Recycling Technology Manual. Produced for the Recycling Advisory Committee, Hamilton, Ontario.

ReVelle, C., Marks, D., and Liebman, J.C. (1970). "An Analysis of Private and Public Sector Location Models." *Management Science*, 16(11): 692-707.

Rhyner, C.R., and Wenger, R.B. (1986). "Capital Costs of Resource Recovery Facilities in the U.S.A." *Waste Management & Research*, 4(3): 321-326.

Rich, G.A. (1990). "Environmental Software Review." *Pollution Engineering*, 22(1): 70-97.

Rogers, P.P., and Fiering, M.B. (1986). "Use of Systems Analysis in Water Management." *Water Resources Research*, 22(9): 146S-158S.

Rolston, D.W. (1988). Principles of Artificial Intelligence and Expert Systems Development. McGraw-Hill Book Company, Toronto.

Rouhani, S., and Kangari, R. (1987). "Landfill Site Selection: A Microcomputer Expert System." *Microcomputers in Civil Engineering*, 2: 47-53.

Rushbrook, P. (1987). "The Benefits of Forward Planning and the Role of Computer Assistance." presented at the HARBINGER Symposium, Llandrindod Wells, UK, June 2, 1987.

Ruth, B.E., Degner, J.D., and Brooks, H.K. (1980). "Sanitary Landfill Site Selection by Remote Sensing." *Transportation Engineering J. (ASCE)*, 106(TE6): 661-673.

Schibuola, S., and Byer, P.H. (1991). "Use of Knowledge-Based Systems for the Review of Environmental Assessments." *Environmental Impact Assessment Review*, 11: 11-27.

Schwartz, S.I., McBride, R.A., and Powell, R.L. (1989). "Models for Aiding Hazardous Waste Facility Siting Decisions." *J. of Environmental Systems*, 18(2): 97-122.

Seo, F., and Sakawa, M. (1979). "A Methodology for Environmental Systems Management: Dynamic Application of the Nested Lagrangian Multiplier Method." *IEEE Trans. on Systems, Man, and Cybernetics*, 9(12): 794-805.

Shimizu, Y. (1981). "Optimization of Radioactive Waste Management System by Application of Multiobjective Linear Programming." *J. of Nuclear Science and Technology*, 18(10): 773-784.

Shimizu, Y. (1983). "Multiobjective Optimization for Expansion Planning of Rad-Waste Management System." *J. of Nuclear Science and Technology*, 20(9): 781-783.

Simonovic, S.P., and Savic, D.A. (1989). "Intelligent Decision Support and Reservoir Management and Operation", *J. of Computing in Civil Engineering (ASCE)*, 3(3): 17-22.

Smith, D.G. (1989). "A Comprehensive Costing Methodology for the Assessment of Municipal Solid Waste Management Alternatives." unpublished Master of Engineering Project Report, McMaster University, Hamilton, Ontario.

Statistics Canada (1992). Profile of Census Tracts in Winnipeg - Part A. Ottawa: Industry, Science and Technology Canada, 1992. 1991 Census of Canada. Catalogue No. 95-360.

Sobral, M.M., Hipel, K.W., and Farquhar, G.J. (1981). "A Multi-criteria Model for Solid Waste Management." *J. of Environmental Management*, 12(2): 97-110.

Sushil, and Vrat, P. (1989). "Waste Management Policy Analysis and Growth Monitoring: An Integrated Approach to Perspective Planning." *Int. J. of Systems Science*, 20(6): 907-926.

Tanaka, M. (1970). "A Linear Programming Model for Solid Wastes Management." unpublished Ph.D. Dissertation, Northwestern University, Evanston, Illinois.

Thomas, B., Tamblyn, D., and Baetz, B.W. (1990). "Expert Systems in Municipal Solid Waste Management Planning." *J. of Urban Planning and Development (ASCE)*, **116**(3): 150-155.

Truitt, M.M., Liebman, J.C., and Kruse, C.W. (1969). "Simulation Model of Urban Refuse Collection." *J. of the Sanitary Engineering Division (ASCE)*, 95(SA2): 289-298.

Turban, E. (1988). Decision Support and Expert Systems: Managerial Perspective. Macmillan Publishing Co., New York.

Turban, E., and Watkins, P.R. (1986). "Integrating Expert Systems and Decision Support Systems." *MIS Quarterly*, **10**: 121-136.

Vigil, S.A., Zevely, J.A., and Yeaman, R. (1987). "Microcomputer Model for Solid Waste Planning." *Public Works*, 118(2): 42-45.

Wahi, P.N., and Peterson, T.I. (1972). "Management Science and Gaming in Waste Management." *J. of the Sanitary Engineering Division (ASCE)*, 98(SA5): 693-706.

Walker, W.E. (1976). "A Heuristic Adjacent Extreme Point Algorithm for the Fixed Charge Problem." *Management Science*, 22(5): 587-596.

Waterman, D.A. (1986). A Guide to Expert Systems. Addison-Wesley Publishing Company, Don Mills, Ontario.

Wenger, R.B., and Cruz-Uribe, B.W. (1990). "Mathematical Models in Solid Waste Management: A Survey." presented at the Joint Meeting - TIMS/ORSA, Las Vegas, May, 1990.

Wenger, R.B., and Rhyner, C.R. (1972). "Evaluation of Alternatives for Solid Waste Systems." *J. of Environmental Systems*, 2(2): 89-108.

Wilson, D.C. (1977). "Strategy Evaluation in Planning of Waste Management to Land - A Critical Review of the Literature." *Applied Mathematical Modelling*, 1(4): 205-217.

Wilson, D.C. (1981). Waste Management: Planning, Evaluation, Technologies. Oxford University Press, New York.

Wilson, D.C., Pugh, M.P, Bradley, V.H., and Hoare, R.W.M. (1984). "The Harwell Waste Management Model and Its Development in Hong Kong." presented at the International Solid Wastes and Public Cleansing Association Congress, Philadelphia, Pennsylvania, Sept. 15-20, 1984.

Wright, W.E. (1975). "Application of Stochastic Decision Models to Solid Waste Management." unpublished Ph.D. Dissertation, North Texas State University.

Yaffe, H.J. (1974). "A Model for Optimal Operation and Design of Solid Waste Transfer Stations." *Transportation Science*, 8(3): 265-306.

Yale, W.W. (1978). "The Design of Solid Waste Systems: An Application of Geometric Programming to Problems in Municipal Solid Waste Management." unpublished Ph.D. Dissertation, Lehigh University, Bethlehem, Pennsylvania.

Zeiss, C.A., and Atwater, J. (1987). "Waste Facilities in Residential Communities: Impacts and Acceptance." *J. of Urban Planning and Development (ASCE)*, 113(1): 19-34.

Zeiss, C.A., and Atwater, J. (1989). "Waste Facility Impacts on Residential Property Values." *J. of Urban Planning and Development (ASCE)*, 115(2): 64-80.

APPENDIX A

Copies of the technical surveys sent to waste management professionals working in municipalities and consulting firms

TECHNICAL SURVEY

(MUNICIPALITIES)

Municipal Solid Waste Management and Planning

- Techniques and Waste System Modelling Tools

1. What is the current population serviced, and an estimate of municipal solid waste (MSW) quantities within your waste management system?

2. Data collection:

   What data, related to solid waste generation, collection and disposal, are collected, and on what temporal basis (eg., individual truckload, hourly, daily, etc.)?

3. To what extent are recycling, composting and waste incineration utilized as waste management alternatives? How have these activities affected the waste management decision making process? How have they affected landfilling (either on a qualitative or a quantitative basis)?

4. At present, what techniques and/or tools are used for planning for the efficient transportation, storage and transfer of waste materials (eg., simulation models, statistical analyses, expert systems, etc.)?

continued on back ...

5. Presently, what tools are used in the design of landfills (for example, liner design, or gas and leachate collection design)? If consultants are responsible for this activity, are you aware of what models or software packages they utilize?

6. Are decisions regarding the collection and disposal of MSW made in isolation, or do the techniques and tools allow for the integrated modelling of these components?

7. Regarding the planning for new waste management facilities, what approaches are used for determining the: 1) types of facilities; 2) potential locations; 3) facility capacities (eg., graphical or statistical methods, computer modelling, etc.)? Please be specific with regard to tools or software used, if any.

8. What do you see as the major deficiencies in the current solid waste management and planning process? Do you have any suggestions for management and planning tools which might aid in the decision making process?

* Please return in the attached envelope.

Name:
Address:
Phone:

Many thanks again for all your help!

TECHNICAL SURVEY

Municipal Solid Waste Management and Planning
- Techniques and Waste System Modelling Tools

(CONSULTING FIRMS)

1. What types of solid waste management and planning projects has your company been involved in? (e.g. public sector, industrial waste management). What data collection is required in connection with such projects?

2. At present, what techniques and/or tools are used for planning for the efficient transportation, storage and transfer of waste materials (eg., simulation models, statistical analyses, expert systems, etc.)?

3. Presently, what tools are used in the design of landfills (for example, liner design, or gas and leachate collection design)?

4. (a) Are decisions regarding the collection and disposal of municipal solid waste made in isolation, or do the techniques and tools allow for the integrated modelling of these components?

continued on back ...

4. (b) Are recycling, composting and waste incineration included in computer programs designed for solid waste management and planning? How are the effects of these activities on landfilling quantified?

5. Regarding the planning for new waste management facilities, what approaches are used for determining the: 1) types of facilities; 2) potential locations; 3) facility capacities (eg., graphical or statistical methods, computer modelling, etc.)? Please be specific with regard to tools or software used, if any.

6. What do you see as the major deficiencies in the current solid waste management and planning process? Do you have any suggestions for management and planning tools which might aid in the decision making process?

* Please return in the attached envelope.

Name:
Address:
Phone:

Many thanks again for all your help!

APPENDIX B

A listing of the source separation drop-off composting program design knowledge-based system component of the prototype decision support system (STEP 3)

C_DROP.KBS -> Design of drop-off composting programs

```
RUNTIME;
ACTIONS
LOADFACTS c:\es\c_parms
LOADFACTS c:\es\data2
FIND dropoff_considered
WOPEN 9,4,9,12,61,6
ACTIVE 9
DISPLAY "
        DROP-OFF COMPOSTING PROGRAM DESIGN
  The main considerations for the design of a drop-off
  composting program are:
    - the expected scope of the program - participation
    - the cost of the program
    - expected waste reduction impact on the waste stream ~ "
WCLOSE 9
WOPEN 9,4,9,11,61,4
ACTIVE 9
DISPLAY "                        NOTE !!
   If you are expanding a program as opposed to designing
   one from scratch, simply enter current values for the
   requested program parameters, eg., number of eligible
   households at start of program. The data will then be
   transferred to a worksheet where the program scope can
   be increased and costs and waste diversions calculated. ~ "
WCLOSE 9
FIND admin_cost
FIND program_design_cost
COLOR = 14
DISPLAY "
> > > Please wait, parameters being transferred to worksheet (3min)!"
COLOR = 0
PWKS acceptable_mat, f5, c:\es\drop
PWKS inflation_rate, f6, c:\es\drop
PWKS interest_rate, f7, c:\es\drop
PWKS admin_cost, f8, c:\es\drop
PWKS program_design_cost, f9, c:\es\drop
CLS
program = sfd
FIND sfd_design
program = mfd
FIND mfd_design
program = ici
FIND ici_design
CLS;

RULE 1
IF    mfd_dropoff = no
AND   sfd_dropoff = no
AND   ici_dropoff = no
THEN  dropoff_considered = no
      CHAIN c_curb;
RULE 2
IF    sfd_dropoff = yes
```

```
OR   mfd_dropoff = yes
OR   ici_dropoff = yes
THEN dropoff_considered = yes;
RULE 3
IF   program = sfd
AND  sfd_dropoff = yes
THEN WOPEN 9,6,9,6,60,6
     ACTIVE 9
     DISPLAY "
          DROP-OFF COMPOSTING PROGRAM DESIGN
           FOR THE SINGLE FAMILY DWELLINGS ~"
     WCLOSE 9
     FIND sfd_dropoff_program
     WOPEN 3,2,8,18,67,6
     ACTIVE 3
     DISPLAY "
                    THE END OF THE
             DESIGN OF THE COMPOSTING PROGRAM
                FOR SINGLE FAMILY DWELLINGS
 NOTE: all numerical results - cost estimates, etc. have been
      transferred to the Lotus spreadsheet: DROP.WK1.
   You can now access that worksheet and make adjustments to
   program parameters if you are not considering the MFD or
   ICI sectors, otherwise you can access the worksheet after
   initial design is done for these sectors.
   Activate C_CURB.KBS after finished with this worksheet. ~"
     WCLOSE 3
     sfd_design = completed;
RULE 4
IF   program = sfd
AND  sfd_dropoff = no
THEN eligible_sfd_hhlds = 0
     sfd_start_up_year = 0
     sfd_participation_rate = 0
     sfd_ad_cost = 0
     COLOR = 14
     DISPLAY "
>>> Please wait, parameters being transferred to worksheet (2min)!"
     COLOR = 0
     PWKS sfd_participation_rate, F15, c:\es\drop
     PWKS eligible_sfd_hhlds, F16, c:\es\drop
     PWKS sfd_start_up_year, F12, c:\es\drop
     PWKS sfd_ad_cost, F13, c:\es\drop
     sfd_design = completed;
RULE 5
IF   program = mfd
AND  mfd_dropoff = yes
THEN CLS
     WOPEN 9,6,9,6,60,6
     ACTIVE 9
     DISPLAY "
          DROP-OFF COMPOSTING PROGRAM DESIGN
          FOR THE MULTIPLE FAMILY DWELLINGS ~"
     WCLOSE 9
     FIND mfd_dropoff_program
```

```
     WOPEN 3,3,8,17,67,6
     ACTIVE 3
     DISPLAY "
                    THE END OF THE
            DESIGN OF THE COMPOSTING PROGRAM
               FOR MULTIPLE FAMILY DWELLINGS
 NOTE: all numerical results - cost estimates, etc. have been
       transferred to the Lotus spreadsheet: DROP.WK1.
   You can now access that worksheet and make adjustments to
   program parameters if you are not considering the ICI sector
   otherwise you can access the worksheet after initial design
   is done for that sector.
   Activate C_CURB.KBS after finished with this worksheet. ~"
     WCLOSE 3
     mfd_design = completed;
RULE 6
IF    program = mfd
AND   mfd_dropoff = no
THEN  eligible_mfd_hhlds = 0
     mfd_start_up_year = 0
     mfd_participation_rate = 0
     mfd_ad_cost = 0
     COLOR = 14
     DISPLAY "
> > > Please wait, parameters being transferred to worksheet (2min)!"
     COLOR = 0
     PWKS mfd_participation_rate, F122, c:\es\drop
     PWKS eligible_mfd_hhlds, F123, c:\es\drop
     PWKS mfd_start_up_year, F119, c:\es\drop
     PWKS mfd_ad_cost, F125, c:\es\drop
     mfd_design = completed;
RULE 7
IF    program = ici
AND   ici_dropoff = yes
THEN  CLS
     WOPEN 9,6,9,6,60,6
     ACTIVE 9
     DISPLAY "
         DROP-OFF COMPOSTING PROGRAM DESIGN
               FOR THE ICI SECTOR ~"
     WCLOSE 9
     FIND ici_dropoff_program
     WOPEN 3,2,8,17,67,6
     ACTIVE 3
     DISPLAY "
                    THE END OF THE
            DESIGN OF THE COMPOSTING PROGRAM
                   FOR THE ICI SECTOR
 NOTE: all numerical results - cost estimates, etc. have been
       transferred to the Lotus spreadsheet: DROP.WK1.
   You can now access that worksheet and make adjustments to
   program parameters.
   Activate C_CURB.KBS after finished with this worksheet. ~"
     WCLOSE 3
     ici_design = completed;
```

```
RULE 8
IF   program = ici
AND   ici_dropoff = no
THEN  eligible_sites = 0
     ici_start_up_year = 0
     ici_participation_rate = 0
     ici_ad_cost = 0
     COLOR = 14
     DISPLAY "
> > > Please wait, parameters being transferred to worksheet (3min)!"
     COLOR = 0
     PWKS eligible_sites, F229, c:\es\drop
     PWKS ici_participation_rate, F228, c:\es\drop
     PWKS ici_start_up_year, F226, c:\es\drop
     PWKS ici_ad_cost, F227, c:\es\drop
     ici_design = completed;
RULE 9
IF   program = sfd
AND   sfd_dropoff = yes
AND   source_separation = mandatory
THEN  FIND step_1_drop
     FIND eligible_sfd_hhlds
     FIND sfd_start_up_year
     FIND sfd_participation_advice
     FIND sfd_participation_rate
     FIND step_2
     FIND sfd_dropoff_costs
     FIND step_3
     FIND sfd_removal
     sfd_dropoff_program = designed;
RULE 10
IF   program = sfd
AND   sfd_dropoff = yes
AND   source_separation = voluntary
THEN  FIND step_1_drop
     FIND eligible_sfd_hhlds
     FIND sfd_start_up_year
     FIND sfd_participation_advice
     FIND sfd_participation_rate
     FIND step_2
     FIND sfd_dropoff_costs
     FIND step_3
     FIND sfd_removal
     sfd_dropoff_program = designed;
RULE 11
IF   program = mfd
AND   mfd_dropoff = yes
AND   source_separation = mandatory
THEN  FIND step_1_drop
     FIND eligible_mfd_hhlds
     ave_num_units = (total_mfd_hhlds/total_mfds)
     FIND ave_units
     FIND mfd_start_up_year
     FIND mfd_participation_advice
     FIND mfd_participation_rate
```

```
    FIND step_2
    FIND mfd_dropoff_costs
    FIND step_3
    FIND mfd_removal
    mfd_dropoff_program = designed;
RULE 12
IF   program = mfd
AND  mfd_dropoff = yes
AND  source_separation = voluntary
THEN  FIND step_1_drop
    FIND eligible_mfd_hhlds
    ave_num_units = (total_mfd_hhlds/total_mfds)
    FIND ave_units
    FIND mfd_start_up_year
    FIND mfd_participation_advice
    FIND mfd_participation_rate
    FIND step_2
    FIND mfd_dropoff_costs
    FIND step_3
    FIND mfd_removal
    mfd_dropoff_program = designed;
RULE 13
IF   program = ici
AND  ici_dropoff = yes
AND  source_separation = mandatory
THEN  FIND step_1_drop
    FIND eligible_sites
    FIND ici_start_up_year
    FIND ici_participation_advice
    FIND ici_participation_rate
    FIND step_2
    FIND ici_dropoff_costs
    FIND step_3
    FIND ici_removal
    ici_dropoff_program = designed;
RULE 14
IF   program = ici
AND  ici_dropoff = yes
AND  source_separation = voluntary
THEN  FIND step_1_drop
    FIND eligible_sites
    FIND ici_start_up_year
    FIND ici_participation_advice
    FIND ici_participation_rate
    FIND step_2
    FIND ici_dropoff_costs
    FIND step_3
    FIND ici_removal
    ici_dropoff_program = designed;
RULE 15
IF   dropoff_considered = yes
THEN  WOPEN 1,3,3,7,74,7
    ACTIVE 1
    DISPLAY "
  STEP 1: Determining the scope for the drop-off composting program."
```

```
    WOPEN 2,7,3,5,74,3
    ACTIVE 2
    DISPLAY "
 The scope of the drop-off program is determined by the number of SFD
 or MFD households or ICI sites that will be eligible for the program,
 and the expected participation rate in the program. ~ "
    WCLOSE 1
    WCLOSE 2
    step_1_drop = found;
RULE 16
IF    program = sfd
AND   sfd_participation_rate_advice = yes
AND   source_separation = voluntary
THEN  WOPEN 2,2,2,20,75,5
    ACTIVE 2
    COLOR = 16
    DISPLAY "
        RECOMMENDATION:   VOLUNTARY PARTICIPATION RATES"
    COLOR = 0
    DISPLAY "
 The following suggestion for participation rates for voluntary
 drop-off composting programs organized by municipal government were
 obtained from composting literature and recycling program literature.
 Where the numbers refer to voluntary recycling program experience, it
 will be indicated and numbers should be used with caution. They have
 been found to vary depending on the type of residential area - for
 example the economic status or education level of residents.
 * Crow Wing County, MN had 5-10% of residents using drop-off sites.
 * recycling drop-off for residents self-hauling waste achieving 82%
 * Biocycle, 1991 reported a range of 10-30% for drop-off recycling
   programs in the US. ~ "
    WCLOSE 2
    sfd_participation_advice = found;
RULE 17
IF    program = sfd
AND   sfd_participation_rate_advice = yes
AND   source_separation = mandatory
THEN  WOPEN 2,2,2,20,75,5
    ACTIVE 2
    COLOR = 16
    DISPLAY "
        RECOMMENDATION:   MANDATORY PARTICIPATION RATES"
    COLOR = 0
    DISPLAY "
 The following suggestion for participation rates for mandatory
 drop-off composting programs organized by municipal government were
 obtained from composting literature and recycling program literature.
 Where the numbers refer to mandatory recycling program experience, it
 will be indicated and numbers should be used with caution. They have
 been found to vary depending on the type of residential area - for
 example the economic status or education level of residents.
 * recycling drop-off for rural residents of US community self-hauling
   waste achieving 90% ~ "
    WCLOSE 2
    sfd_participation_advice = found;
```

```
RULE 18
IF   program = sfd
AND  sfd_participation_rate_advice = no
THEN sfd_participation_advice = found;
RULE 19
IF   program = mfd
AND  mfd_participation_rate_advice = yes
AND  source_separation = voluntary
THEN  WOPEN 2,2,2,20,75,5
     ACTIVE 2
     COLOR = 16
     DISPLAY "
          RECOMMENDATION:   VOLUNTARY PARTICIPATION RATES"
     COLOR = 0
     DISPLAY "
  The following suggestion for participation rates for voluntary
  drop-off composting programs organized by municipal government were
  obtained from composting literature and recycling program literature.
  Where the numbers refer to voluntary recycling program experience, it
  will be indicated and numbers should be used with caution. They have
  been found to vary depending on the type of residential area - for
  example the economic status or education level of residents. -- "
     DISPLAY "
  The following results have been reported:
  * Crow Wing County, MN had 5-10% of residents using drop-off sites.
  * recycling drop-off for residents self-hauling waste achieving 82%
  * Biocycle, 1991 reported a range of 10-30% for drop-off recycling
    programs in the US. -- "
     WCLOSE 2
     mfd_participation_advice = found;
RULE 20
IF   program = mfd
AND  mfd_participation_rate_advice = yes
AND  source_separation = mandatory
THEN  WOPEN 2,2,2,20,75,5
     ACTIVE 2
     COLOR = 16
     DISPLAY "
          RECOMMENDATION:   MANDATORY PARTICIPATION RATES"
     COLOR = 0
     DISPLAY "
  The following suggestion for participation rates for mandatory
  drop-off composting programs organized by municipal government were
  obtained from composting literature and recycling program literature.
  Where the numbers refer to mandatory recycling program experience, it
  will be indicated and numbers should be used with caution. They have
  been found to vary depending on the type of residential area - for
  example the economic status or education level of residents.

  As a result, it is recommended that community-specific data be
  generated through a survey of residents (either all or a portion
  thereof) as soon as possible.  A good estimate of the impact of
  drop-off composting will also assist in tracking residential waste
  and producing a more realistic estimate of waste generation rates.
  * recycling drop-off for rural residents of US community self-hauling
```

```
   waste achieving 90% ~ "
     WCLOSE 2
     mfd_participation_advice = found;
RULE 21
IF    program = mfd
AND   mfd_participation_rate_advice = no
THEN  mfd_participation_advice = found;
RULE 22
IF    program = ici
AND   ici_participation_rate_advice = yes
THEN  WOPEN 2,2,2,15,75,5
     ACTIVE 2
     COLOR = 16
     DISPLAY "
          RECOMMENDATION:  ICI PARTICIPATION RATES"
     COLOR = 0
     DISPLAY "
  There was no indication in literature regarding drop-off of
  compostable materials by ICI generators, either voluntarily or
  mandated by law.

  As a result, it is recommended that community-specific data be
  generated through a survey of generators (either all or a portion
  thereof) as soon as possible.  A good estimate of the impact of
  drop-off composting will also assist in tracking ICI waste and
  producing a more realistic estimate of waste generation rates. ~ "
     WCLOSE 2
     ici_participation_advice = found;
RULE 23
IF    program = ici
AND   ici_participation_rate_advice = no
THEN  ici_participation_advice = found;
RULE 24
IF    dropoff_considered = yes
THEN  WOPEN 1,3,3,7,74,7
     ACTIVE 1
     DISPLAY "
 STEP 2: Determining the annual and present value costs of the drop-off
      composting program."
     WOPEN 3,7,3,11,74,3
     ACTIVE 3
     DISPLAY "
       DATA REQUIREMENTS FOR ECONOMIC ANALYSIS OF A DROP-OFF
                 COMPOSTING PROGRAM
  The following data will be needed for an analysis of the costs of
  a drop-off composting program:
      - advertising and promotion costs
      - administrative costs
      - program design costs ~ "
      WCLOSE 1
      WCLOSE 3
      step_2 = found;
RULE 25
IF    program = sfd
THEN  FIND sfd_ad_cost
```

```
    COLOR = 14
    DISPLAY "
> > > Please wait, program parameters being transferred to worksheet (3min)!"
    COLOR = 0
    PWKS sfd_participation_rate, F15, c:\es\drop
    PWKS eligible_sfd_hhlds, F16, c:\es\drop
    PWKS sfd_start_up_year, F12, c:\es\drop
    PWKS sfd_ad_cost, F13, c:\es\drop
    PWKS sfd_per_hhld, F14, c:\es\drop
    sfd_dropoff_costs = found;
RULE 26
IF    program = mfd
THEN  FIND mfd_ad_cost
    COLOR = 14
    DISPLAY "
> > > Please wait, program parameters being transferred to worksheet (3min)!"
    COLOR = 0
    PWKS mfd_participation_rate, F122, c:\es\drop
    PWKS eligible_mfd_hhlds, F123, c:\es\drop
    PWKS ave_units, F121, c:\es\drop
    PWKS mfd_start_up_year, F119, c:\es\drop
    PWKS mfd_ad_cost, F120, c:\es\drop
    PWKS mfd_per_hhld, f126, c:\es\drop
    mfd_dropoff_costs = found;
RULE 27
IF    program = ici
THEN  FIND ici_ad_cost
    COLOR = 14
    DISPLAY "
> > > Please wait, program parameters being transferred to worksheet (3min)!"
    COLOR = 0
    PWKS eligible_sites, F229, c:\es\drop
    PWKS ici_participation_rate, F228, c:\es\drop
    PWKS ici_start_up_year, F226, c:\es\drop
    PWKS ici_ad_cost, F227, c:\es\drop
    ici_dropoff_costs = found;
RULE 28
IF    dropoff_considered = yes
THEN  WOPEN 1,1,3,5,74,7
    ACTIVE 1
    DISPLAY "
  STEP 3: Determining the material removal levels from the drop-off
        composting program."
    WOPEN 3,5,3,16,74,3
    ACTIVE 3
    DISPLAY "
  Materials that should be targeted are organic materials that can
  be separated from the bulk MSW and for which higher grade uses
  through recycling are not available or feasible (eg.,YARD WASTE,
  FOOD WASTE,CONTAMINATED PAPER).

  The materials that can generally be included are: yard waste,
  all types of food waste, and some types of paper waste - paper
  napkins, paper towel and facial tissue.
```

```
 The materials that generally cannot be included are: inorganics
 - glass, metals, and plastics; facial tissue, paper towel or
 paper napkin contaminated with motor oil, antifreeze, paints,
 turpentine or other hazardous material; and most other paper. ~"
    DISPLAY "
 The potential impact of the program will depend on the number of
 sites participating, the amount of material generators are able
 to capture and prevent from entering their waste stream, and the
 expected continued participation. The estimate of waste reduction
 potential can be calculated by multiplying the quantity of a
 specific compostable present in the residential waste stream by
 the participation and material capture rates.

 Again, you will have an opportunity to adjust parameters and examine
 the 20 year period after the initial design information is provided
 by activating worksheet DROP.WK1. ~"
     WCLOSE 1
     WCLOSE 3
     step_3 = found;
RULE 29
IF    program = sfd
THEN  CLS
     WOPEN 1,4,10,12,60,4
     ACTIVE 1
     COLOR = 16
     DISPLAY "                    NOTE !!"
     COLOR = 0
     DISPLAY "
   This is a reminder that the following materials are
   accepted at the centralized composting facility:
      {acceptable_mat}
    If a compostable is not accepted at the facility
    enter 0 for its material capture rate. ~"
     WCLOSE 1
     COLOR = 15
     FIND sfd_leave_capture
     FIND sfd_yard_capture
     FIND sfd_food_capture
     COLOR = 0
     WCLOSE 1
     COLOR = 14
     DISPLAY "
>>> Please wait, waste reduction data being transferred to worksheet (2min)!"
     COLOR = 0
     PWKS sfd_leave_capture, E53, c:\es\drop
     PWKS sfd_yard_capture, E54, c:\es\drop
     PWKS sfd_food_capture, E55, c:\es\drop
     PWKS num_hhlds, F17, c:\es\drop
     PWKS sfd_growth_rate, F18, c:\es\drop
     sfd_removal = done;
RULE 30
IF    program = mfd
THEN  CLS
     WOPEN 1,4,10,12,60,4
     ACTIVE 1
```

```
    COLOR = 16
    DISPLAY "                    NOTE !!"
    COLOR = 0
    DISPLAY "
  This is a reminder that the following materials are
  accepted at the centralized composting facility:
    {acceptable_mat}
   If a compostable is not accepted at the facility
   enter 0 for its material capture rate. ~"
    WCLOSE 1
    COLOR = 15
    FIND mfd_leave_capture
    FIND mfd_yard_capture
    FIND mfd_food_capture
    COLOR = 0
    WCLOSE 1
    COLOR = 14
    DISPLAY "
> > > Please wait, waste reduction data being transferred to worksheet (2min)!"
    COLOR = 0
    PWKS mfd_leave_capture, E159, c:\es\drop
    PWKS mfd_yard_capture, E160, c:\es\drop
    PWKS mfd_food_capture, E161, c:\es\drop
    PWKS total_mfds, F124, c:\es\drop
    PWKS total_mfd_hhlds, F125, c:\es\drop
    PWKS mfd_growth_rate, F126, c:\es\drop
    mfd_removal = done;
RULE 31
IF    program = ici
THEN  CLS
    WOPEN 1,4,10,12,60,4
    ACTIVE 1
    COLOR = 16
    DISPLAY "                    NOTE !!"
    COLOR = 0
    DISPLAY "
  This is a reminder that the following materials are
  accepted at the centralized composting facility:
    {acceptable_mat}
   If a compostable is not accepted at the facility
   enter 0 for its material capture rate. ~"
    WCLOSE 1
    COLOR = 15
    FIND ici_leave_capture
    FIND ici_other_yard_capture
    FIND %_leaves
ici_yard_capture=((1-(%_leaves/100))*ici_other_yard_capture+(%_leaves/100*ici_leave_capture))
    FIND ici_food_capture
    COLOR = 0
    WCLOSE 1
    DISPLAY "
> > > Please wait, waste reduction data being transferred to worksheet (2min)!"
    COLOR = 0
    PWKS ici_yard_capture, E265, c:\es\drop
    PWKS ici_food_capture, E266, c:\es\drop
```

```
    ici_removal = done;

ASK sfd_leave_capture: "
 What is the expected material capture rate of leaves from the waste
 stream as a percentage of the leaves, ENTER 0 if not accepted ?";
ASK mfd_leave_capture: "
 What is the expected material capture rate of leaves from the waste
 stream as a percentage of the leaves, ENTER 0 if not accepted ?";
ASK ici_leave_capture: "
 What is the expected material capture rate of leaves from the waste
 stream as a percentage of the leaves, ENTER 0 if not accepted ?";
ASK %_leaves: " What percentage of the yard waste is leaves ?";
ASK sfd_yard_capture: "
 What is the expected material capture rate of the yard waste (excluding
 leaves) from the waste stream as a percentage of the yard waste
 (excluding leaves), ENTER 0 if not accepted ?";
ASK mfd_yard_capture: "
 What is the expected material capture rate of the yard waste (excluding
 leaves) from the waste stream as a percentage of the yard waste
 (excluding leaves), ENTER 0 if not accepted ?";
ASK ici_other_yard_capture: "
 What is the expected material capture rate of the yard waste (excluding
 leaves) from the waste stream as a percentage of the yard waste
 (excluding leaves), ENTER 0 if not accepted ?";
ASK sfd_food_capture: "
 What is the expected material capture rate of food waste from the waste
 stream as a percentage of the food waste, ENTER 0 if not accepted ?";
ASK mfd_food_capture: "
 What is the expected material capture rate of food waste from the waste
 stream as a percentage of the food waste, ENTER 0 if not accepted ?";
ASK ici_food_capture: "
 What is the expected material capture rate of food waste from the waste
 stream as a percentage of the food waste, ENTER 0 if not accepted ?";
ASK sfd_participation_rate_advice:"
 Would you like advice on estimating SFD participation rates?";
CHOICES sfd_participation_rate_advice: yes, no;
ASK mfd_participation_rate_advice:"
 Would you like advice on estimating MFD participation rates?";
CHOICES mfd_participation_rate_advice: yes, no;
ASK ici_participation_rate_advice:"
 Would you like advice on estimating ICI participation rates?";
CHOICES ici_participation_rate_advice: yes, no;
ASK sfd_participation_rate:"
 Enter your estimate of the expected initial rate of participation in the
 SFD drop-off composting program, as a percentage.";
ASK mfd_participation_rate:"
 Enter your estimate of the expected initial rate of participation in the
 MFD drop-off composting program, as a percentage.";
ASK ici_participation_rate:"
 Enter your estimate of the expected initial rate of participation in the
 ICI drop-off composting program, as a percentage.";
ASK eligible_sfd_hhlds: "
 How many of the {num_hhlds} SFD households are eligible for the program
 in its first year (often programs begin with a small pilot project area) ?";
ASK eligible_mfd_hhlds: "
```

```
 How many of the {total_mfd_hhlds} MFD households are eligible for the program
 in its first year (often programs begin with a small pilot project area) ?";
ASK ave_units: "
 What is the average number of units of buildings that will be eligible for
 this program ?
 * reminder:  {small_units} units in the small MFDs
              {large_units} units in the large MFDs
              {ave_num_units} units is the average for all MFDs";
ASK eligible_sites: "
 How many of the {ici_sites} sites are eligible for the program in its first
 year (often programs begin with a small pilot project area) ?";
ASK sfd_start_up_year: "How many years from the present will the SFD program be initiated ?
 * REMINDER: the first year the composting facility will accept material
   is {facility_startup}
 * Enter 0 if expanding an existing program.";
ASK mfd_start_up_year: "
How many years from the present will the MFD program be initiated ?
 * REMINDER: the first year the composting facility will accept material
   is {facility_startup}
 * Enter 0 if expanding an existing program.";
ASK ici_start_up_year: "
 How many years from the present will the ICI program be initiated ?
 * REMINDER: the first year the composting facility will accept material
   is {facility_startup}
 * Enter 0 if expanding an existing program.";
ASK sfd_ad_cost: "
 What is the estimated cost of advertising and promoting the program, as
 $/hhld/yr for the SFDs ?
   -> $0.20/capita has been used for curbside recycling programs;
   -> a Glass Packaging Institute survey of 19 US communities found
      $.10-.75/hhld/yr for ongoing promotion of curbside recycling programs";
ASK mfd_ad_cost: "
 What is the estimated cost of advertising and promoting the program, as
 $/hhld/yr for the MFD program ?
   -> $0.20/capita has been used for curbside recycling programs;
   -> a Glass Packaging Institute survey of 19 US communities found
      $.10-.75/hhld/yr for ongoing promotion of curbside recycling programs";
ASK ici_ad_cost: "
 What is the estimated cost of advertising and promoting the program, as
 $/site/yr for the ICI program ?
   -> $0.20/capita has been used for  curbside recycling programs;
   -> a Glass Packaging Institute survey of 19 US communities found
      $.10-.75/hhld/yr for ongoing promotion of curbside recycling programs";
ASK admin_cost: "
 Enter the yearly cost of administering the drop-off composting program:
 * administrative costs reflect the need to design promotional material,
   and oversee the effect on the waste stream and compliance.";
ASK program_design_cost: "
 What is your estimate of the cost of designing the drop-off composting
 program (or expansion) in current dollars ?";
```

APPENDIX C

A listing of the EFW facility data collection/estimation knowledge-based system component of the prototype decision support system (STEP 5)

FAC_EFW.KBS -> Knowledge base for: Energy-From-Waste Facilities

```
RUNTIME;
ACTIONS
LOADFACTS c:\es\data
LOADFACTS c:\es\optimal
FIND efw
WOPEN 1,4,4,15,72,6
ACTIVE 1
DISPLAY "
              INCINERATION OR ENERGY-FROM-WASTE
                      TECHNOLOGIES
   This component of the decision support system introduces the
   user to different energy-from-waste options for the separation
   of the combustible fraction of mixed waste and burning with or
   without energy recovery - if they wish to include EFW plants in
   their integrated MSW management system. The purpose of this
   component is also to derive estimates for important operational
   and cost parameters for all existing and potential EFW plants
   for use in the facility sizing and waste allocation model. ~"
WCLOSE 1
COLOR = 14
DISPLAY "
 -> Please wait, parameters being transferred to worksheet: FAC_EFW.WK1 !"
COLOR = 0
PWKS interest_rate, e4, c:\es\fac_efw
PWKS inflation_rate, e5, c:\es\fac_efw
PWKS year, e6, c:\es\fac_efw
PWKS exchange_rate, e7, c:\es\fac_efw
CLS
FIND existing
FIND potential
WOPEN 1,2,6,19,68,6
ACTIVE 1
DISPLAY "
              THE END OF THE EXAMINATION OF
             INCINERATION OR ENERGY-FROM-WASTE
                     TECHNOLOGIES
   All parameters for both existing and potential facilities
   have been transferred to FAC_EFW.WK1. These figures can
   then be used to investigate waste allocation and facility
   sizing, location and timing of development issues using the
   MILP model. Within the spreadsheet you will also derive the
   estimates for costs of potential EFW plants if they are to
   be considered.

   Cost and operational parameters will first be collected for
   landfill facilities. Then you will have a chance to examine
   all the facility data worksheets before model formulation
   (if an optimization study is to be done). ~"
 WCLOSE 1
total_efws = (potential_efws+existing_efws)
 SAVEFACTS efw_facs
 CHAIN fac_lf;
```

```
RULE 0
IF    efw_considered = no
THEN  existing_efws = 0
      potential_efws = 0
      total_efws = 0
      SAVEFACTS efw_facs
      CHAIN fac_lf
      efw = found;
RULE 1
IF    existing_fac = yes
THEN  CLS
      WOPEN 1,5,22,5,36,6
      ACTIVE 1
      DISPLAY "
   OPERATING AND COST PARAMETERS
      FOR EXISTING EFW PLANTS ~"
      WCLOSE 1
      X = 1
      FIND fac_name
      WHILEKNOWN fac_name
       CLS
       COLOR = 1
       DISPLAY " EXISTING EFW FACILITY NUMBER {X}: {fac_name}"
       COLOR = 0
       efw_name[X] = (fac_name)
       FIND technology
       tech[X] = (technology)
       FIND capacity
       cap[X] = (capacity)
       RESET capacity
       FIND capacity_utilization
       cap_use[X] = (capacity_utilization)
       RESET capacity_utilization
       FIND expansion_capacity
       expand[X] = (expansion_capacity)
       RESET expansion_capacity
       FIND expansion_cost
       expand$[X] = (expansion_cost)
       RESET expansion_cost
       FIND operating_days
       op_days[X] = (operating_days)
       RESET operating_days
       max_cap[X] = (cap[X]*op_days[X])
       op_cap[X] = (max_cap[X]*cap_use[X])
       FIND operating_cost
       o&m[X] = (operating_cost)
       RESET operating_cost
       FIND tipping_fee
       tip_fee[X] = (tipping_fee)
       RESET tipping_fee
       FIND e_exist
       energy_type[X] = (e_exist)
       RESET e_exist
       FIND energy_revenue_exist
       energy_rev[X] = (energy_revenue_exist)
```

```
    RESET energy_revenue_exist
    FIND rdf_existing
    RESET rdf_existing
    RESET technology
    FIND ferrous
    RESET ferrous
    RESET ferrous_recovered
    FIND volume_reduction
    vol_red[X] = (volume_reduction)
    RESET volume_reduction
    FIND mass_reduction
    mass_red[X] = (mass_reduction)
    RESET mass_reduction
    FIND residuals
    resids[X] = (residuals)
    RESET residuals
    FIND disposal_cost
    disposal[X] = (disposal_cost)
    RESET disposal_cost
    X = (X+1)
    RESET fac_name
    CLS
    FIND fac_name
    END
    existing_efws = (X-1)
    COLOR = 14
    DISPLAY "
-> Please wait, data being transferred to worksheet: FAC_EFW.WK1 (3min)!"
    COLOR = 0
    PWKS existing_efws, e12, c:\es\fac_efw
    PWKS efw_name, e13..i13, c:\es\fac_efw
    PWKS tech, e14..i14, c:\es\fac_efw
    PWKS cap, e15..i15, c:\es\fac_efw
    PWKS max_cap, e16..i16, c:\es\fac_efw
    PWKS op_cap, e17..i17, c:\es\fac_efw
    PWKS cap_use, e18..i18, c:\es\fac_efw
    PWKS op_days, e19..i19, c:\es\fac_efw
    PWKS o&m, e20..i20, c:\es\fac_efw
    PWKS tip_fee, e21..i21, c:\es\fac_efw
    PWKS energy_type, e22..i22, c:\es\fac_efw
    PWKS energy_rev, e23..i23, c:\es\fac_efw
    PWKS rdf_%, e24..i24, c:\es\fac_efw
    PWKS rdf_rev, e25..i25, c:\es\fac_efw
    PWKS ferrous_fac, e26..i26, c:\es\fac_efw
    PWKS ferrous_rev, e27..i27, c:\es\fac_efw
    PWKS vol_red, e28..i28, c:\es\fac_efw
    PWKS mass_red, e29..i29, c:\es\fac_efw
    PWKS resids, e30..i30, c:\es\fac_efw
    PWKS disposal, e31..i31, c:\es\fac_efw
    PWKS expand, e32..i32, c:\es\fac_efw
    PWKS expand$, e33..i33, c:\es\fac_efw
    CLS
    existing = yes;
RULE 2
IF   potential_fac = yes
```

```
THEN  CLS
      WOPEN 1,5,22,5,36,6
      ACTIVE 1
      DISPLAY "
   OPERATING AND COST PARAMETERS
     FOR POTENTIAL EFW PLANTS~"
      WCLOSE 1
      COLOR = 1
      DISPLAY "
 You will be asked to supply information on the potential sites available
 for the construction of an EFW facility: site name, and total available
 area in hectares."
      COLOR = 0
      X = 1
      FIND site_name
      WHILEKNOWN site_name
       efw_site[X] = (site_name)
       FIND site_area
       area_open[X] = (site_area)
       RESET site_area
       RESET site_name
       X = (X+1)
       FIND site_name
      END
      potential_efws = (X-1)
      FIND max_efws
      COLOR = 14
      DISPLAY "
 --> Please wait, data being transferred to worksheet: FAC_EFW.WK1 !"
      COLOR = 0
      PWKS potential_efws, e98, c:\es\fac_efw
      PWKS site, e99..i99, c:\es\fac_efw
      PWKS area_open, e100..i100, c:\es\fac_efw
      PWKS max_efws, e104, c:\es\fac_efw
      CLS
      WOPEN 1,1,2,20,75,3
      ACTIVE 1
      DISPLAY "
                    MAIN CONSIDERATIONS
   AIR POLLUTION CONTROL:
   State-of-the-art combustion facilities are equipped with pollution
   control equipment that greatly reduce air emissions.  These
   measures include:
   - combustion control -> proper design, operation and maintenance,
     in particular proper combustion conditions, limit the formation
     of dioxins and furans
   - particulate matter control -> using fabric filters referred to
     as a baghouse or electrostatic precipitators that use voltage
     to charge and remove particles
   - acid gas control -> sometimes referred to as scrubbers they use
     a lime spray or a dry sorbent to remove acid gas~"
      CLS
      DISPLAY "
   ASH MANAGEMENT:
   Residual ash is produced during normal operations that consists of
```

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the inorganic, noncombustible waste fraction and fly ash and bottom
ash from the air pollution control systems. Bottom ash is comprised
of the noncombustible material passing out of the combustion chamber.
It is usually collected by conveyor and cooled by some type of water
quench. It constitutes 75 to 90% of all ash produced depending on
the technology used. Fly ash is a lighter material suspended in the
flue gas and collected in the air pollution control equipment. ~ "
  DISPLAY "
There is concern that this ash, particularly fly ash contains
contaminants such as heavy metals which may leach from the ash, and
the landfill should have approval to accept the materials. As
research continues, there is the possibility that ash or at least
fly ash will no longer be classified as non-hazardous and will be
treated as a hazardous waste. This would significantly increase
handling and off-site disposal costs. Approximately 10% by volume
of the materials combusted will be left as ash residue. ~ "
  DISPLAY "
RESIDUALS DISPOSAL COSTS:
The cost represents 11-31% of reported O&M costs, but may be
substantially higher if treatment is required prior to disposal as
fly ash may be considered hazardous and also potentially the bottom ash. ~ "
  DISPLAY "
FACILITY SIZING
EFW plants are expensive to build and some economy-of-scale may be
experienced if a large capacity is developed. However, then one
runs the risk of tying up capital and affecting the ability for
proper combustion and economic viability due to over sizing. If
undersized, trucks may have to be re-routed to potentially distant
landfills. Thus, flow controls are often set by private owners or
operators to ensure a minimum waste stream, based on the capacity
of the facility. For public facilities, this problem may be dealt
with by adjusting the waste streams for current and future source
separation (recycling and composting) and waste reduction and not
allowing a facility to be built unless the waste stream received is
always within a certain fraction of design capacity. One may also
wish to set a minimum on the capacity of the facility based on the
technical viability of the technology, eg. units begin at 100 t/d. ~ "
  DISPLAY "
It is important to know seasonal peaks for design of throughput
rates and storage requirements. It is extremely important not to
overestimate the available waste tonnage as it affects revenues
(energy and tipping fees). ~ "
  WCLOSE 1
  WOPEN 1,2,2,19,75,4
  ACTIVE 1
  COLOR = 16
  DISPLAY "                     NOTE !!"
  COLOR = 0
  DISPLAY "
KEY QUESTIONS TO ASK WHEN CONSIDERING ENERGY-FROM-WASTE
TECHNOLOGY AS A WASTE MANAGEMENT OPTION:
1. Is sufficient solid waste available to support an energy-from-waste
  project and can it be committed to the facility in the long term ?
2. Do realistic long-term markets exist for the energy produced ?
3. Are sites and technologies available for deriving energy from the
```

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  incineration of municipal solid waste which are both environmentally
  sound and politically acceptable ?
4. Is the project financially feasible ?
5. How does an energy-from-waste facility compare to landfilling and
  other non-recovery disposal alternatives ?
6. Do suitable sites (often zoned for industrial development) exist
  close to generation sources and with good road/utility access ? ~ "
   WCLOSE 1
   WOPEN 1,1,3,20,74,3
   ACTIVE 1
   DISPLAY "
             INTERRELATIONSHIPS AMONG PROGRAMS
The encouragement of waste reduction and re-use will no doubt affect
an energy-from-waste facility.  They are compatible activities, but
one must use the revised quantity and composition estimates based on
predicted effects of these efforts.  For certain materials, such as
soiled paper and plastics that are presently non-recyclable but have
high energy content, incineration may be a viable option particularly
if there is energy generation and possible revenue generation.  As
well these plants usually recover recyclables from the waste stream,
primarily oversized items and ferrous metals. ~ "
   DISPLAY "
In addition, setting aside recyclables and/or compostables through
source separation programs will also impact the quantity and
composition (and thus energy recovery potential) of the waste stream
available for the energy-from-waste facility.  In certain cases, it
is a beneficial interrelationship, as glass, metals and organics
which cause trouble for incineration may be removed prior to the
incineration process. ~ "
   DISPLAY "
The economics of energy-from-waste projects are sensitive to changes
in throughput as it affects revenues from tipping fees and especially
energy sales.  It is thus extremely important not to overestimate the
tonnage available.  Compositional analysis is used to determine the
recoverable quantities of energy and thus revenues.

This is why you were first asked to make predictions for both waste
quantity and composition taking waste reduction/re-use into account.
Then you provided information on existing and/or planned recycling
and composting programs to allow adjustment of the quantity and
composition estimates. ~ "
   DISPLAY "
However, the material separation done at these plants is usually
limited (more separation is done in MIXED MSW PROCESSING PLANTS)
so there may still be a large quantity of materials that burn poorly
such as glass, metals and organics remaining in the incinerated
waste stream.  There is the possibility to recover more materials
through more advanced separation techniques, primarily done to
produce refuse-derived-fuel (RDF) that can be used in boilers as an
alternative fuel source.  To produce adequate RDF separation is more
advanced.  The mixed MSW processing plants also separate recyclables
and may produce a combustible stream but differ as they also provide
for the composting of organics recovered. ~ "
   WCLOSE 1
   WOPEN 1,3,2,14,75,3
```

```
   ACTIVE 1
   DISPLAY "
             PRICING ENERGY DERIVED FROM WASTE
On the basis of phone calls to potential energy purchasers, ascertain
current and future fuel costs to derive estimates of revenue expected
from refuse-based energy, both steam and electricity.

Steam and/or electricity can be recovered.  Steam customers should
be within 2.5-3.5 km from the plant.  Steam plants will have lower
development costs (less sophisticated turbine); higher net operating
cost (lower revenue).  Utility contracts are generally more reliable
than steam contracts. ~ "
   WCLOSE 1
   WOPEN 1,1,3,20,74,3
   ACTIVE 1
   DISPLAY "
               EFW FACILITY TECHNOLOGIES
 One must consider the advantages and disadvantages of available EFW
 technologies, along with their availability, capabilities and the
 appropriateness.  Information gathered from literature is provided.
 In addition, calls can be made to facility managers, manufacturers
 and suppliers of equipment.

 The type of technology used for an EFW facility is dependent on
 the characteristics and volume of the waste.          A number of
 technologies are available, but the following are most commonly used
 in North America:
        1) Mass Burn or Direct Combustion
        2) Two-Stage Combustion/Modular Incineration
        3) Semi-Suspension Incineration.  ~ "
   CLS
   DISPLAY "
1. SITE-BUILT MASS BURN OR DIRECT COMBUSTION:
Mass burn systems combust waste without any pre-processing except
the removal of large objects.  These facilities have the longest
history of resource recovery technologies.  Waste is continually fed
on moving grates into a single combustion chamber, where the entire
combustion process occurs.  Steam is produced, and energy extraction
efficiency is generally 50-60%.  They usually have 2 or 3 combustion
units ranging in capacity from 50 to 900 tonnes/d.  It is most common
for mid to large-size facilities, about 200-3000 tonnes/d.  They
usually require upwards of 300 to 500 tonnes/d capacity to be cost
effective.  Because of their larger size they are field fabricated or
site built.  Construction times are in the range of 24-36 months. ~ "
    DISPLAY "
The estimated life span is normally in excess of 20 years.  Generally,
refractory-lined or waterwall combustion chambers are used which have
lower operating costs, higher heat recovery efficiencies and longer
useful lives than modular systems (assuming waterwall units) ~ "
    DISPLAY "
i) refractory-lined incineration:
   - furnace coated with a temperature resistant material to decrease
     heat transfer to outside areas and protects the furnace
   - to cool the walls requires large volumes of excess combustion
     air so emission control costs are generally higher than for
```

waterwall incinerators and results in low temperature steam
best suited for district heating and industrial process use
but less useful for electricity generation

- eg. the now closed Metro Toronto Commissioners Street facility – "

DISPLAY "

ii) waterwall incineration:

- furnaces are lined with tubes filled with circulating water which acts as a coolant for the walls and a heat recovery medium
- higher heat recovery efficiency than refractory-lined with generated steam marketed directly or passed through a turbine to produce electricity
- they require less air for combustion, and thus less pollution control equipment

The EPA (1989) reports that all new systems use waterwall combustion chambers for energy recovery, while older facilities may have refractory-lined combustion chambers with no energy recovery. There are Canadian plants in: St. David, PQ (80 tonne/d); Commissioner St., Toronto (3X193 tonne/d units); Quebec City, PQ (4X230 tonne/d units) They have been recommended for capacities of 500 to 3000 tonnes/day. – "

CLS
DISPLAY "

2. TWO STAGE OR MODULAR MASS BURN INCINERATION:

A two stage combustion facility is designed to have combustion occur in two separate chambers. Modular refers to a pre-fabrication and assembly procedure rather than an incineration systems. The units are pre-fabricated which provides for better cost and quality control then shipped to the site and installed with minimum field work. It is particularly well suited for two-stage combustion facilities. They are small mass burn units of 5 to 100 tonne/d capacities and these plants usually have one to four combustor units so at present, modular incinerators are being built for the range of 15-400 tonnes/d and can be set up as single units or in parallel. The range of energy extraction efficiency is between 45-70%. The normal life span of these units is estimated at 20 years. – "

DISPLAY "

The process begins in the first chamber where waste is burned under starved air conditions to limit the entrainment of particulates in flue gases, lower gas velocities, minimize disturbance of the fuel bed, and control temperatures to reduce volatilization of salts and metals.

The EPA (1989) reports that all new modular combustion facilities are expected to have energy recovery. There are a number of suppliers with experience with municipal solid wastes and the marketplace should be very competitive. A discussion of physical and operational aspects of these systems is in a report by Tricil describing an existing plant in PEI. – "

DISPLAY "

They have lower capital costs than site-built mass burn facilities. and shorter construction times of 12 to 24 months. They also offer flexibility in sizing and the potential for system redundancy, but must generally be less than 500 tonnes/d capacity. There are plants in: Charlottetown, PEI (3X36 tonne/d units); Victoria Hospital, London (3X91 tonne/d units).

They have been recommended for capacities of 500 to 3000 tonnes/day. – "

CLS

```
   DISPLAY "
3. SEMI-SUSPENSION OR REFUSE-DERIVED FUEL INCINERATION:
These facilities provide for more advanced separation techniques
to remove materials that burn poorly and degrade the potential
fuel value of the waste stream.  Often, these materials may also
be recyclable.  Materials usually removed include oversized material
such as appliances, glass, metals and organics.  Waste must be
pre-processed by shredding and separating non-combustibles such as
metal and glass.  The combustible fraction is referred to as refuse-
derived fuel (RDF).  Individual RDF combustors range from 300 to 1000
tonnes/d capacity. Plants typically have 2 to 4 combustor units, so
capacities range from 600 to 4000 tonnes/d. - "
   DISPLAY "
Several different types of RDF exist and can be classified as: coarse,
(minimal processing - screening); prepared (further processing to
remove ferrous metals, fines, glass, ceramics and grit); recovery
prepared (larger portion of metals removed as are glass fractions)
THESE ARE USED IN DEDICATED RDF BOILERS; fluff RDF (shredding, air
classification, magnetic separation, screening) and densified or
pellet RDF (compaction of fluff into cubes, pellets or etc. making
it less costly to transport) THESE CAN ALSO BE CO-FIRED IN COAL
BURNERS.  Each category produces a different amount of residuals
as the level of processing increases with each category. ~ "
   CLS
   DISPLAY "
RDF PRODUCTION AND BURN:
The RDF may be blown into a single chamber with combustion occurring
partly in suspension.  These dedicated boilers associated with the
plant can use RDF only or a combination of fuels to even out the
energy flow.  They produce less ash than mass burn or modular facilities.
eg. SWARU facility in Hamilton, ON is the longest operating dedicated
   RDF incinerator with 2 300 tonne/d waterwall boilers, with 25-30%
   by weight of ash produced (5-6% by volume) deposited in Glanbrook
   Landfill, and produces steam for internal use and electricity sold
   to Ontario Hydro - no cost information is available ~ "
   DISPLAY "
RDF PRODUCTION ONLY:
The RDF may be transported and burned at an off-site industrial
location .  This step reduces the capital costs and eliminates the
need for an additional combustion operation.  ~ "
   DISPLAY "
4.  FLUIDIZED BED COMBUSTION
This is largely a developing technology that burns processed waste
in a heated bed of non-combustible material (such as sand).  Existing
and planned fluidized bed combustors have capacities ranging from
200 to 500 tonne/d.  Plant capacity is estimated to be 300 to 1000
tonnes/d. ~ "
   WCLOSE 1
   WOPEN 1,3,5,15,70,4
   ACTIVE 1
   COLOR = 16
   DISPLAY "            NOTE!!:  KEY CONSIDERATIONS"
   COLOR = 0
   DISPLAY"
One must ascertain the AVAILABILITY, CAPABILITIES, ADVANTAGES,
```

```
DISADVANTAGES AND APPROPRIATENESS OF various EFW technologies.
This can be done through calls to manufacturers, suppliers and
managers of existing facilities, review of available literature
and past experience.  One must also realize that anyone can make
slick promotional material. To find out about a company you can:
check with regulatory agencies where the company currently
operates facilities; inspect existing plants (unannounced)
yourself perhaps with some consultative assistance. ~"
    WCLOSE 1
    FIND technology
    PWKS technology, e77, c:\es\fac_efw
    CLS
    WOPEN 1,5,3,12,74,5
    ACTIVE 1
    DISPLAY "
RECOMMENDED MINIMUM CAPACITY DUE TO TECHNOLOGICAL CONSTRAINTS:
            Mass-burn: 50 tonnes/d
            Modular incineration: 5 tonne/d
            RDF production and burn: 300 tonne/d ~"
    COLOR = 15
    FIND minimum_capacity
    PWKS minimum_capacity, e78, c:\es\fac_efw
    COLOR = 0
    WCLOSE 1
    WOPEN 1,5,3,12,74,5
    ACTIVE 1
    DISPLAY "
RECOMMENDED MAXIMUM CAPACITY DUE TO TECHNOLOGICAL CONSTRAINTS:
            Mass-burn: none cited
            Modular incineration: 500 tonne/d
            RDF production and burn: none cited ~"
    COLOR = 15
    FIND maximum_capacity
    PWKS maximum_capacity, e79, c:\es\fac_efw
    COLOR = 0
    WCLOSE 1
    WOPEN 1,3,4,18,72,5
    ACTIVE 1
    DISPLAY "
    CAPACITY UTILIZATION FACTOR:
    It has been suggested that a capacity utilization of 65-
    75% be assumed, which has been observed in practice and
    allows for maintenance work to be performed if there are
    multiple processing lines.
    Some plants are achieving 80-85% capacity utilization.
    The New Brunswick WM study assumed 85%.
    If flows are much higher than this average flow waste may
    be turned away, if considerably lower auxiliary fuel may
    be needed for proper combustion. ~"
    COLOR = 15
    FIND capacity_utilization
    PWKS capacity_utilization, e80, c:\es\fac_efw
    FIND operating_days
    PWKS operating_days, e81, c:\es\fac_efw
    COLOR = 0
```

```
    WCLOSE 1
    WOPEN 1,3,10,13,63,5
    ACTIVE 1
    DISPLAY "
REVENUES:
Revenues result from: sale of energy; tipping fees; sale of
ferrous metal; and sale of RDF.

Smith (1989) recommends that the price of energy from these
facilities be discounted 15% relative to fossil fuel costs
for it to be attractive to customers. ~"
    WCLOSE 1
    FIND pot_energy
    PWKS pot_energy, e82, c:\es\fac_efw
    PWKS energy_revenue, e83, c:\es\fac_efw
    CLS
    FIND rdf
    PWKS rdf_factor, e84, c:\es\fac_efw
    PWKS rdf_revenue, e85, c:\es\fac_efw
    CLS
    WOPEN 1,2,3,18,74,3
    ACTIVE 1
    DISPLAY "
 MATERIAL RECYCLING CONSIDERATIONS:
Separating recyclable material from the waste stream in order
to improve the fuel value of the waste and recover valuable
materials will add to operating and capital costs with the
need for magnetic separation and manual sorting. In addition,
the material recovered is often difficult to market due to
contamination, particularly paper. For example, newspaper,
glass and metal from the now dismantled Cole Resource Recovery
Facility (St. Catherines landfill site) was so contaminated
the contractor experienced difficulty in marketing it. The
process was also inefficient and quite expensive at $220/tonne
of recyclable material (1986) and was a major reason in the
decommissioning of the facility. ~"
    DISPLAY "
* While an EFW plant may be an effective means of retrieving ferrous
  metal through magnetic separation techniques, it is less effective
  than source separation for materials such as paper and cardboard
  (due to contamination problems) and glass (due to breakage and
  colour separation problems). Thus, generally these plants will
  limit material recovery to ferrous metal. ~"
    WCLOSE 1
    FIND p_ferrous
    PWKS ferrous_factor, e86, c:\es\fac_efw
    PWKS ferrous_revenue, e87, c:\es\fac_efw
    WOPEN 1,3,3,17,74,5
    ACTIVE 1
    DISPLAY "
               LAND AREA REQUIREMENTS:
          The following estimates are available:
 - 1.6 ha for a 180 tonne/d modular facility -> 89 m2/tonne/d
 - 5.2 ha for a 1350 tonne/d waterwall steam facility -> 38 m2/t/d
 - 3.2 ha for a 900 tonne/d RDF/burn facility -> 35 m2/tonne/d ~"
```

```
COLOR = 15
FIND area_factor
PWKS area_factor, c96, c:\es\fac_efw
COLOR = 0
WCLOSE 1
WOPEN 1,2,5,17,71,5
ACTIVE 1
DISPLAY "
                TIME FRAME
The time required to plan, develop, and construct a
facility will vary, but at least 5 to 8 years are
required to bring a new facility from the earliest
planning stages to in-service.  Construction times:
        * mass burn = 2 to 3 years
        * modular systems = 1 to 2 years ~ "
COLOR = 15
FIND facility_startup
PWKS facility_startup, c97, c:\es\fac_efw
COLOR = 0
WCLOSE 1
WOPEN 1,3,8,12,64,5
ACTIVE 1
DISPLAY "
VOLUME REDUCTION:
The expected reduction in volume of combusted waste
is in the range of: 90-95%. ~ "
COLOR = 15
FIND volume_reduction
PWKS volume_reduction, c90, c:\es\fac_efw
COLOR = 0
WCLOSE 1
WOPEN 1,3,10,15,61,5
ACTIVE 1
DISPLAY "
MASS REDUCTION:
The expected reduction in mass of combusted waste
is in the range of: 60-70%.  Often used for design
purposes.  Some plants in operation are achieving
20% residues.  An RDF-BURN plant with ferrous
recovery produces 30% residuals, another 40%. ~ "
COLOR = 15
FIND mass_reduction
PWKS mass_reduction, c91, c:\es\fac_efw
COLOR = 0
WCLOSE 1
WOPEN 1,2,3,19,73,5
ACTIVE 1
DISPLAY "
  MASS OF NON-COMBUSTIBLES:
  The expected reduction in mass of combusted waste is in
  the range of: 60-70% due to the production of ash and
  non-combustibles such as glass and metals (15%) unless
  significant materials recovery is utilized, and waste
  diverted during scheduled or unscheduled maintenance.
  Approximately, 5% of inflow is bypassed due to scheduled
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  and unscheduled downtime. Residuals are in the range of
  35-45% of incoming tonnage. ~"
 COLOR = 15
 FIND residuals
 PWKS residuals, e88, c:\es\fac_efw
 FIND disposal_cost
 PWKS disposal_cost, e89, c:\es\fac_efw
 COLOR = 0
 WCLOSE 1
 CLS
 WOPEN 1,2,3,17,74,3
 ACTIVE 1
 DISPLAY "
COST ESTIMATION:
Cost factors vary considerably from facility to facility so specific
guidance is difficult to give.  Variable factors include: size;
technology; location (labour and construction costs can vary); type
of financing; ownership; pollution control equipment; and the cost
of ash disposal.

You will be asked for estimates for planning and design costs, and
you will be provided with information to assist you.  Examples of
capital and operating costs will be listed and have been transferred
to worksheet FAC_EFW.WK1 where you can estimate fixed and variable
capital(and operating cost)parameters as related to capacity for use
in the facility sizing and waste allocation model. ~"
 WCLOSE 1
 WOPEN 1,1,3,20,74,5
 ACTIVE 1
 DISPLAY "
1) CONCEPTUALIZATION AND PLANNING:
 * In Ontario, an Environmental Assessment is required for EFW
   plant approval and this will add substantially to the capital cost
   of establishing an EFW plant.
 * There is limited experience with the process, so little cost
   information is available.
 * Added difficulties are that legislation varies, and there may be
   large public opposition.
 * The following information is available:
  - it is estimated that the approval process, including preliminary
    design and engineering for a 364 tonne/d facility in Brampton,
    ON has cost $2.5M over 3 years (1989). ~"
 COLOR = 15
 FIND planning_cost
 PWKS planning_cost, e92, c:\es\fac_efw
 COLOR = 0
 WCLOSE 1
 WOPEN 1,1,3,20,74,5
 ACTIVE 1
 DISPLAY "
2) DESIGN AND ENGINEERING:
 * Required for both the EA process and the Environmental Protection
   Act in Ontario.
 * It is difficult to estimate these costs as: legislation will vary
   and public opposition may impede the process, and also literature
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  reported costs may be included in different categories.
 * The following information is available:
  - Smith (1989) suggests using 5% of the total construction cost
    for design
  - a 180 tonne/d MODULAR BURN system in Auburn, Maine had $260000
    (1981US$) in design costs -- "
   COLOR = 15
   FIND design_cost
   PWKS design_cost, e93, c:\cs\fac_efw
   COLOR = 0
   WCLOSE 1
   WOPEN 1,2,3,18,74,5
   ACTIVE 1
   DISPLAY "
3) CAPITAL COSTS:
 * The cost to construct an EFW plant involves buildings, structures,
   air pollution control equipment, power generation equipment,
   connection to energy customer, engineering and contingencies and
   may include interest during construction.
 * These capital costs are subject to wide variations depending on:
   type of energy produced, technology utilized, and capacity of the
   facility, among other factors.
 * The following information is available:
 - the cost for the 364 tonne/d facility in Brampton, ON has been
   estimated at $52M (1989) -- "
    DISPLAY "
 The EPA (1989) reports the following average figures which are
 broad national averages in the US:
 * mass burn facilities: $100000-110000 (1988US$)/tonne/d of rated
   capacity for large facilities
 * modular incineration: $88000-100000 (1988US$)/tonne/d of rated
   capacity when they are < 360 tonnes/d
 * RDF-burning facility costs are generally lower than for mass
   burn because of the more homogeneous fuel source but this may
   be offset by the capital costs of processing equipment -- "
    DISPLAY "
- $51M (including land) (1977US$) for a 1350 tonne/d WATERWALL, STEAM
  plant in Saugus, Mass. with ferrous recovery
- $40M for a 900 tonne/d RDF-BURN facility in Akron, Ohio (1980US$)
  with ferrous recovery and STEAM production (no land)
- $4.5M (1980US$) for a 220 tonne/d RDF incineration facility in
  Madison, Wisconsin -- "
    COLOR = 15
    DISPLAY "
  These cost figures have been transferred to worksheet FAC_EFW.WK1
  to use LOTUS to derive estimates for fixed and variable costs for
  potential facilities by relating capital cost to capacity. -- "
    COLOR = 0
    CLS
    DISPLAY "
4) OPERATION AND MAINTENANCE:
 * For EFW facilities O&M costs include: staffing and administration,
   equipment maintenance and repair for turbines and generators,
   condensers, transformers, air pollution control equipment, ash
   treatment and disposal, utilities, fuels, supplies, insurance,
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    and a monitoring program for air emissions.
  * Similar to capital costs, these costs can vary substantially.
  * The following information is available:
    - for the 364 tonne/d Brampton facility an estimate of $4.5M(1989)
    - for a 180 tonne/d MODULAR BURN (STEAM) plant in Auburn, Maine,
      operating costs and debt service costs were $1M (1983US$) and
      $85000 for administration, excluding landfill costs with ferrous
      recovery ~"
     DISPLAY "
    - for a plant in Saugus, Mass. operating costs were $3.8M with
      a WATERWALL-STEAM plant processing 1080 tonne/d (1977US$)
      with a design capacity of 1350 tonne/d with ferrous recovery
    - for a 315 tonne/d electricity generating plant in New Brunswick
      $65/tonne was estimated, $68/tonne/yr for co-generation, not
      including residuals disposal (1989, proposed) which includes
      capital financing costs minus revenue or $30/tonne and $31
      tonne for just O&M costs
  * The EPA (1989) reports that average costs for O&M for a 1800
    tonne/d facility have been estimated at $20/tonne/d on an
    annual basis (1988US$). ~"
     DISPLAY "
Gottinger (1991) in his study reported (1973US$):
* EFW steam: $11.5/tonne for 900 tonne/d, 300 d/yr
* EFW electricity: $14.4/t for 900 t/d, 300 d/yr
 Levinson (1990) reported (1990US$): $21.5/t for a 2040 tonne/d EFW
 facility for Newark, N.J. ~"
     COLOR = 15
     FIND operating_cost
     PWKS operating_cost, e94, c:\es\fac_efw
     COLOR = 0
     WCLOSE 1
     WOPEN 1,5,12,10,57,5
     ACTIVE 1
     DISPLAY "
TIPPING FEES: used to cover operating costs.
The EPA (1989) reports that the average facility tip
fee in the US in 1988 ranged from $45 to $70/tonne. ~"
     COLOR = 15
     FIND tipping_fee
     PWKS tipping_fee, e95, c:\es\fac_efw
     COLOR = 0
     WCLOSE 1
     WCLOSE 1
     potential = yes;
RULE 3
IF    energy = none
THEN  energy_revenue = 0
      pot_energy = none;
RULE 4
IF    e_exist = none
THEN  energy_revenue_exist = 0;
RULE 5
IF    energy = steam
THEN  WOPEN 1,3,5,13,69,5
      ACTIVE 1
```

```
      DISPLAY "
    STEAM GENERATION:
    A MODULAR BURN plant in Auburn, Maine was producing 2000
    kg steam/tonne of incoming waste.
    An RDF-BURN plant in Akron, Ohio was producing 4200 kg/tonne
    of incoming waste as steam.
    Generally steam is produced at a rate of 2500 kg/tonne. ~ "
      CLS
      DISPLAY "
    STEAM REVENUE:
    A plant in Auburn, Maine using MODULAR BURN was receiving
    $27/tonne in steam revenue in 1983US$.
    An RDF-BURN facility in Akron, Ohio was to receive $19/tonne
    of input for steam generation (1980US$).
    Gottinger (1991) reported (1973US$): $3.7/t ~ "
      COLOR = 15
      FIND energy_revenue
      COLOR = 0
      WCLOSE 1
      pot_energy = steam;
RULE 6
IF    energy = electricity
THEN  WOPEN 1,3,4,18,71,5
      ACTIVE 1
      DISPLAY "
  ELECTRICITY GENERATION
  * generally 1 MW generating capacity/45 tonnes of MSW per day
  * a New Brunswick study estimated 4450 kW-hrs/tonne/yr handled
    a sale price of $60/MWhr (conservatively - also up to $120)
    or $26/tonne/yr handled
  * For a US study, an electricity price of $80/MWhr is used to
    represent the optimal case that the energy is sold to a utility
    at the full avoided cost.  More conservatively, a figure of
    $60/MWhr is used (1985US$).
  * Gottinger (1991) reported (1973US$): $4/tonne ~ "
      COLOR = 15
      FIND energy_revenue
      COLOR = 0
      WCLOSE 1
      pot_energy = electricity;
RULE 7
IF    technology = rdf_recovery
OR    technology = rdf_burn
THEN  WOPEN 1,3,7,15,66,5
      ACTIVE 1
      DISPLAY "
  RDF GENERATION:
  An RDF-BURN plant in Madison, WI averages 55% of input as RDF
  while also recovering ferrous metal.
  An RDF-BURN facility in Madison, Wisconsin receives $20/tonne
  of RDF (1980US$). ~ "
      COLOR = 15
      FIND rdf_factor
      FIND rdf_revenue
      COLOR = 0
```

```
    WCLOSE 1
    rdf = found;
RULE 8
IF   technology < > rdf_recovery
AND  technology < > rdf_burn
THEN rdf_factor = 0
    rdf_revenue = 0
    rdf = found;
RULE 9
IF   technology = rdf_recovery
OR   technology = rdf_burn
THEN FIND rdf_factor
    rdf_%[X] = (rdf_factor)
    RESET rdf_factor
    FIND rdf_revenue
    rdf_rev[X] = (rdf_revenue)
    RESET rdf_revenue
    rdf_existing = found;
RULE 10
IF   technology < > rdf_recovery
AND  technology < > rdf_burn
THEN rdf_%[X] = 0
    rdf_rev[X] = 0
    rdf_existing = found;
RULE 11
IF   ferrous_recovered = no
THEN ferrous_fac[X] = 0
    ferrous_rev[X] = 0
    ferrous = found;
RULE 12
IF   ferrous_recovered = yes
THEN FIND ferrous_factor
    ferrous_fac[X] = (ferrous_factor)
    RESET ferrous_factor
    FIND ferrous_revenue
    ferrous_rev[X] = (ferrous_revenue)
    RESET ferrous_revenue
    ferrous = found;
RULE 13
IF   ferrous_recovered = yes
THEN WOPEN 1,3,3,12,74,5
    ACTIVE 1
    DISPLAY "
     FERROUS RECOVERY:
     A plant in Saugus, Mass. is recovering 6% of input as
     recyclable ferrous metal. A Saugus, Mass. plant achieves
     7% of input recovered as ferrous metal. -"
    COLOR = 15
    FIND ferrous_factor
    FIND ferrous_revenue
    COLOR = 0
    p_ferrous = found;
RULE 14
IF   ferrous_recovered = no
THEN ferrous_factor = 0
```

```
    ferrous_revenue = 0
    p_ferrous = found;

ASK efw_considered: "
 Would you like to include EFW facilities in your MSW management system
 planning problem ?";
CHOICES efw_considered: yes, no;
ASK existing_fac: " Are there any existing EFW facilities in your community ?";
CHOICES existing_fac: yes, no;
ASK potential_fac:"Would you like to consider including EFW plants in your system ?";
CHOICES potential_fac: yes, no;
ASK fac_name: " Enter the name of your EFW facility number {X}, ? if no more facilities:";
ASK capacity: " What is the maximum capacity of the plant (tonne/d) ?";
ASK operating_cost: " Enter the operating cost at the plant ($/tonne).";
ASK ferrous_recovered: " Is ferrous metal recovered in the plant ?";
CHOICES ferrous_recovered: yes, no;
ASK ferrous_factor: " What fraction of the incoming waste is recovered as ferrous ?";
ASK ferrous_revenue: " Enter the revenue from recovered ferrous metal ($/tonne).";
ASK energy: " What type of energy is generated at the plant ?";
CHOICES energy: steam, electricity, none;
ASK e_exist: " What type of energy is generated at the plant ?";
CHOICES e_exist: steam, electricity, none;
ASK energy_revenue: " Enter the amount of energy revenue generated ($/tonne incoming
 less RDF material if recovered).";
ASK energy_revenue_exist: " Enter the amount of energy revenue generated ($/tonne incoming).";
ASK volume_reduction: " Enter the reduction in the volume of incoming material (%)
 (through combustion).";
ASK mass_reduction: " Enter the reduction in the mass of incoming material (%)
 (through combustion).";
ASK residuals: "What fraction of incoming tonnage is residuals requiring disposal ?";
ASK disposal_cost: " Enter the cost of residuals disposal ($/tonne).";
ASK capacity_utilization: " What fraction of the total capacity is used in normal operation ?";
ASK tipping_fee: " What is the tipping fee at the facility ($/tonne) ?";
ASK expansion_capacity: " Enter the capacity expansion potential of the site (tonne/day), 0 if none is
possible";
ASK expansion_cost: " Enter the capacity expansion cost at the site ($/tonne/day),
 0 if none is possible
 * NOTE; this value can be updated using the cost data available in FAC_EFW.WK1";
ASK area_factor:" Enter an estimate of area requirements for an EFW plant (m2/t/d).";
ASK facility_startup: " Enter the earliest time from the present a plant may be operational.";
ASK technology: " What type of technology is/will be in the EFW plant ?";
CHOICES technology: mass_burn, modular, RDF_recovery, RDF_burn;
ASK planning_cost:"What is your estimate for the cost of planning of an EFW plant ?";
ASK design_cost: " What is your estimate of design and engineering costs per facility?";
ASK minimum_capacity: " What is the minimum capacity of the facility due to any technological
considerations (tonne/day) ?";
ASK maximum_capacity: " What is the maximum capacity of the facility due to any technological
considerations (tonne/day) ?";
ASK operating_days: " Enter the number of operating days per year.";
ASK rdf_revenue: " Enter the revenue generated for the RDF ($/tonne).";
ASK rdf_factor: " What fraction of incoming waste becomes RDF ?";
ASK site_name: " Enter the name of site {X}, ? if no more sites to consider.";
ASK site_area:" Enter the total area available at site {site_name} (ha).";
ASK max_efws: " Enter the maximum number of facilities that can be developed at these
 {potential_efws} sites over the 20 year planning horizon.";
```

APPENDIX D

A complete listing of the mathematical model formulation and accompanying documentation for use in conducting an optimization study (STEP 6)

MILP or LP (OPTIMIZATION) MODEL FORMULATION

The following material assists with the development of the necessary mathematical statements for using a linear or mixed-integer linear programming solution package to investigate facility location and waste allocation issues. It is assumed that the facility knowledge bases and spreadsheet models have been consulted to develop facility-related model parameters, and a consultation has been completed with INPUT.KBS to collect several other necessary problem parameters prior to this model formulation stage.

DEFINITION OF DECISION VARIABLE NAMES USED IN THE FORMULATION: decision variables are highlighted in bold; several additional model parameters that are predefined are included simply to assist with the understanding of the formulation.

NOTE: the units for variables will not be per year (t/year) unless an annual analysis is to be done (i.e., 20 time periods (T from MODEL)); if T is any value other than 20, you must adjust the waste generation units to tonnes per length of time period in years (=20/T) to ensure that the decision variables will have similar units (tonnes per length of time period in years), and dividing by the length of the time periods (in years) will give an AVERAGE yearly value

NOTE: this description refers to flows of waste; recyclables or compostables can be substituted in place of waste if an isolated system of MRFs/CCFs is being investigated to manage source separated materials

FLOW[WL]$_{wlt}$ = flow of waste from waste source area w to landfill site l in time period t [tonnes/time period years]

FLOW[WF]$_{wft}$ = flow of waste from waste source area w to processing facility f in time period t [t/time period years]

FLOW[WS]$_{wst}$ = flow of waste from waste source area w to transfer station s in time period t [t/time period years]

FLOW[SF]$_{sft}$ = flow of waste from transfer station s to processing facility f in time period t (only possible for EFW and mixed MSW processing facilities) [tonnes/time period years]

FLOW[SL]$_{slt}$ = flow of waste from transfer station s to landfill l in time period t [tonnes/time period years]

FLOW[FL]$_{flt}$ = flow of residuals from processing facility f to landfill l in time period t [tonnes/time period years]

USELF$_{lt}$ = (0,1) integer variable for landfills (landfill l is used/not used in time period t - this variable = 1 for the time period it is first opened and zero for all other time periods)

USETS$_{st}$ = (0,1) integer variable for transfer stations (see description above)

USEF$_{ft}$ = (0,1) integer variable for processing facilities (see description above)

CAPF$_{ft}$ =(0,...,MAXF) integer variable that represents the number of units of capacity that are developed when potential processing facility f first opens, that can take on integer values from 0 up to a maximum of MAXF units, eg., you may decide that EFW facilities will be developed with initial capacity of 100 tonnes/day, 200 tonnes/day... up to 500 tonnes/day corresponding to 100 t/day * operating days per year (from FAC_***.WK1) * capacity utilization factor * length of time period; in this case CAPF = (0,1,2,3,4,or 5) (a capacity constraint will ensure that the maximum capacity of a particular facility is not exceeded)

UNITF$_f$ = the basic unit of installed capacity for a particular processing facility [tonnes/time period years], eg., 100 tonnes/day * capacity utilization factor * operating days per year (from FAC_***.WK1) * * length of time period, etc.

DCF$_{ft}$ = initial design capacity (under normal operation; divide this value by the capacity utilization factor to get the maximum design capacity) of potential processing facility f in time period t (MRFs, CCFs, mixed MSW processing or EFW facilities), only one of which will be non-zero [tonnes/time period years] (this variable will be non-zero in time period t* (i.e., t* is the optimal time period to invest in a particular facility))

$CAPTS_{st}$ = (0,...,MAXTS) integer variable that represents the number of units of capacity that are developed when potential transfer station s first opens that can take on integer values from 0 up to a maximum of MAXTS units, eg., you may decide that transfer stations will be developed with initial capacity of 100 tonnes/day, 200 tonnes/day... up to 500 tonnes/day corresponding to 100 t/day * capacity utilization factor * operating days per year (from FAC_TS.WK1) * length of time period; in this case CAPTS = (0,1,2,3,4,or 5) (a capacity constraint will ensure that the maximum capacity of a particular site is not exceeded)

UNITTS = the basic unit of installed capacity for a transfer station [tonnes/time period years], eg., 100 tonnes/day * capacity utilization factor * operating days per year (from FAC_TS.WK1) * length of time period, etc.

$DCTS_{st}$ = initial design capacity (under normal operation; divide this value by the capacity utilization factor to get the maximum design capacity) of potential transfer station s in time period t, only one of which will be non-zero [tonnes/time period years] (this variable will be non-zero in time period t* (i.e., t* is the optimal time period to invest in a particular transfer station))

NOTE: the CAP and UNIT variables are only required if you wish to restrict the installed capacities to specific levels as opposed to allowing the model to set their values; for example the model may decide a 1005 tonnes/year facility should be developed; the UNIT variables are not decision variables but were included in this section to assist with the understanding of the model formulation

XF_{ft} = (0,...,MF) integer variable that represents the number of units of capacity that are developed when potential or existing processing facility f is expanded that can take on integer values from 0 up to a maximum of MF units, eg., you may decide that EFW facilities can only be expanded in units of 100 tonnes/day capacity up to 500 tonnes/day corresponding to 100 t/day * operating days per year (from FAC_***.WK1) * length of time period; in this case XF = (0,1,2,3,4,or 5)

UF_f = the basic unit of expanded capacity for processing facility f [tonnes/time period years], eg., for the EFW facility example above this would be 100 tonnes/day * operating days per year (from FAC_***.WK1) * length of time period, etc.

$EXPF_{ft}$ = expansion capacity of processing facility f in time period t (MRFs, CCFs, mixed MSW processing or EFW facilities) [tonnes/time period years]; for potential facilities, all values before the optimal investment time period, t*, +1 will be zero as a facility cannot be expanded until at least the first time period after it is opened

$EXPFO_{ft^*t}$ = the expansion capacity for potential facility f in time period t assuming the facility is first used (opened) in time period t*, only one of which will be non-zero [tonnes/time period years]

XTS_{st} = (0,...,MTS) integer variable that represents the number of units of capacity that are developed when potential or existing transfer station s is expanded that can take on integer values from 0 up to a maximum of MTS units, eg., you may decide that transfer stations can only be expanded in units of 100 tonnes/day capacity up to 500 tonnes/day corresponding to 100 t/day * operating days per year (from FAC_TS.WK1) * length of time period; in this case XTS = (0,1,2,3,4,or 5)

UTS = the basic unit of expanded capacity for a transfer station [tonnes/time period years], eg., for the example above this would be 100 tonnes/day * operating days per year (from FAC_TS.WK1) * length of time period, etc.

$EXPTS_{st}$ = expansion capacity of transfer station s in time period t [tonnes/time period years]; for potential transfer stations, all values referring to time periods before the optimal investment period, t*, +1 will be zero as a transfer station cannot be expanded until at least the first time period after it is opened

$EXPTSO_{st^*t}$ = the expansion capacity for potential transfer station s in time period t assuming the transfer station is first used (opened) in time period t*, only one of which will be non-zero [tonnes/time period years]

NOTE: the X and U variables are only required if you wish to restrict the capacity expansions to specific levels as opposed to allowing the model to set their values; for example the model may decide to expand a facility by 23 tonnes/year; the U variables are not decision variables but were included in this section to assist with the understanding of the model formulation

WF_{ft},WTS_{st},WLF_{lt} = waste originating from all outside sources that is transferred to processing facility f, transfer station s or landfill l in time period t (i.e., not collected or financed by the municipality or community but accepted at the facility) [tonnes/time period years]

OBJECTIVE FUNCTION:

MINIMIZE (TOTAL PRESENT VALUE SYSTEM COST):

$$\sum_{t=1}^{T} B_t \Big(\sum_{w=1}^{TOTWSA} \sum_{f=1}^{TOTFACS} COLL_{ft} \cdot FLOW[WF]_{wft} + HAUL[WF]_{ft} \cdot FLOW[WF]_{wft}$$

(1) sum of the costs for collecting and transporting waste from waste source areas to processing facilities

$$+ \sum_{w=1}^{TOTWSA} \sum_{s=1}^{TOTTS} GCOLL_t \cdot FLOW[WS]_{wst} + HAUL[WS]_t \cdot FLOW[WS]_{wst}$$

(2) sum of the costs for collecting and transporting waste from waste source areas to transfer stations

$$+ \sum_{w=1}^{TOTWSA} \sum_{l=1}^{TOTLFS} GCOLL_t \cdot FLOW[WL]_{wlt} + HAUL[WL]_t \cdot FLOW[WL]_{wlt}$$

(3) sum of the costs for collecting and transporting waste from waste source areas directly to landfills

$$+ \sum_{s=1}^{TOTTS} \sum_{f=1}^{TOTFACS} HAUL[SF]_t \cdot FLOW[SF]_{sft}$$

(4) sum of the costs for transporting waste from transfer stations to processing facilities

$$+ \sum_{s=1}^{TOTTS} \sum_{l=1}^{TOTLFS} HAUL[SL]_t \cdot FLOW[SL]_{slt}$$

(5) sum of the costs for transporting waste from transfer stations to landfills

$$+ \sum_{f=1}^{TOTFACS} \sum_{l=1}^{TOTLFS} HAUL[FL]_{ft} \cdot FLOW[FL]_{flt} \Big)$$

(6) sum of the costs for transporting residuals from processing facilities to landfills

$$+\sum_{t=1}^{T} B_t*(\sum_{l=1}^{TOTLFS} OMLF_{lt}*(\sum_{w=1}^{TOTWSA} FLOW[WL]_{wlt}+\sum_{s=1}^{TOTTS} FLOW[SL]_{slt}+\sum_{f=1}^{TOTFACS} FLOW[FL]_{flt}+WLF_{lt}))$$

(7) total operating cost at landfills given waste flows from waste source areas, transfer stations, processing facilities and outside sources

$$+\sum_{t=1}^{T} B_t*(\sum_{s=1}^{TOTTS} OMTS_{st}*(\sum_{w=1}^{TOTWSA} FLOW[WS]_{wst}+WTS_{st}))$$

(8) total operating cost at transfer stations given waste flows from waste source areas and outside sources

$$+\sum_{t=1}^{T} B_t*(\sum_{f=1}^{TOTFACS} OMF_{ft}*(\sum_{w=1}^{TOTWSA} FLOW[WF]_{wft}+\sum_{s=1}^{TOTTS} FLOW[SF]_{sft}+WF_{ft}))$$

(9) total operating cost at processing facilities given waste flows from waste source areas, transfer stations and outside sources

$$+\sum_{t=1}^{T}\sum_{l=1}^{POTLF} FCLF_{lt}*USELF_{lt}$$

(10) fixed cost for landfills (capital investment required to open a facility at its maximum site capacity)

$$+\sum_{t=1}^{T}\sum_{f=1}^{POTFAC} FCF_{ft}*USEF_{ft}$$

(11) fixed cost for processing facilities

$$+\sum_{t=1}^{T}\sum_{s=1}^{POTTS} FCTS_{st}*USETS_{st}$$

(12) fixed cost for transfer stations

$$+\sum_{t=1}^{T} B_t*(\sum_{f=1}^{POTFAC} CEXPF_{ft}*DCF_{ft}+\sum_{s=1}^{POTTS} CEXPTS_{st}*DCTS_{st})$$

(13) capital investment in processing facilities and transfer stations as a function of capacity

$$+\sum_{t=1}^{T} B_t*(\sum_{f=1}^{TOTFACS} CEXPF_{ft}*EXPF_{ft}+\sum_{s=1}^{TOTTS} CEXPTS_{st}*EXPTS_{st})$$

(14) linear expansion cost for processing facilities and transfer stations

$$-\sum_{t=1}^{T} B_t*(\sum_{f=1}^{TOTFACS} REV_{ft}*RFACTOR_f*(\sum_{w=1}^{TOTWSA} FLOW[WF]_{wft}+\sum_{s=1}^{TOTTS} FLOW[SF]_{sft}+WF_{ft}))$$

(15) revenue from the sale of materials and/or energy recovered at processing facilities

where: (coefficients can be taken from the facility spreadsheet models or from the data collected by INPUT.KBS in file: MODEL; if a certain technology is not used simply ignore the terms that relate to it)

(a) Indices you specify:

t = time period index = (1,...,T)
T = total number of time periods in the analysis (MODEL)
timeperiod = length in years of each time period (=20/T)
w = waste source area index
TOTWSA = total number of waste source areas (MODEL)
f = processing facility index (refers to MRFs, CCFs, EFW facilities and mixed MSW processing facilities; NOT transfer stations or landfills)
TOTFACS = total number of processing facilities (existing + potential) (total_processing from MODEL)
POTF = total number of potential processing facilities (potential_processing from MODEL)
s = transfer station index
TOTTS = total number of transfer stations (total_ts from MODEL)
POTTS = total number of potential transfer stations (potential_ts from MODEL)
l = landfill index
TOTLFS = total number of landfills (total_lfs from MODEL)
POTLF = total number of potential landfills (potential_lfs from MODEL)

NOTE: the indices for facilities start at 1 and go to the total number (existing+potential); the indexing of facilities should begin with potential facilities (i.e., from 1 to total potential) then continue to existing facilities (i.e., from (total potential + 1) to total facilities (TOTFACS))

NOTE: for all potential facilities you should consider the start-up year (specified in FAC_***.WK1) which specifies the first year facility development is possible, as variables are not needed for time periods before this year (eg., if potential MRFs start-up year is 3, and you are doing a 2 year analysis (10 time periods), variables pertaining to MRFs with the subscript t=1 are not required)

(b) Cost and operational parameters you specify:

$$B_t = \frac{1}{(1 + \textit{discounting factor})^{**((t-1)*timeperiod)}}$$

(16) discounting factor (interest rate or discount rate) applied to costs to calculate present value costs

NOTE: cost coefficients are either: inflated to the start (or end) of the time period (t) referenced in the subscript then discounted to time zero using the interest rate in the above equation; or simply left in current dollar terms and discounted from the start (or end) of the time period to time zero using the discount rate (inflation-free) (from MODEL)
NOTE: some parameter units will have to be adjusted; you will be advised when and how you should do this, otherwise the units remain as they were originally estimated

HAUL[WF]$_t$ = linehaul cost for transporting waste from waste source areas to processing facilities at the start of time period t [\$/tonne]
= mrf_linehaul (from MODEL) if destination is a MRF
= ccf_linehaul (from MODEL) if destination is a CCF
= garbage_linehaul (from MODEL) if destination is a mixed MSW processing or EFW facility
HAUL[WS]$_t$ = linehaul cost for transporting waste from waste source areas to transfer stations at the start of time period t [\$/tonne]
= garbage_linehaul (from MODEL)
HAUL[WL]$_t$ = linehaul cost for transporting waste from waste source areas to landfills at the start of time period t [\$/tonne]

= garbage_linehaul (from MODEL)

$\mathbf{HAUL[SF]}_t$ = linehaul cost for transporting waste from transfer stations to processing facilities (only EFW and mixed MSW processing facilities are valid destinations as recycling and composting systems do not use transfer stations) at the start of time period t [$/tonne]
= transfer_linehaul (from MODEL)

$\mathbf{HAUL[FL]}_{ft}$ = linehaul cost for transporting residuals from processing facility f to landfills for disposal at the start of time period t [$/tonne]
= dependent on the type of transport vehicle used by a facility
= may use garbage_linehaul (from MODEL)

$\mathbf{GCOLL}_t$ = the cost of garbage collection at the start of time period t [$/tonne] (from file: DATA developed by INTRO.KBS)

$\mathbf{COLL}_{ft}$ = the cost of collecting waste or materials bound for a specific processing facility, f, at the start of time period t [$/tonne] not including the transportation cost to haul waste/materials to the facility: for EFW and mixed MSW processing facilities this is the garbage collection cost (from file: DATA collected by INTRO.KBS); for MRFs this is the cost for collecting recyclables which will depend on the type of program being considered, there is information in the various recycling program knowledge bases R_***.KBS that can assist you in developing an approximate estimate for this parameter - if a system is being designed to manage recyclables in isolation using drop-off programs this cost can be assumed to be 0; similarly for CCFs, drop-off programs will have no collection cost but curbside collection program costs depend on the type of collection system (C_CURB.KBS and SFD_CURB.WK1 may be consulted to develop an approximate estimate) - adjust for the expected average linehaul cost

$\mathbf{OMLF}_{lt}$ = operating cost at landfill l (from FAC_LF.WK1) at the start of time period t [$/tonne]

$\mathbf{OMF}_{ft}$ = operating cost at processing facility f (from FAC_***.WK1) at the start of time period t [$/tonne]

if you are designing a system for recyclables or compostables in isolation of the rest of the MSW management system (i.e., only including MRFs or CCFs) you must also include a cost for the disposal of processing residuals = disposal cost ($/tonne) * residuals factor, and this $/tonne figure should then be added to the general operating cost

$\mathbf{OMTS}_{st}$ = operating cost at transfer station s (from FAC_TS.WK1) at the start of time period t [$/tonne]

$\mathbf{FCLF}_{lt}$ = fixed capital cost at potential landfill l at the start of time period t to develop the maximum capacity of the site (i.e, when a landfill is to be used the entire site is developed at once with no potential for expansion) (from regression analysis FAC_LF.WK1 - use the regression parameters and the maximum available capacity of the site to determine the fixed capital cost for a landfill should it be opened) [$]

$\mathbf{FCF}_{ft}$ = fixed capital cost at potential processing facility f (from FAC_***.WK1) at the start of time period t [$]

$\mathbf{FCTS}_{st}$ = fixed capital cost at potential transfer station s (from FAC_TS.WK1) at the start of time period t [$]

$\mathbf{CEXPF}_f$ = variable capital cost (or linear expansion cost) for processing facility f (from regression analysis in FAC_***.WK1 / capacity utilization factor / time period [years]) at the start of time period t [$/tonnes/time period years]; may also need to include an additional term CLANDF*DCF if land purchase costs were not included in the costs used in the regression analysis, where CLANDF for each processing facility = land cost ($/ha) * area_factor ($m^2$/t/day) / operating days/year / 10000 (m^2/ha) / timeperiod [years] / capacity utilization factor) (all data in FAC.***.WK1)

$\mathbf{CEXPTS}_s$ = variable capital cost (or linear expansion cost) for potential transfer station s (from regression analysis in FAC_TS.WK1 / capacity utilization factor / timeperiod [years]) [$/tonnes/time period years]; may also need to include an additional term CLANDTS*DCTS if land purchase costs were not included in the capital costs used for the regression analysis, where CLANDTS for each transfer station = land cost ($/ha) * area_factor ($m^2$/t/day) / operating days/year / 10000 (m^2/ha) / timeperiod [years] / capacity utilization factor) (all data in FAC.TS.WK1)

REV_{ft} = expected revenue from materials recovered at processing facility f at the start of time period t [$/tonne]
= average revenue from FAC_MRF.WK1 for MRFs
= compost revenue from FAC_CCF.WK1 for CCFs

$RFACTOR_f$ = fraction of the input material to processing facility f that is recovered as materials or energy and produces revenue

NOTE: a) for EFW facilities that recover energy, RDF or ferrous metal, you provide a term for each of these products ((energy revenue * (1-rdf_factor) + (ferrous revenue * ferrous factor) + (rdf_revenue * rdf_factor)) as the REV*RFACTOR value (from FAC_EFW.WK1)
b) for mixed MSW processing facilities that recover recyclables, produce compost and/or RDF you must consider all terms ((average recycling revenue * recycling_factor)+(compost revenue * compost_factor)+(rdf_revenue * rdf_factor)) as the REV*RFACTOR value (from FAC_MSW.WK1)
c) for MRFs and CCFs RFACTOR is (1 - residuals_factor) (from FAC_MRF.WK1 or FAC_CCF.WK1)

CONSTRAINTS: The first set of constraints are those that must be included in any planning problem formulation (assuming the technology it refers to is being considered). Then optional constraints will be explained.

NOTE: a time period index with a superscript * refers to the optimal time period in which a potential facility should be opened

(1) Mass balance at all WSAs and outside sources (i.e., remove all waste from generation locations):

$$\sum_{f=1}^{TOTFACS} FLOW[WF]_{wft}+\sum_{l=1}^{TOTLFS} FLOW[WL]_{wlt}+\sum_{s=1}^{TOTTS} FLOW[WS]_{wst}=WASTE_{wt}$$

(17) a constraint is written for every combination of waste source areas (w=1,..,TOTWSA) and time periods (t=1,..,T)

$$\sum_{f=1}^{TOTFACS} WF_{ft}+\sum_{s=1}^{TOTTS} WTS_{st}+\sum_{l=1}^{TOTLFS} WLF_{lt}=W_t$$

(18) a constraint is written for every time period (t=1,..,T)

(2) Mass balance around all transfer stations (i.e., what comes in must leave):

$$WTS_{st}+\sum_{w=1}^{TOTWSA} FLOW[WS]_{wst}=\sum_{l=1}^{TOTLFS} FLOW[SL]_{slt}+\sum_{f=M,E} FLOW[SF]_{sft}$$

(19) a constraint is written for every transfer station (s=1,..,TOTTS) for every time period (t=1,..,T) including all potential and existing mixed MSW processing facilities and EFW facilities within the set (f=1,..,TOTFACS)

(3) Mass balance around processing facilities (i.e., residuals from a processing facility sent for landfilling equal what comes in multiplied by the residuals factor):

$$RESFAC_f*(WF_{ft}+\sum_{s=1}^{TOTTS} FLOW[SF]_{sft}+\sum_{w=1}^{TOTWSA} FLOW[WF]_{wft})=\sum_{l=1}^{TOTLFS} FLOW[FL]_{flt}$$

(20) a constraint is written for every processing facility (f=1,..,TOTFACS) for every time period (t=1,..,T) with the FLOW[SF] terms only included for all potential and existing mixed MSW processing facilities and EFW facilities

(4) Only one fixed cost, at most, for potential facilities has to be paid over the planning horizon (i.e., it is a one time only cost outlay).

$$\sum_{t=1}^{T} USELF_{lt}\leq 1$$

(21) a constraint is written for every potential landfill (l=1,..,POTLF)

$$\sum_{t=1}^{T} USEF_{ft}\leq 1$$

(22) a constraint is written for every potential processing facility (f=1,..,POTF)

$$\sum_{t=1}^{T} USETS_{st}\leq 1$$

(23) a constraint is written for every potential transfer station (s=1,..,POTTS)

(5) The design capacity of a potential facility that may only be developed in discrete levels is equal to the installed unit of capacity multiplied by the number of units selected to be installed at the chosen optimal investment time period.

$$DCF_{ft}=CAPF_{ft}*UNITF_f$$

(24) a constraint is written for every potential processing facility (f=1,..,POTF) for every time period (t=1,..,T)

$$DCTS_{st} = CAPTS_{st} * UNITTS$$

(25) a constraint is written for every potential transfer station (s=1,..,POTTS) for every time period (t=1,..,T)

(6) The expanded capacity of a facility that may only be developed in discrete levels is equal to the installed unit of capacity multiplied by the number of units selected to be installed at the chosen expansion times.

$$EXPF_{ft} = XF_{ft} * UF_{f}$$

(26) a constraint is written for every processing facility (f=1,..,TOTFACS) for every time period expansion is possible within the set (t=1,..,T)

$$EXPTS_{st} = XTS_{st} * UTS$$

(27) a constraint is written for every transfer station (s=1,..,TOTTS) for every time period expansion is possible within the set (t=1,..,T)

(7) Maximum capacity restriction on all potential facilities must be checked and with the second equation it ensures that a potential facility cannot be expanded until the next period after which it was assigned its initial design capacity. Only one of the first set of equations will be non-zero as the facility can only be opened once during the entire time period - t* refers to this optimal time period for opening a facility. Thus, the equation corresponding to the time when the facility will be opened will ensure that the initial installed capacity DC (at t*) + any expansions from (t*+1) to the last time period, T, will be less than the maximum available capacity of the site. An additional set of variables are included for this purpose only, which are indexed with respect to the optimal start-up time period as well, to ensure these constraints are met. The second set of equations is then used to equate the expansion decision variables with the expansions indexed with respect to the start-up period in the first set of equations. Due to the first set of equations, only one term on the right side of the second set of equations will be non-zero.

$$DCF_{ft^*} + \sum_{t=t^*+1}^{T} EXPFO_{ft^*t} - (MCF_{f} * USEF_{ft^*}) \leq 0$$

(28) a constraint is written for every potential processing facility (f=1,..,POTF) for every time period (t*=1,..,T)

$$EXPF_{ft} = \sum_{t^*=1}^{t-1} EXPFO_{ft^*t}$$

(29) a constraint is written for every potential processing facility (f=1,..,POTF) for every time period when expansion is possible (at least year 2) (t=2,..,T)

$$DCTS_{st^*}+\sum_{t=t^*+1}^{T} EXPTSO_{st^*t}-(MCTS_s*USETS_{st^*})\leq 0$$

(30) a constraint is written for every potential transfer station (s=1,..,POTTS) for every time period (t*=1,..,T)

$$EXPTS_{st}=\sum_{t^*=1}^{t-1} EXPTSO_{st^*t}$$

(31) a constraint is written for every potential transfer station (s=1,..,POTTS) for every time period when expansion is possible (at least year 2) (t=2,..,T)

(8) Maximum capacity constraint on existing facilities (considering current capacity + expansions):

$$\sum_{t=1}^{T} EXPF_{ft}\leq MCF_f-DCF_f$$

(32) a constraint is written for every existing processing facility (f=POTF+1,..,TOTFACS)

$$\sum_{t=1}^{T} EXPTS_{st}\leq MCTS_s-DCTS_s$$

(33) a constraint is written for every existing transfer station (s=POTTS+1,..,TOTTS)

(9) Inflow to a facility has to be less than the capacity at that time (initial + any expansions):
Note: the DCF_{ft}, $DCTS_{st}$ are decision variables for potential facilities, but for existing facilities simply enter the corresponding current capacities DCF_f, $DCTS_s$

$$-\sum_{s=1}^{TOTTS} FLOW[SF]_{sft}-\sum_{w=1}^{TOTWSA} FLOW[WF]_{wft}-WF_{ft}+(\sum_{t'=1}^{t} DCF_{ft'}+\sum_{t'=1}^{t} EXPF_{ft'})\geq 0$$

(34) a constraint is written for every processing facility (f=1,..,TOTFACS) for every time period (t=1,..,T)

$$-\sum_{w=1}^{TOTWSA} FLOW[WS]_{wst}-WTS_{st}+(\sum_{t'=1}^{t} DCTS_{st'}+\sum_{t'=1}^{t} EXPTS_{st'})\geq 0$$

(35) a constraint is written for every transfer station (s=1,..,TOTTS) for every time period (t=1,..,T)

(10) Maximum capacity of an existing landfill must not be exceeded:

$$\sum_{t=1}^{T}\Big(\sum_{f=1}^{TOTFACS} FLOW[FL]_{flt}+\sum_{w=1}^{TOTWSA} FLOW[WL]_{wlt}+\sum_{s=1}^{TOTTS} FLOW[SL]_{slt}+WLF_{lt}\Big)\leq MCLF_{l}$$

(36) a constraint is written for every existing landfill (l=POTLF+1,..,TOTLFS)

(11) Maximum capacity of a potential landfill must not be exceeded from the time it is opened to the end of the planning horizon:

$$\sum_{t=t^{*}}^{T}\Big(\sum_{f=1}^{TOTFACS} FLOW[FL]_{flt}+\sum_{w=1}^{TOTWSA} FLOW[WL]_{wlt}+\sum_{s=1}^{TOTTS} FLOW[SL]_{slt}+WLF_{lt}\Big)\leq MCLF_{l}*\sum_{t=t^{*}}^{T} USELF_{lt}$$

(37) a constraint is written for every potential landfill (l=1,,..,POTLF) for every time period (t=1,..,T)

(12) Maximum amount of recyclables or compostables that may be diverted to MRFs or CCFS for processing (depending on the composition of the waste) within an integrated system:

$$\sum_{f=R} FLOW[WF]_{wft}\leq WASTE_{wt}*REC_{t}$$

(38) a constraint is written for every waste source area (w=1,..,TOTWSA) for every time period (t=1,..,T) including all potential and existing MRFs within the set (f=1,..,TOTFACS)

$$\sum_{f=R} WF_{ft}\leq W_{t}*REC_{t}$$

(39) a constraint is written for every time period (t=1,..,T)

$$\sum_{f=C} FLOW[WF]_{wft}\leq WASTE_{wt}*COMP_{t}$$

(40) a constraint is written for every waste source area (w=1, .,TOTWSA) for every time period (t=1,..,T) including all potential and existing CCFs within the set (f=1,..,TOTFACS)

$$\sum_{f=C} WF_{ft}\leq W_{t}*COMP_{t}$$

(41) a constraint is written for every time period (t=1,..,T)

(13) Non-negativity - to ensure flows and capacities are never negative (most packages automatically account for this):

$$FLOW[WS]_{wst}\geq 0;\ FLOW[WF]_{wft}\geq 0;\ FLOW[WL]_{wlt}\geq 0;\ FLOW[SF]_{sft}\geq 0;\ FLOW[SL]_{slt}\geq 0;\ FLOW[FL]_{flt}\geq 0$$

(42) a constraint is written for every possible flow link for every time period (t=1,..,T)

$$WF_{ft} \geq 0;\ WTS_{st} \geq 0;\ WLF_{kt} \geq 0$$

(43) a constraint is written for every possible flow from outside sources to every possible facility for every time period (t=1,..,T)

$$DCF_{ft} \geq 0;\ DCTS_{st} \geq 0;\ DCLF_{kt} \geq 0$$

(44) a constraint is written for every potential facility for every time period (t=1,..,T)

$$EXPF_{ft} \geq 0;\ EXPTS_{st} \geq 0;\ EXPLF_{kt} \geq 0$$

(45) a constraint is written for every potential and existing facility for every time period (t=1,..,T)

$$EXPFO_{ft^*t} \geq 0;\ EXPTSO_{st^*t} \geq 0$$

(46) a constraint is written for every potential facility for every combination of time period (t=1,..,T) and optimal investment time period (t*=1,..,T)

(14) Integer constraints - to account for fixed costs using a use/not use (0,1) variable for each potential facility (different solution packages may have different methods of specifying this):

$$USEF_{ft}=(0,1);\ USETS_{st}=(0,1);\ USELF_{kt}=(0,1)$$

(47) a constraint is written for every potential facility with a fixed capital cost (other than 0) for every time period (t=1,..,T)

(15) Integer constraints - to account for discrete design and expansion capacities being developed using a (0,..,MAX) variable (different solution packages may have different methods of specifying this):

$$CAPF_{ft}=(0,..,MAXF);\ CAPTS_{st}=(0,..,MAXTS)$$

(48) a constraint is written for every potential facility with discrete (integer) design capacities for every time period (t=1,..,T)

$$XF_{ft}=(0,..,MF);\ XTS_{st}=(0,..,MTS)$$

(49) a constraint is written for every existing and potential facility with discrete (integer) expansion capacities for every time period (t=1,..,T)

where: (coefficients can be taken from the facility spreadsheet models or from the data collected by INPUT.KBS in file: MODEL; or from waste generation data collected in the spreadsheet: WASTE.WK1; if a certain technology is not used simply do not include the terms relating to it)

$WASTE_{wt}$ = the total waste originating from waste source area w during time period t (from WASTE.WK1); if the length of time periods (in years) is > 1 (i.e., not an annual analysis) then the data have to be aggregated - for example, if 5 time periods of 4 year lengths are to be modelled then 4 years of data have to be combined (eg., using 4 * the maximum flow rate during each time period, to ensure sufficient capacity is developed) changing the units from tonnes/year to tonnes/4 years. This waste stream should be only that which the municipality is paying to collect and transport to a facility. If managing a portion of the waste stream is not the responsibility of the community or municipality (for certain large ICI generators this may be the case) then it should not be included. These waste flows are accounted for using the WF, WTS, WLF decision variables [t/time period years] (portions of the total waste flow from outside sources, W).

W_t = the total waste originating from all outside sources (not collected or financed by the municipality) that will be managed within the MSW management system [tonnes/time period years] (can estimate using spreadsheets ICI.WK1 and WASTE.WK1)

DCF_f,$DCTS_s$ = the initial design capacity of existing processing facility f and existing transfer station s - the current capacity of the facility (known) (which has taken into account a factor for capacity utilization (from FAC_***.WK1)); it refers to the maximum operating capacity [tonnes/year] of an existing facility (before expansions) * 20/T OR the maximum design capacity [t/day] * operating days per year * capacity utilization factor * 20/T to get the maximum operating capacity [tonnes/time period years]

MCF_f,$MCTS_s$ = the maximum design capacity of a facility which is known for all existing and potential facility sites - for EXISTING FACILITIES: (current operating capacity of the facility + the maximum expansion operating capacity)*(20/T) which has taken into account a factor for capacity utilization (from FAC_***.WK1) [tonnes/time period years] OR the (maximum design capacity + maximum design expansion capacity) [t/day] * operating days per year * capacity utilization factor * 20/T to get the maximum operating capacity [tonnes/time period years]; POTENTIAL FACILITY SITES: maximum operating capacity of the site * 20/T [t/time period years] OR maximum capacity [t/day] * operating days per year * capacity utilization * 20/T - this maximum may be due to area restrictions or technical or economic factors. If no maximum capacity restriction is to be set, the maximum capacity parameter should read 10000 tonnes/day in FAC_***.WK1.

$MCLF_l$ = the maximum capacity of landfill site l [tonnes] for all existing and potential facilities is (available in: FAC_LF.WK1 = maximum (remaining) capacity [m^3] * material density in landfill [kg/m^3] /1000 [kg/tonne]) due to the area available at a site

$RESFAC_f$ = the fraction of the input flow to a MRF or CCF that is residuals requiring disposal in a landfill (from FAC_MRF.WK1 or FAC_CCF.WK1)

REC_t = the maximum fraction of the waste stream originating from the waste source areas that is recyclable and can be expected to be recovered for processing at MRFs in a specified time period. For a recyclables system in isolation this factor would equal one (as the flow estimates represent the flows of recyclables from waste source areas) and this constraint is not needed. If you are including MRFs in an integrated planning problem you will have to develop this estimate, which is affected by numerous decisions including: the materials accepted at the MRFs; the limitations that may be expected in the number of materials collected through recycling programs; the program participation rates and material capture rates; and waste composition considerations. You must look at the composition of waste generated in the SFDs, MFDs and ICI sites from which materials are expected to be picked up over each time period (from spreadsheets SFDS20.WK1, MFDS20.WK1 and ICI.WK1) and consider the expected program participation rates and the amounts of available materials generators will capture for recycling (dependent on program type - R_***.KBS can be consulted).

$COMP_t$ = the maximum fraction of the waste stream originating from the waste source areas that is compostable and may be recovered at CCFs in a specified time period. For a compostables system in isolation this factor is one (as flow estimates represent the flows of compostables from waste source areas) and this constraint is not needed. If you are including CCFs in an integrated planning problem you will have to develop an estimate for this factor, which is affected by numerous decisions including: the materials accepted at the CCFs; the impacts of on-site (backyard) composting efforts; the limitations that may be expected in the number of materials collected through composting programs; the effects of program participation and material capture rates; and waste composition. You must look at the composition of waste generated in the SFDs, MFDs and ICI sites from which materials are picked up over each time period (from spreadsheets SFDS20.WK1, MFDS20.WK1,ICI.WK1) and consider the expected program participation rates and the amount of an acceptable material actually captured for composting by generators (dependent on program type - C_***.KBS can be consulted).

M = index referring to mixed MSW processing facilities in the set (f=1,..,TOTFACS) or (f=1,..,POTF)
E = index referring to EFW facilities in the set (f=1,..,TOTFACS) or (f=1,..,POTF)
R = index referring to MRFs in the set (f=1,..,TOTFACS) or (f=1,..,POTF)
C = index referring to CCFs in the set (f=1,..,TOTFACS) or (f=1,..,POTF)

CONSTRAINTS: The following constraints are optional, depending on the system being studied, and may be included to account for other restrictions placed on the operation of the system to represent waste diversion goals, or additional political, social, technical, economic or environmental considerations.

(16) The initial capacity of a potential facility (processing or transfer) must be greater than a specified minimum for the facility to be built - to account for economic or technical considerations.

$$\sum_{t=1}^{T} DCF_{ft} \geq MINF_f * \sum_{t=1}^{T} USEF_{ft}$$

(50) a constraint may be written for every potential processing facility (f=1,..,POTF)

$$\sum_{t=1}^{T} DCTS_{st} \geq MINTS_s * \sum_{t=1}^{T} USETS_{st}$$

(51) a constraint may be written for every potential transfer station (s=1,..,POTTS)

(17) Waste diversion goals:

(a) Limit on the total fraction of the waste stream that may be landfilled and/or incinerated during a particular time period:

$$\sum_{l=1}^{TOTLFS} (WLF_{lt} + \sum_{w=1}^{TOTWSA} FLOW[WL]_{wlt} + \sum_{f=1}^{TOTFACS} FLOW[FL]_{flt} + \sum_{s=1}^{TOTTS} FLOW[SL]_{slt}) \leq L_t * (W_t + \sum_{w=1}^{TOTWSA} WASTE_{wt})$$

(52) a constraint may be written for every time period (t=1,..,T) including all landfills

$$\sum_{f \in E} (WF_{ft} + \sum_{w=1}^{TOTWSA} FLOW[WF]_{wft} + \sum_{f \in E} FLOW[SF]_{sft}) \leq I_t * (W_t + \sum_{w=1}^{TOTWSA} WASTE_{wt})$$

(53) a constraint may be written for every time period (t=1,..,T) including all EFW facilities in the set (f=1,..,TOTFACS)

(b) The other method of setting waste diversion goals is to set a restriction on the minimum fraction of waste diverted from landfills through recycling and composting (you may or may not wish to include waste processed in mixed MSW processing facilities):

$$\sum_{f=R,C,M}(WF_{ft}+\sum_{w=1}^{TOTWSA} FLOW[WF]_{wft}+\sum_{s=1}^{TOTTS} FLOW[SF]_{sft})*(RFAC_f+CFAC_f)\geq DV_t*(W_t+\sum_{w=1}^{TOTWSA} WASTE_{wt})$$

(54) a constraint may be written for every time period (t=1,...,T) for which a goal is to be set including MRFs, CCFs, and/or mixed MSW processing facilities from the set (f=1,...,TOTFACS)

(18) Limit on the total budget available in a particular planning period:

$$OBJECTIVE\ FUNCTION_t\leq BUDGET_t$$

(55) a constraint may be written for any or all time periods in the set (t=1,...,T)

(19) Limit on the total number of individual types of potential facilities or the total number of potential facilities that may be developed over the planning horizon:

$$\sum_{t=1}^{T}\sum_{f=R,C,E,M} USEF_{ft}\leq NUMF$$

(56) a constraint may be written for the potential MRFs, CCFs, EFW facilities, and/or mixed MSW processing facilities

$$\sum_{t=1}^{T}\sum_{s=1}^{POTTS} USETS_{st}\leq NUMTS$$

(57) a constraint may be written for the potential transfer stations

$$\sum_{t=1}^{T}\sum_{l=1}^{POTLF} USELF_{lt}\leq NUMLF$$

(58) a constraint may be written for the potential landfills

$$\sum_{t=1}^{T}(\sum_{f=1}^{POTF} USEF_{ft}+\sum_{s=1}^{POTTS} USETS_{st}+\sum_{l=1}^{POTLF} USELF_{lt})\leq TOTNUM$$

(59) a constraint may be written to include all potential facilities of any type

(20) Limits on the amounts of recyclables, energy or RDF that may be recovered in a particular time period due to market demand limitations:

$$\sum_{f=R,M,E} (WF_{ft} + \sum_{w=1}^{TOTWSA} FLOW[WF]_{wft} + \sum_{s=1}^{TOTTS} FLOW[SF]_{sft}) * RFAC_f \leq DREC_t$$

(60) a constraint may be written to restrict the amount of recyclables recovered in any or all time periods (t=1,..,T)

$$\sum_{f=C,M} (WF_{ft} + \sum_{w=1}^{TOTWSA} FLOW[WF]_{wft} + \sum_{s=1}^{TOTTS} FLOW[SF]_{sft}) * CFAC_f \leq DCOMP_t$$

(61) a constraint may be written to limit the amount of compostables recovered in any or all time periods (t=1,..,T)

$$\sum_{f=E} (WF_{ft} + \sum_{w=1}^{TOTWSA} FLOW[WF]_{wft} + \sum_{s=1}^{TOTTS} FLOW[SF]_{sft}) * ENGFAC_f \leq DENG_t$$

(62) a constraint may be written to limit the amount of materials used to produce energy in any or all time periods (t=1,..,T)

$$\sum_{f=M,E} (WF_{ft} + \sum_{w=1}^{TOTWSA} FLOW[WF]_{wft} + \sum_{s=1}^{TOTTS} FLOW[SF]_{sft}) * RDFFAC_f \leq DRDF_t$$

(63) a constraint may be written to limit the amount of RDF recovered in any or all time periods (t=1,..,T)

where: (coefficients can be taken from the facility spreadsheets or from the data collected by INPUT.KBS in file: MODEL; or from waste generation data collected in the spreadsheet: WASTE.WK1; if a certain technology is not used simply do not include the terms relating to it)

$MINF_f$ = minimum capacity for potential processing facility f due to economic or technical reasons (from FAC_***.WK1) [t/day] * operating days per year * capacity utilization factor * 20/T [tonnes/time period years]; if no minimum capacity restriction is to be set the parameter should read 0 (in FAC_***.WK1)

$MINTS_s$ = minimum capacity for potential transfer station s due to economic or technical reasons (from FAC_***.WK1) [t/day] * operating days per year * capacity utilization factor * 20/T [tonnes/time period years]; if no minimum capacity restriction is to be set the parameter should read 0 (in FAC_***.WK1)

L_t = maximum fraction of the waste stream that may be landfilled in time period t

I_t = maximum fraction of the waste stream that may be incinerated in time period t

DV_t = minimum fraction of the waste stream that should be diverted from landfills or incinerators during time period t to allow waste diversion targets or goals to be set

$BUDGET_t$ = total budget available for MSW management in time period t (to restrict the total system cost as calculated by the objective function equation for time period t)

NUMF = maximum number of a specific processing facility that may be developed from the potential sites over the entire planning horizon (data in FAC_***.WK1); if no restriction is to be set (i.e., NUMF = number of available sites) this constraint is not needed

NUMTS = maximum number of a transfer stations that may be developed from the number of potential sites over the entire planning horizon (data in FAC_TS.WK1); if no restriction is to be set (i.e., NUMTS = number of available sites) this constraint is not needed

NUMLF = maximum number of a landfills that may be developed from the number of potential sites over the entire planning horizon (data in FAC_LF.WK1); if no restriction is to be set (i.e., NUMLF = number of available sites) this constraint is not needed

TOTNUM = total maximum number of potential sites (including all facility types) that may be developed over the entire planning horizon (from information on maximum number of facilities of each type in FAC_***.WK1) (You may also wish to limit the number of facilities developed within the same geographical area.)

$RFAC_f$ = fraction of the input waste stream recovered as recyclables at processing facility f (from FAC_***.WK1)
= (1 - residuals factor) for MRFs (R)
= ferrous factor for EFW facilities (E)
= recycling factor for mixed MSW processing facilities (M)

$CFAC_f$ = fraction of the input stream recovered as compostables at processing facility f (from FAC_***.WK1)
= (1 - residuals factor) for CCFs (C)
= composting factor for mixed MSW processing facilities (M)

$ENGFAC_f$ = fraction of the input waste stream recovered as energy at processing facility f (assumed to be = 1 for EFW facilities that combust waste (E) as energy generation was assumed to be based on the total input)

$RDFFAC_f$ = fraction of the input waste stream recovered as RDF at processing facility f (from FAC_***.WK1)
= RDF factor for mixed MSW processing facilities (M)
= RDF factor for EFW facilities (E) that produce RDF without combustion

$DCOMP_t$ = total demand for compostables in time period t [tonnes/time period years]
$DREC_t$ = total demand for recyclables in time period t [tonnes/time period years]
$DENG_t$ = total energy demand - as a limit on waste incinerated in time period t [tonnes/time period years]
$DRDF_t$ = total demand for RDF in time period t [tonnes/time period years]

NOTE: The mathematical statements representing system constraints are generally entered into optimization solution software with the linear combination of decision variables on the left-hand side of the relationship (=, >, <, >=, <=) and a single numeric value on the right-hand side of the relationship.

MODELLING ASSUMPTIONS:

- All parameter values are deterministic.
- Information on projects can be transformed into cash flows.
- The possibility of improvements in technologies that will lead to increases or decreases in costs are not considered. Replacements are not considered.
- A single discounting factor is applied to all cost components.
- It is assumed that operating costs for facilities include depreciation costs; however, the model does not account for any value a facility may have if closed before the end of its useful, economic life.
- Due to the use of linear costing relationships, no economies of scale are considered (beyond the fixed costs).

- Interactions with other public sector investment decisions are omitted.
- The land available for facility siting and expansions remains the same over the entire planning period.
- If used, the entire available site for a potential landfill must be acquired.
- No backlogs of waste are allowed, i.e., there is no storage within the community - whatever is generated is collected.
- Once a facility is opened, it will not close (unless it is a landfill which reaches its design capacity).
- Expansions are not possible until at least the first time period after a facility is opened.

APPENDIX E

A listing of the optimization study knowledge-based system component of the prototype decision support system for the generation of near-optimal system solutions (STEP 6)

NEAR_OPT.KBS -> **Assistance in generating near-optimal system solutions.**

```
RUNTIME;
ACTIONS
WOPEN 1,4,10,14,61,6
ACTIVE 1
DISPLAY "          METHODS OF GENERATING ALTERNATIVES
   This component of the decision support tool assists
   with methods of generating alternative near-optimal
   solutions to a waste management systems planning
   problem that has been solved using the optimization
   program to generate an optimal (least-cost) solution.
   In order to produce other alternative systems with
   near-optimal costs, certain changes must be made to
   the mathematical formulation of the original problem. ~ "
WCLOSE 1
WOPEN 1,1,2,20,75,3
ACTIVE 1
DISPLAY "                    INTRODUCTION
  Methods for Generating Alternatives are techniques used to try
  and derive as much information from a model as possible.
  The objective is to generate alternatives that are different than the
  optimal solution but still good. The term 'different' in the case of
  facilities planning for MSW management refers to different facility
  development and usage patterns through to different waste allocations
  to facilities. The solution should still be good with respect to the
  modelled objective, in this case the minimization of the total
  present value cost of the system.

  It is of assistance in decision-making to have several good (with
  respect to cost), but different alternatives to consider so a more
  informed decision can be made. This will aid in understanding the
  system and taking other objectives into consideration relating to
  the social, political and environmental implications of a MSW system. ~ "
DISPLAY "
  LP and MILP models are generally limited in the amount of helpful
  information they can provide if they are used to generate only one
  'optimal' solution.  This is particularly true as they often only
  consider economic elements when public sector planning is concerned
  with many other effects when planning MSW management systems.

  If other objectives (environmental, social, political, etc.) are not
  considered within the model formulation this means that the optimal
  solution derived by the model may not be the 'best' solution.
  This is particularly true for public sector planning such as for MSW
  management systems, as the systems are very complex and cannot be
  represented fully by a mathematical model. ~ "
DISPLAY "
  These approaches offer a way to use these models to investigate MSW
  systems especially if they are used not to derive a single solution to
  a planning problem but to provide additional information. Sensitivity
  analysis is one method of extending the benefit of these types of
  models in public sector planning. These techniques offer additional
  means for the models to provide support for decision-making. ~ "
DISPLAY "
```

In fact, most researchers and planners agree that these models are best used in generating planning alternatives and providing a means with which alternatives can be evaluated and elaborated upon. They can provide a decision-maker with additional insights into a problem and serve as a spark for new ideas. It has been suggested that a number of modelling tools be used in a planning study and used more thoroughly. (Reference list will be supplied at end of consultation).

As a result of these opinions, this planning tool has been designed using several modelling tools and assistance is provided to attempt to more fully utilize the capabilities of previously developed models. ~ "

DISPLAY "

There are several approaches to developing alternatives using an LP or MILP optimization model.

1) Ad hoc changing of the model: This approach was mentioned with respect to sensitivity analysis. You may wish to simply create 'what-if' scenarios, changing constraints, adding new constraints or changing the objective. For example, you may wish to adjust some of the right-hand side values of the constraints to investigate the effects of uncertainty by doing experimental runs with a value at +50% and -50% of the original estimate. ~ "

DISPLAY "

You may also add a constraint(s) that specifies a maximum limit on the number of the potential facility sites in a certain area that can be developed to establish some degree of equity among communities with respect to hosting waste receiving facilities. The objective of the model may also be changed. The current cost objective may be changed to a constraint (OBJECTIVE FUNCTION <= specified cost) or included simply to provide the total system cost (TOT_COST = OBJECTIVE FUNCTION) and a new objective may be formulated. For example, you could MAXIMIZE flows to MRFs and CCFs (i.e., maximize source separation). ~ "

DISPLAY "

2) Generate Alternatives at random: you may wish to create scenarios with different potential facility sites set as used or not used, or set the capacities of one or more facilities using the results of the initial optimal solution. For example, if the original solution calls for the use of a mixed MSW processing facility, you may wish to investigate what would happen if this site was not used. You may also wish to set capacities for facilities, as the optimal solution may set capacity expansions in each time period. ~ "

DISPLAY "

Chang et al. (1982) maximize the sum of several randomly selected decision variables in an MILP formulation. Harrington and Gidley (1985) generate a uniformly distributed [-1,1] number as a coefficient to all the decision variables in an LP formulation. The problem with this approach is that you may concentrate on one section of all total possible solutions. It may also not be very efficient to generate alternatives in this manner. This method may be applicable if several distinct alternatives are to be investigated, or you wish to look at systems incorporating two competing technologies such as EFW and mixed MSW processing plants. ~ "

DISPLAY "

3) Use information available from the solution package: This approach is possible only for MILP models solved using what is called the Branch and Bound method. To solve an MILP model formulation, the

```
  solution package explores all the various combinations of facility
  usage (branches) and determines if they are feasible (i.e., meet
  the constraints) and if so, which one is the best feasible solution.
  Therefore, if the solution package allows the examination of other
  feasible solutions (branches) it found, you may look at the value
  of the objective function (total system cost) and compare it to the
  optimal least-cost solution and decide if it is an acceptable
  alternative to consider. Brill (1979) warns that the solution
  packages are designed primarily to provide 'the answer' and may
  not be designed to store or display additional information. -- "
WCLOSE 1
WOPEN 1,1,2,20,75,5
ACTIVE 1
DISPLAY "  RECOMMENDATION: on the Method of Generating Alternatives
 The problem with the above methods is that they do not ensure that
 different and good solutions are produced as they do not directly
 include a driving force within the model algorithm.  None of the
 approaches provides a general, routine method of getting different
 alternatives.  Some may not even produce different alternatives. As
 a result, a more direct technique of producing alternative near-
 optimal solutions has been devised.
 4) Hop Skip Jump (HSJ) method: This approach is based on the idea
   that we can generate alternatives by jumping around the system
   After obtaining the optimal, feasible solution to a systems
   planning problem, you can adjust the model formulation to try and
   force the production of a different but good alternative solution.
   This is done by creating a constraint out of the objective function
                 OBJECTIVE FUNCTION  < = maximum cost. -- "
DISPLAY "
  The maximum cost is usually set as a certain percentage greater
  than the optimal least-cost solution.  Previous studies of water
  resources planning problems used 10 % (i.e., maximum cost = 1.1 *
  LEAST-COST O.F. VALUE).  This constraint is used to specify what a
  'good' solution is (i.e., in this case it is assumed that good
  solutions, when unmodelled issues are considered, are not very
  likely to have costs 10% higher than the previous least-cost case).
  To force the model to produce a good, but also 'different' solution
  (with respect to facility usage patterns and thus waste assignments)
  you create an objective function from the decision variables.  The
  suggestion is that you MINIMIZE the sum of the capacities (design
  and expansions) for facilities and/or the flows to facilities [i.e.,
  the continuous, non-integer variables] from the previous optimal solution. -- "
DISPLAY "
  This forces the model to try to not use these facilities unless it has
  to, to meet the constraints. It may be that another solution cannot be
  found that meets all the original constraints and meets the cost
  constraint except the original least-cost solution.  You may wish to
  relax the total cost constraint if the output analysis provided
  indicates this constraint is binding (i.e., SLACK VARIABLE = 0). -- "
DISPLAY "
  If an alternative is produced and you wish to generate an additional
  solution, the suggestion is that you minimize the sum of decision
  variables that were positive in the first AND second runs.  In this
  case the capacities of facilities used in either run.  This will
  generate an alternative, if it is possible, that is different from
```

```
   the first and second solutions. Alternatively, you may minimize the
   sum of the non-zero continuous decision variables (i.e., capacities
   as opposed to the non-continuous integer variables) in the second
   solution. This process of minimizing the sum of non-zero continuous
   decision variables in one or more previous solutions can continuc
   until an adequate number of alternatives are generated or until no
   new (different) systems are produced. ~ "
DISPLAY "
   In the extreme case it drives the previous non-zero decision variables
   to zero producing a completely different system, however, this is
   usually not possible given the other constraints on the solution.
   You can also start with different initial solutions produced by
   examining other branches (as explained previously) for a MILP
   formulation, or by proposing different scenarios with different
   sets of technologies or different constraints. ~ "
WCLOSE 1
WOPEN 1,1,3,20,74,3
ACTIVE 1
DISPLAY "  Other modifications to the HSJ method:
 a) You can assign weighting factors to the decision variables in a new
    objective function, i.e., force the model to try to reduce capacities
    (possibly to the point where they are not used) of certain facilities
    as a priority over others.
 b) If it is an MILP model formulation, you may wish to experiment by
    creating a new objective function which minimizes the integer valued
    decision variables. This would involve summing the previous facility
    (0,1) decision variables that were assigned a 1 value. In this case,
    the model would try to derive a solution in which these facilities
    were not used, if possible. Chang et al.(1983) found this approach
    to be less effective as there is no driving force to reduce capacities
    of plants that cannot be made zero (i.e., if a facility cannot be removed
    from the system -> there will be no 'push' to decrease its capacity).
    If a facility does not have to be used, it may be driven out of solution. ~ "
WCLOSE 1
WOPEN 1,1,2,20,75,5
ACTIVE 1
DISPLAY "  OBSERVATIONS AND RECOMMENDATIONS FROM RESEARCHERS:
   * It may be more useful to generate a small set of very different
     solutions that span a range of choices as it is difficult to deal
     with a large number of alternatives.
   * The use of these approaches is important in areas such as MSW
     management where many objectives (environmental, political, social)
     may not be included in the model but are critical to decision-making.
   * For some problems, there may be few alternatives generated due to the
     limiting effect of constraints or a limited number of options for
     technologies or sites being investigated. Also, there may be a number
     of alternatives generated, but they may be only marginally different. ~ "
DISPLAY "
   * You may find that certain decision variable values may fluctuate
     widely, while others will remain relatively constant in the
     alternative systems produced. This reflects the sensitivity of
     the model (or system) to these technologies. If a decision
     variable can vary widely without significantly affecting costs,
     there is more choice for its value so more precise measurements of
     the other, non-economic effects of this variable may be important.
```

```
    If a decision variable is relatively invariant then it has a
    significant impact on the system cost and it may be worthwhile to
    invest time in more precisely  determining the costs of this
    option. (This was found to be the case for a problem of sizing
    reservoirs and power plants. See Harrington and Gidley (1985).)~"
DISPLAY "
  * It must be remembered that all decision variables are interrelated.
    Therefore, you must be cautious in interpreting variations. For
    example, while the total capacity of the system is invariant as
    all waste must be managed, individual facility capacities may vary.
    However, there may be a trade-off between competing facilities,
    i.e, if in one solution one facility has a large capacity and the
    other a small, the next solution may involve the reverse.  If a
    certain technological option has a relatively small cost compared
    to the rest of the system then its decision variables may fluctuate
    widely with the overall cost still near the optimal providing this
    does not result in a direct trade-off effect with the capacity of
    an expensive option.  For example, transfer station capacities may
    vary widely in a system with expensive EFW or landfill facilities.  ~"
WCLOSE 1
WOPEN 1,2,4,17,73,3
ACTIVE 1
DISPLAY "  LOOKING FOR A DIFFERENCE BETWEEN SOLUTIONS:
 a) alternatives generated may be different with respect to unmodelled, but
    important, objectives such as equity among the various areas of the
    region with respect to hosting facilities, the creation of employment
    or the environmental risks of implementing a proposed group of technologies;
 b) alternatives may suggest the same technologies but varying locations;
 c) alternatives may be different with respect to the types of technologies
    used and/or the suggested capacities of facilities.~"
WCLOSE 1
WOPEN 1,2,3,15,74,1
ACTIVE 1
DISPLAY "                    MAIN REFERENCES:
   E.D. Brill, Jr. (1979). The Use of Optimization Models in Public-
   Sector Planning. Management Science, 25(5): 413-422.

   S-Y.C. Chang, E.D. Brill, Jr. and L.D. Hopkins. (1982). Use of
   Mathematical Models to Generated Alternative Solutions to Water
   Resources Planning Problems. Water Resources Research, 18(1): 58-64.

   J.J. Harrington and J.S. Gidley. (1985). The Variability of
   Alternative Decisions in a Water Resources Planning Problem. Water
   Resources Research, 21(12): 1831-1840.~"
WCLOSE 1
WOPEN 1,4,7,13,64,6
ACTIVE 1
DISPLAY "  THE END OF THE CONSULTATION on GENERATING ALTERNATIVE
   (near-optimal) SOLUTIONS to LP/MILP model FORMULATIONS
   You may now exit VP-Expert and investigate the generation
   of alternative (near-optimal) solutions to a planning
   problem.  You may then return to VP-Expert to receive
   information on the use of the simulation model for further
   investigation of a MSW management system planning problem.~"
WCLOSE 1;
```

APPENDIX F

A complete listing of the simulation program (developed in FORTRAN) and accompanying documentation for use in conducting a simulation study (STEP 7)

```
C *****************************************************************
C *
C *                          SIM.FOR
C *
C *  This program simulates a municipal solid waste management system that
C *  was developed through the MILP model or by some other means.  It provides
C *  a user with a tool with which to investigate the impact of uncertainty
C *  in waste generation data on the resulting costs and waste allocations of
C *  a given MSW management system. This simulation model also allows a user
C *  to investigate the impacts of changes to other estimated parameters for
C *  an existing or proposed MSW management system.
C *
C *  A user must specify the system - flow assignments to the facilities; the
C *  collection, transportation, and operating costs; capacity and waste flow
C *  limitations; residuals and revenue factors; residuals disposal costs and
C *  revenues - for each time period for which periodic data are available
C *
C *****************************************************************
C
C *****************************************************************
C *
C *                    VARIABLE DICTIONARY
C *
C *****************************************************************
C *  WASTE GENERATION DATA (available series):
C *  IYEAR = index for years
C *  TOTWSA = number of waste sources areas
C *  IN.DAT = name of file with waste generation data series
C *  NUMYRS = number of years of waste generation data available
C *  IP = number of periods in each year of waste generation data
C *  WASTE(W,IYEAR,J) = total waste generation rate for waste source area W
C *                          in year IYEAR, period J  [tonnes/PERIOD]
C *
C *  WASTE GENERATION DATA (synthetic series generation):
C *  IYEAR = index for years
C *  TOTWSA = number of waste source areas
C *  HIST.DAT = name of file with historical data for each WSA
C *  IP = number of periods in each year of the historical data series
C *  IY = number of years in the historical data series
C *  YAVE = average annual forecasted waste generation rate [tonnes/year]
C *  RN = uniformly distributed random number
C *  WASTE(W,IYEAR,J) = synthetic waste flow for waste source area W in year
C *                           IYEAR, period J  [tonnes/period]
C *******************************************************************
C *  MSW MANAGEMENT SYSTEM SIMULATION:
C *  (data required from MILP run or other analysis)
C *  SYS.DAT = name of the file with the MSW management system data
C *  BT = discount rate
C *  W = waste source area index
C *  L = landfill index
```

```
C *  F = processing facility index
C *  S = transfer station index
C *  I = index for all facilities included as one set
C *  TOTWSA = number of waste source areas
C *  TOTLFS = total number of landfills (existing and potential)
C *  TOTFAC = total number of processing facilities (existing and potential)
C *  TOTTS = total number of transfer stations (existing and potential)
C *  TOTAL = total number of facilities in the MSW management system
C *  T = time period index for the MSW management system data
C *  IT = total number of time periods represented in the MSW management system data
C *  TIME = number of years in each time period for the MSW management system data
C *
C *  WASTE GENERATION SOURCE AREA DATA:
C *  FLOWW(W,T,I) = fraction of the flow originating from waste source area
C *                 W in time period T sent to facility I
C *  COLLN(I),HAULWF(W,I) = collection and transportation costs for waste
C *                         going to facility I from WSA W [$/tonne]
C *  WO(T,I) = waste originating from outside sources that is received during
C *            time period T at facility I
C *
C *  FACILITY DATA:
C *  RESFAC(F) = residuals factor for facility F
C *  FLOWFL(F,T,L) = fraction of residuals from facility F transported to
C *                  landfill L in time period T
C *  HAULFL(F,L) = transportation costs for residuals flows from facility F
C *                to landfill L (may include disposal if MRF/CCF system)
C *  FLOWSL(S,T,L) = fraction of output from transfer station S transported
C *                  to landfill L during time period T
C *  HAULSL(S,L) = transportation cost from transfer station S to landfill
C *                L [$/tonne]
C *  FLOWSF(S,T,F) = fraction of output from transfer station S transported
C *                  to facility F during time period T
C *  HAULSF(S,I) = transportation cost from transfer station S to facility
C *                I [$/tonne]
C *  FC(I) = total capital cost for facility I  [$]
C *  OM(I) = operating cost at facility I  [$/tonnes/year]
C *  MAXLF(L) = total capacity of landfill L  [tonnes]
C *  BACKUP(I) = backup landfill facility for facility I (referring to index)
C *  MAXF(F,T) = capacity of facility F in time period T  [tonnes/year]
C *  RFACTR(F) = fraction of input recoverable to produce revenues at
C *              processing facility F
C *  RECFAC(F) = fraction of input recovered as recyclables at facility F
C *  CFAC(F) = fraction of input recovered for composting at facility F
C *  RDFFAC(F) = fraction of input recovered as RDF at facility F
C *  REV(F) = revenue from sale of materials or energy at processing facility
C *           F  [$/tonne]
C *
C *  SIMULATION CALCULATIONS:
C *  ACAP(F,IYEAR,J) = available capacity of facility F in year IYEAR, period J
C *                    [tonnes/period]
```

```
C * FCOST(I,IYEAR) = annual cost (PV$) of operating facility I in year IYEAR
C * FLOTOT(I,IYEAR) = total waste flow received at facility I in year IYEAR (t)
C * WTOT(IYEAR) = total waste handled by the system in year IYEAR (tonnes)
C * ACOST(IYEAR) = total annual cost of operating MSWM system in year
C *                   IYEAR [PV$]
C * REVTOT(IYEAR) = total revenues in year IYEAR of simulation  [PV$]
C * TOTOM(IYEAR) = total operation and maintenance cost of the system  [PV$]
C * R(IYEAR),C(IYEAR),RDF(IYEAR) = total material recycled, composted, and
C *                                   recovered as RDF in year IYEAR [tonnes]
C * TOTCOL(IYEAR) = total cost for collection in year IYEAR [PV$]
C * TRANS(IYEAR) = total transportation cost in year IYEAR  [PV$]
C * CAPCST = total capital cost of the system (PV$)
C * COST = total system cost (PV$)
C ************************************************************************
C
C *** PART 1:  DEFINE VARIABLES.  ***
C
      INTEGER TOTWSA,NUMYRS,W,F,S,TOTLFS,TOTFAC,TOTTS,L
      INTEGER TOTAL,T,TIME,BACKUP(15),START(5)
      CHARACTER*4 NAME(20)
      CHARACTER*1 SYSTEM
      DOUBLE PRECISION Z
      DIMENSION WASTE(12,20,12),WO(20,20),FLOWW(12,20,20),COLLN(15)
      DIMENSION HAULWF(12,20),FLOWFL(10,20,5),HAULFL(10,5)
      DIMENSION FLOWSL(5,20,5),FLOWSF(5,20,10),FC(20),OM(20)
      DIMENSION RFACTR(10),RECFAC(10),CFAC(10),YAVE(20)
      DIMENSION RDFFAC(10),REV(10),FCOST(20,20),FLOTOT(20,20)
      DIMENSION ACOST(20),REVTOT(20),C(20),RDF(20),TOTCOL(20)
      DIMENSION HAULSL(5,5),CAP(20,20,52),ACAP(20,20,52),WTOT(20)
      DIMENSION TRANS(20),FLOW(20,20,52),TOTOM(20),R(20),CDF(20)
      DIMENSION HAULSF(5,10),AVE(10,20),IFREQ(20)
      REAL MAXF(15,20),MAXLF(5)
C
C *** PART 2:  READ IN INPUT PARAMETERS.  ***
C
      WRITE (*,34)
34    FORMAT(/' What type of system is involved ?'/' R = recyclables'/'
     +C = compostables'/' E = entire mixed MSW stream'/' D = residuals'
     +/' ENTER AS CAPITAL LETTER IN QUOTATION MARKS.')
      READ *, SYSTEM
      WRITE (*,21)
21    FORMAT(/,2X,'Enter 1 if you are using a predetermined waste flow s
     +eries'/,2X,'or 2 if you would like to generate stochastic waste fl
     +ow'/,2x,'data based on an existing set of historical periodic data
     +', 2X,'for each waste source area.'/)
      READ (*,*) INUM
      IF (INUM.EQ.1) GOTO 1100
C
C     * Generate synthetic waste series based on historical data  *
C
```

```
      WRITE (*,22)
22    FORMAT(/,2X,'How many years of synthetic data would you like to ge
     +nerate?'/,2X,'(Should correspond with the total number of years re
     +presented'/,2X,'in the MSW management system data.)'/)
      READ (*,*) NUMYRS
      OPEN(UNIT=1,FILE='HIST.DAT',STATUS='OLD')
      READ (1,*) IY,IP,TOTWSA
      WRITE (*,23)
23    FORMAT(//,2X,'Enter an integer seed value for random number genera
     +tor.')
      READ (*,*) NUM
      Z = DBLE(NUM)
      DO 600 W=1,TOTWSA
      DO 610 II=1,IY
      SUM = 0
      READ (1,*) (WASTE(W,II,J),J=1,IP)
      DO 616 J=1,IP
      SUM = SUM+WASTE(W,II,J)
616   CONTINUE
      AVE(W,II) = SUM/IP
610   CONTINUE
600   CONTINUE
      DO 611 W=1,TOTWSA
      READ (1,*) (YAVE(IYEAR),IYEAR=1,NUMYRS)
      GMIN = 1000
      GMAX = 0
      DO 650 II=1,IY
      DO 660 J=1,IP
      WASTE(W,II,J) = WASTE(W,II,J)/AVE(W,II)
      IF (WASTE(W,II,J).LT.GMIN) GMIN = WASTE(W,II,J)
      IF (WASTE(W,II,J).GT.GMAX) GMAX = WASTE(W,II,J)
660   CONTINUE
650   CONTINUE
      DO 651 K=1,10
      IFREQ(K) = 0
651   CONTINUE
      DIV = (GMAX-GMIN)/10
      DO 642 II=1,IY
      DO 641 J=1,IP
      DO 643 K=1,20
      IF (WASTE(W,II,J).LT.GMIN+(K*DIV)) THEN
      IFREQ(K)=IFREQ(K)+1
      GOTO 641
      ENDIF
643   CONTINUE
641   CONTINUE
642   CONTINUE
      CDF(1) = FLOAT(IFREQ(1))/(IY*IP)
      DO 681 K=2,10
      KK=K-1
```

```
      CDF(K) = CDF(KK)+(FLOAT(IFREQ(K))/(IY*IP))
681   CONTINUE
      DO 680 IYEAR=1,NUMYRS
      DO 690 J=1,IP
      CALL URAND(Z,RN)
      DO 700 K=1,10
      IF (RN.LE.CDF(K)) THEN
      IF (K.EQ.1) CDFB=0
      IF (K.GT.1) CDFB=CDF(K-1)
      X = (RN-CDFB)*DIV/(CDF(K)-CDFB)
      WASTE(W,IYEAR,J) = YAVE(IYEAR)/IP*(GMIN+((K-1)*DIV)+X)
      GOTO 690
      ENDIF
700   CONTINUE
690   CONTINUE
680   CONTINUE
611   CONTINUE
      GOTO 1200
1100  OPEN(UNIT=3,FILE='IN.DAT',STATUS='OLD')
      READ (3,*) NUMYRS,IP,TOTWSA
C
C        * Read in predetermined waste generation data series  *
C
      DO 10 W=1,TOTWSA
      DO 20 IYEAR=1,NUMYRS
      READ (3,*) (WASTE(W,IYEAR,J),J=1,IP)
20    CONTINUE
10    CONTINUE
C
C        * Read in MSW management system data *
C
C
1200  OPEN(UNIT=2,FILE='SYS.DAT',STATUS='OLD')
      READ (2,*) IT,TIME,TOTWSA,BT
      READ (2,*) TOTFAC,TOTTS,TOTLFS
      TOTAL = TOTLFS+TOTFAC+TOTTS
      READ(2,*) (NAME(I),I=1,TOTAL)
      DO 40 W=1,TOTWSA
      DO 50 T=1,IT
      READ (2,*) (FLOWW(W,T,I),I=1,TOTAL)
50    CONTINUE
40    CONTINUE
      DO 80 W=1,TOTWSA
      READ (2,*) (HAULWF(W,I),I=1,TOTAL)
80    CONTINUE
      DO 100 T=1,IT
      READ (2,*) (WO(T,I),I=1,TOTAL)
100   CONTINUE
      LF1 = TOTFAC+TOTTS+1
      DO 120 L=LF1,TOTAL
```

```
      READ(2,*) FC(L),OM(L),MAXLF(L),BACKUP(L),START(L),COLLN(L)
120   CONTINUE
      DO 130 F=1,TOTFAC
      READ (2,*) FC(F),OM(F),RFACTR(F),RECFAC(F),CFAC(F),RDFFAC(F),
     +    REV(F),BACKUP(F),COLLN(F)
130   CONTINUE
      DO 140 F=1,TOTFAC
      READ (2,*) (MAXF(F,T),T=1,IT)
140   CONTINUE
      IF (TOTLFS.GT.0) THEN
      DO 160 F=1,TOTFAC
      DO 170 T=1,IT
      READ (2,*) (FLOWFL(F,T,L),L=LF1,TOTAL)
170   CONTINUE
160   CONTINUE
      DO 190 F=1,TOTFAC
      READ (2,*) (HAULFL(F,L),L=LF1,TOTAL)
190   CONTINUE
      ENDIF
      IS1 = TOTFAC+1
      IS2 = TOTFAC+TOTTS
      IF (TOTTS.GT.0) THEN
      DO 210 S=IS1,IS2
      READ (2,*) FC(S),OM(S),BACKUP(S),COLLN(S)
210   CONTINUE
      DO 220 S=IS1,IS2
      READ (2,*) (MAXF(S,T),T=1,IT)
220   CONTINUE
      DO 240 S=IS1,IS2
      DO 250 T=1,IT
      READ (2,*) (FLOWSL(S,T,L),L=LF1,TOTAL)
250   CONTINUE
240   CONTINUE
      DO 241 S=IS1,IS2
      READ(2,*) (HAULSL(S,L),L=LF1,TOTAL)
241   CONTINUE
      DO 270 S=IS1,IS2
      DO 280 T=1,IT
      READ (2,*) (FLOWSF(S,T,F),F=1,TOTFAC)
280   CONTINUE
270   CONTINUE
      DO 300 S=IS1,IS2
      READ(2,*) (HAULSF(S,F),F=1,TOTFAC)
300   CONTINUE
      ENDIF
C
C *** PART 3:  SIMULATION OF A MSW MANAGEMENT SYSTEM.  ***
C
C       * Calculation of total capital cost of system  *
C
```

```
      CAPCST = 0
      DO 315 I=1,TOTAL
      CAPCST = CAPCST+FC(I)
315   CONTINUE
      COST = CAPCST
C
C        * Determine capacities of facilities for each time period *
C
      DO 320 IYEAR=1,NUMYRS
      DO 330 I=1,TOTFAC+TOTTS
      T=INT((IYEAR+TIME-1)/TIME)
      DO 340 J=1,IP
      CAP(I,IYEAR,J) = MAXF(I,T)/TIME/IP
340   CONTINUE
330   CONTINUE
320   CONTINUE
C
C        * Simulate the operation of the MSW management system  *
C
      DO 400 IYEAR=1,NUMYRS
      ACOST(IYEAR) = 0
      REVTOT(IYEAR) = 0
      TOTOM(IYEAR) = 0
      R(IYEAR) = 0
      C(IYEAR) = 0
      RDF(IYEAR) = 0
      WTOT(IYEAR) = 0
      TOTCOL(IYEAR) = 0
      TRANS(IYEAR) = 0
      DO 410 I=1,TOTAL
      FCOST(I,IYEAR) = 0
      FLOTOT(I,IYEAR) = 0
      DO 420 J=1,IP
      FLOW(I,IYEAR,J) = 0
420   CONTINUE
410   CONTINUE
400   CONTINUE
      IF (SYSTEM.EQ.'R'.OR.SYSTEM.EQ.'C') THEN
      DO 444 IYEAR=1,NUMYRS
      DO 445 J=1,IP
      FLOW(15,IYEAR,J) = 0
445   CONTINUE
      FLOTOT(15,IYEAR) = 0
444   CONTINUE
      DO 446 W=1,TOTWSA
      HAULWF(W,15) = 0.0
446   CONTINUE
      ENDIF
C
      REM = 0
```

```
      IYEAR = 0
      NF = TOTFAC+TOTTS
5000  IYEAR = IYEAR + 1
      IF (SYSTEM.EQ.'R'.OR.SYSTEM.EQ.'C') ACAP(15,1,1) = 100000000.
      D = 1/((1+BT)**(IYEAR-1))
      T=INT((IYEAR+TIME-1)/TIME)
      DO 430 J=1,IP
C
C        * Waste flows from waste source areas to facilities *
C
      DO 440 I=1,TOTAL
      IF (I.LE.NF) ACAP(I,IYEAR,J)=CAP(I,IYEAR,J)
      IF (I.GT.NF) THEN
      IF (IYEAR.LT.START(I)) ACAP(I,IYEAR,J)=0
      IF (J.EQ.1.AND.IYEAR.EQ.START(I)) ACAP(I,IYEAR,J)=MAXLF(I)
      IF (J.GT.1) ACAP(I,IYEAR,J) = ACAP(I,IYEAR,(J-1))
      IB = IYEAR-1
      IF (J.EQ.1.AND.IYEAR.GT.START(I)) ACAP(I,IYEAR,J)=ACAP(I,IB,IP)
      ENDIF
      IB = IYEAR-1
      IF ((SYSTEM.EQ.'R'.OR.SYSTEM.EQ.'C').AND.J.EQ.1.AND.IYEAR.GT.1) AC
     +AP(15,IYEAR,J)=ACAP(15,IB,IP)
      IF ((SYSTEM.EQ.'R'.OR.SYSTEM.EQ.'C').AND.J.GT.1) ACAP(15,IYEAR,J)=
     +ACAP(15,IYEAR,(J-1))
440   CONTINUE
      DO 441 I=1,TOTAL
      WOUT = WO(T,I)/TIME/IP
      WTOT(IYEAR) = WTOT(IYEAR)+WOUT
      ACAP(I,IYEAR,J) = ACAP(I,IYEAR,J)-WOUT
      FLOW(I,IYEAR,J) = FLOW(I,IYEAR,J)+WOUT
      DO 450 W=1,TOTWSA
      IF (I.EQ.1) WTOT(IYEAR)=WTOT(IYEAR)+WASTE(W,IYEAR,J)
      FL=AMIN1(WASTE(W,IYEAR,J)*FLOWW(W,T,I),ACAP(I,IYEAR,J))
      FLOW(I,IYEAR,J) = FLOW(I,IYEAR,J)+FL
      ACAP(I,IYEAR,J) = ACAP(I,IYEAR,J)-FL
      REM = WASTE(W,IYEAR,J)*FLOWW(W,T,I)-FL
      ACAP(BACKUP(I),IYEAR,J) = ACAP(BACKUP(I),IYEAR,J)-REM
      FLOW(BACKUP(I),IYEAR,J) = FLOW(BACKUP(I),IYEAR,J)+REM
TRANS(IYEAR)=TRANS(IYEAR)+(FL*HAULWF(W,I)+REM*HAULWF(W,BACKUP(I)))
     +*D
      TOTCOL(IYEAR)=TOTCOL(IYEAR)+WASTE(W,IYEAR,J)*FLOWW(W,T,I)*COLLN(I)
     +*D
450   CONTINUE
441   CONTINUE
C
C        * Waste flows from transfer stations to processing facilities *
C
      DO 460 F=1,TOTFAC
      DO 470 S=IS1,IS2
      FL = AMIN1(FLOW(S,IYEAR,J)*FLOWSF(S,T,F),ACAP(F,IYEAR,J))
```

```
      FLOW(F,IYEAR,J) = FLOW(F,IYEAR,J)+FL
      ACAP(F,IYEAR,J) = ACAP(F,IYEAR,J)-FL
      REM = FLOW(S,IYEAR,J)*FLOWSF(S,T,F)-FL
      ACAP(BACKUP(F),IYEAR,J)=ACAP(BACKUP(F),IYEAR,J)-REM
      FLOW(BACKUP(F),IYEAR,J)=FLOW(BACKUP(F),IYEAR,J)+REM
      TRANS(IYEAR)=TRANS(IYEAR)+(FL*HAULSF(S,F)+(REM*HAULSL(S,BACKUP(F))
     +)*D)
470   CONTINUE
460   CONTINUE
C
C       * Residuals waste flows from processing facilities to landfills *
C
      DO 480 L=LF1,TOTAL
      DO 490 F=1,TOTFAC
      FL = AMIN1(FLOW(F,IYEAR,J)*FLOWFL(F,T,L),
     +ACAP(L,IYEAR,J))
      FLOW(L,IYEAR,J) = FLOW(L,IYEAR,J)+FL
      ACAP(L,IYEAR,J) = ACAP(L,IYEAR,J)-FL
      REM = FLOW(F,IYEAR,J)*FLOWFL(F,T,L)-FL
      ACAP(BACKUP(L),IYEAR,J)=ACAP(BACKUP(L),IYEAR,J)-REM
      FLOW(BACKUP(L),IYEAR,J)=FLOW(BACKUP(L),IYEAR,J)+REM
      TRANS(IYEAR)=TRANS(IYEAR)+(FL*HAULFL(F,L)+(REM*HAULFL(F,BACKUP(L))
     +)*D)
490   CONTINUE
480   CONTINUE
C
C       * Waste flows from transfer stations to landfills *
C
      DO 500 L=LF1,TOTAL
      DO 510 S=IS1,IS2
      FL = AMIN1(FLOW(S,IYEAR,J)*FLOWSL(S,T,L),ACAP(L,IYEAR,J))
      FLOW(L,IYEAR,J) = FLOW(L,IYEAR,J)+FL
      ACAP(L,IYEAR,J) = ACAP(L,IYEAR,J)-FL
      REM = FLOW(S,IYEAR,J)*FLOWSL(S,T,L)-FL
      ACAP(BACKUP(L),IYEAR,J)=ACAP(BACKUP(L),IYEAR,J)-REM
      FLOW(BACKUP(L),IYEAR,J)=FLOW(BACKUP(L),IYEAR,J)+REM
      TRANS(IYEAR)=TRANS(IYEAR)+(FL*HAULSL(S,L)+(REM*HAULSL(S,BACKUP(L))
     +)*D)
510   CONTINUE
500   CONTINUE
      DO 501 I=1,TOTAL
      FLOTOT(I,IYEAR) = FLOTOT(I,IYEAR)+FLOW(I,IYEAR,J)
501   CONTINUE
      IF (SYSTEM.EQ.'R'.OR.SYSTEM.EQ.'C') THEN
      FLOTOT(15,IYEAR) = FLOTOT(15,IYEAR)+FLOW(15,IYEAR,J)
      ENDIF
430   CONTINUE
C
C       * Calculate totals *
C
```

```
      DO 530 I=1,TOTAL
      TOTOM(IYEAR) = TOTOM(IYEAR)+FLOTOT(I,IYEAR)*OM(I)*D
      FCOST(I,IYEAR) = FCOST(I,IYEAR)+FLOTOT(I,IYEAR)*OM(I)*D
530   CONTINUE
      DO 540 F=1,TOTFAC
      REVTOT(IYEAR) = REVTOT(IYEAR)+FLOTOT(F,IYEAR)*RFACTR(F)*REV(F)*D
      FCOST(F,IYEAR)=FCOST(F,IYEAR)-FLOTOT(F,IYEAR)*RFACTR(F)*REV(F)*D
      R(IYEAR) = R(IYEAR)+FLOTOT(F,IYEAR)*RECFAC(F)
      C(IYEAR) = C(IYEAR)+FLOTOT(F,IYEAR)*CFAC(F)
      RDF(IYEAR) = RDF(IYEAR)+FLOTOT(F,IYEAR)*RDFFAC(F)
540   CONTINUE
      D=1/((1+BT)**IYEAR)

ACOST(IYEAR)=TOTOM(IYEAR)+TRANS(IYEAR)+TOTCOL(IYEAR)-REVTOT(IYEAR)
      COST=COST+ACOST(IYEAR)
      IF (IYEAR.EQ.NUMYRS) GOTO 1000
      GOTO 5000
C
C ***  PART 4:  PRINT-OUT OF SIMULATION RESULTS.  ***
C
1000  OPEN(UNIT=4,FILE='OUT.DAT',STATUS='NEW')
      WRITE (4,15)
15    FORMAT (//' WASTE GENERATION AT WASTE SOURCE AREAS (t/period)')
      DO 561 W=1,TOTWSA
      WRITE (4,16) W
16    FORMAT (/' WASTE SOURCE AREA: ',I3)
      DO 562 IYEAR=1,NUMYRS
      WRITE (4,14) (WASTE(W,IYEAR,J),J=1,IP)
562   CONTINUE
561   CONTINUE
14    FORMAT(1X,12F6.0/,1X,12F6.0/,1X,12F6.0/1X,12F6.0/,1X,4F6.0)
      WRITE (4,1)
1     FORMAT(/' TOTAL FLOWS TO THE FACILITIES FOR EACH SIMULATED YEAR')
      DO 560 I=1,TOTAL
      WRITE (4,3) NAME(I),(FLOTOT(I,IYEAR),IYEAR=1,NUMYRS)
560   CONTINUE
3     FORMAT(1X,A5,10F7.0,/,1X,10F7.0)
      IF (SYSTEM.EQ.'R'.OR.SYSTEM.EQ.'C') THEN
      WRITE (4,32)
32    FORMAT(/' ADDITIONAL FLOWS REQUIRING DISPOSAL FOR EACH SIMULATED
       YEAR'/' AS THE AVAILABLE CAPACITY OF THE FACILITIES IS EXCEEDED')
      WRITE (4,33) (FLOTOT(15,IYEAR),IYEAR=1,NUMYRS)
33    FORMAT (1X,10F7.0/,1X,10F7.0)
      ENDIF
      WRITE (4,17)
      IF (TOTLFS.GT.0) THEN
17        FORMAT(/' FLOWS TO LANDFILLS IN EACH YEAR AND MAXIMUM
CAPACITIES')
      DO 563 L=LF1,TOTAL
      WRITE (4,18) NAME(L),(FLOTOT(L,IYEAR),IYEAR=1,NUMYRS),MAXLF(L)
```

```
563  CONTINUE
18   FORMAT(1X,A4,10F7.0/,1X,11F7.0)
     ENDIF
     WRITE (4,4)
4    FORMAT(///' TOTAL NET OPERATING COST AT THE FACILITIES FOR EACH SI
    +MULATED YEAR (PV$)')
     DO 570 I=1,TOTAL
     WRITE (4,5) NAME(I),(FCOST(I,IYEAR),IYEAR=1,NUMYRS)
570  CONTINUE
5    FORMAT(1X,A4,10F7.0/,6X,10F7.0)
     WRITE (4,6)
6    FORMAT(///' TOTAL ANNUAL COSTS AND REVENUES FOR MSW SYSTEM (PV$)')
     WRITE (4,7)
7    FORMAT(/' YEAR',4X,'O&M',3X,'TRANSPORT',1X,'COLLECTION',1X,'REVENU
    +ES',2X,'TOTAL COST')
     DO 580 IYEAR=1,NUMYRS
     WRITE (4,8) IYEAR,TOTOM(IYEAR),TRANS(IYEAR),TOTCOL(IYEAR),
    +REVTOT(IYEAR),ACOST(IYEAR)
580  CONTINUE
8    FORMAT(1X,I3,5F10.0)
     WRITE (4,9)
9    FORMAT(///' ANNUAL WASTE RECOVERY WITH THE MSW SYSTEM (tonnes)')
     WRITE (4,12)
12   FORMAT(/' YEAR',3X,'WASTE',2X,'RECYCLABLES',' COMPOSTABLES',2X,'RD
    +F')
     DO 590 IYEAR=1,NUMYRS
     WRITE(4,11) IYEAR,WTOT(IYEAR),R(IYEAR),C(IYEAR),RDF(IYEAR)
590  CONTINUE
11   FORMAT(1X,I3,4F10.0)
     WRITE(4,13) COST
13   FORMAT(///' TOTAL COST OF THE MSW SYSTEM (PV$) = $',F10.0)
C
     STOP
     END
C
C    * SUBROUTINE: Generate uniformly distributed random numbers *
C
     SUBROUTINE URAND(Z,RN)
     DOUBLE PRECISION Z
     M = 2**21
     A = 5**8
     C = 1.0/M
     Z = Z*A-DINT(Z*A/M)*M
     Z = Z*A-DINT(Z*A/M)*M
     RN = SNGL(C*Z)
     Z = Z*A-DINT(Z*A/M)*M
     RETURN
     END
```

BRIEF EXPLANATION OF THE SIMULATION PROGRAM (SIM.FOR):

STEP 1: The type of systems planning problem being investigated is indicated, along with the type of waste generation or total material recovery data available (whether a predetermined forecasted series of waste or material flows are available, or synthetic periodic waste generation data are to be produced based on the variation exhibited in a historical series of waste flow data).

STEP 2: If a series of synthetic periodic waste flows are to be generated:

1) The number of years, periods and waste source areas in the historical data series are read from file HIST.DAT along with the historical waste series for each waste source area. The user must also specify the number of years of data to be generated which represents the simulation study time horizon.
2) For each waste source area, the forecasted annual waste flows are read from file HIST.DAT.
3) For each year of historical data, a mean value for the periodic data values is calculated.
4) All of the periodic waste flow values (for every year data are available) are normalized by dividing them by the corresponding mean flow value. This produces a set of values that represent the fractional deviation from the yearly mean exhibited by the historical data series.
5) Using this entire set of data, the range of the deviations exhibited is determined, and then this range is divided into 10 equal sections.
6) The total occurrences of data values within each range are then calculated.
7) These frequency values are used to develop a cumulative distribution function (CDF) which represents the relationship between the expected probability of occurrence and specific ranges of normalized waste flows.
8) To produce a single synthetic periodic waste flow value, a uniformly distributed random number (between 0 and 1) is produced using subroutine URAND. Using the CDF and the random number, a synthetic normalized flow value is determined.
9) The actual flow value is calculated by multiplying this normalized flow value by the forecasted mean for a specific year of the simulation study period which has been divided by the number of time periods to be modelled in each year to produce a forecasted mean periodic flow value.

If a predetermined series of waste generation or total material recovery data is available, the number of years, the number of periods in each year, and the number of waste source areas to be modelled are read from file IN.DAT. The waste flow data are then read from file IN.DAT.

STEP 3: The data which describes the MSW management system that is to be simulated are read from file SYS.DAT. All costs are assumed to be in present value dollars. As well, the total time horizon represented in the MSW management system data should correspond to the length of the simulated or forecasted waste or material flow series. The data required are:

* the number of time periods for the data, the length in years of the time periods, the number of waste source areas (WSAs), and the discount rate;
* the number of processing facilities, transfer stations and landfills;
* the fractions of the total flows originating from each WSA to be assigned to each facility for every time period and year;
* the flows from outside sources transferred to each facility for each time period and year;
* for each landfill: the fixed capital cost, the operating cost, the capacity, a backup landfill (should capacity be exceeded), the facility start-up year (1 if existing), and the collection costs associated with waste flows from WSAs to the landfills;

- for each processing facility: the fixed capital cost; the operating cost; the recovery factor (the fraction of the input that generates revenue); the factors representing the fraction of input recovered for recycling, composting and RDF; the average revenue for recovered materials or energy; a backup landfill (should capacity be exceeded during any time period); and the collection costs associated with waste or material flows from the WSAs to each facility;
- the maximum capacities of the processing facilities for each time period;
- the fractional flow assignments from the processing facilities to the landfills, and the associated transportation costs;
- for transfer stations: the fixed capital cost, the operating cost, a backup landfill, and the collection costs associated with waste flows originating in the WSAs that are taken to the transfer stations.

STEP 4: The total fixed capital cost, including all the facilities, is calculated.

STEP 5: The starting capacities for all the processing facilities and transfer stations are calculated for each period of each year of the simulation study time horizon.

STEP 6: Variables used to keep track of total flow assignments and the associated system costs are initialized to zero.

STEP 7: The flow of waste or materials through the specified MSW management system is simulated starting at year 1, period 1. The simulation steps are:

1) Waste (or source separated materials) from the WSAs are assigned to the facilities according to the fractional waste assignments specified for the specific time period. If the flow to be assigned is less than the available capacity, the entire flow is assigned to the facility, and the available capacity is adjusted along with the total flow the facility receives. If capacity is exceeded, the maximum amount of waste or materials that can be assigned to the facility is assigned (the capacity and total flow variables are updated) and the remaining portion of the flow is assigned to the specified backup landfill site (and the corresponding capacity and total flow variables are updated). The associated collection and transportation costs are calculated.
2) In a similar manner, waste flows from transfer stations are assigned to processing facilities.
3) Residuals from processing facilities are assigned to landfills.
4) Finally, waste flows from transfer stations are assigned to landfills.

STEP 8: After carrying out the simulation steps for every period of a year, totals are calculated for the flows assigned to facilities and the annual system costs (facility operation, transportation, collection, revenues, and the net cost). The simulation then continues for the next year of the simulation study time horizon.

STEP 9: At the end of the simulation study time horizon, the results of the simulation are transferred to file OUT.DAT.

SAMPLE INPUT FILE: IN.DAT -> **Predetermined forecasts for waste or total material generation rates for the waste source areas (WSAs) of the study region.**

```
5, 2, 2      * number of years, periods and waste source areas (WSAs) in waste generation data
102.0 120.0
104.0 126.0  *  for waste source area 1, the total flow for each period of each year
109.0 132.0     [t/time period]
114.0 140.0
120.0 149.0

50.0 60.0
52.0 61.0    * for waste source area 2, the total flow for each period of each year [t/time period]
54.0 63.0
55.0 65.0
60.0 69.0
```

* These data are developed with the assistance of WASTE.WK1 and represent the total flows of waste or source separated materials originating from the waste source areas that are collected by the municipality or community, or contracted out to other agencies but paid for by the municipality or community.

SAMPLE INPUT FILE: HIST.DAT-> **Historical waste generation data, and forecasted annual waste generation rates for use in developing synthetic, periodic waste flow data.**

```
20, 2, 2  *  the number of years, periods and WSAs in the historical waste flow series
1.0 2.0
2.0 3.0
3.0 4.0   *  historical waste generation rates for each period of each year of data for
4.0 5.0      WSA 1 [t/time period]
5.0 6.0
6.0 7.0
7.0 8.0
8.0 9.0
9.0 10.0
10.011.0
11.012.0
12.013.0
13.014.0
14.015.0
15.016.0
16.017.0
17.018.0
18.019.0
19.020.0
20.020.0
```

```
4.0 5.0   * historical waste generation rates for each period of each year of data for WSA 2
5.0 6.0     [t/time period]
6.0 7.0
7.0 8.0
8.0 9.0
9.0 10.
10.0 11.0
11.0 12.0
12.0 13.0
13.0 14.0
14.0 15.0
15.0 16.0
16.0 17.0
17.0 18.0
18.0 19.0
19.0 20.0
20.0 21.0
21.0 22.0
22.0 23.0
23.0 24.0
                                * forecasts for waste generation for
10.0 20.0 30.0 40.0 50.0        each WSA for the number of years in
10.0 20.0 30.0 40.0 50.0        the planning horizon [t/year] (WASTE.WK1)
```

SAMPLE INPUT FILE: SYS.DAT -> Description of the MSW management system.

* These data are either developed based on the results of an optimization study (using the time period settings, facility parameters, flow assignments and costs estimated or predicted by an MILP or LP model) or have been developed through some other means.
* The fractional flow assignments represent a rule for assigning waste or materials from WSAs to facilities, or between facilities based on the resulting flow assignments made by the optimization model for each time period modelled. These flow assignment rules may also be set without the use of an optimization study.
* Facilities are identified for modelling purposes by an index number within the entire set of facilities in the system - first the processing facilities are labelled, then the transfer stations, and finally, the landfills. Data requested with respect to these facilities are ordered according to their placement within this set. For example, for the facilities specified below, mrfA would be referenced as facility 1, ccfA as 2, etc.

```
5, 1, 2, .05  * the number of time periods, length of each time period [years], the number of
                WSAs and the discount rate
2 0 2         * the number of processing facilities, transfer stations, and landfills in the system
                (existing and potential)

'mrfA' 'ccfA' 'ldf1' 'ldf2'   *   facility names for: processing facilities first, then
                                  transfer stations then landfills (4 letters in quotes)
```

```
.15 0.0 .85 0.0  * the fraction of the flow generated at WSA 1
.15 0.1 .75 0.0  assigned to each facility (in the order specified
.15 0.1 .75 0.0  above) for each time period
.15 0.1 0.0 .75  * all facilities are accounted for, but if
.15 0.1 0.0 .75  no link is possible or no flow should be
                 assigned 0.0 is entered
.15 0.0 .85 0.0
.15 0.1 .75 0.0  * fractional flow assignments for WSA 2
.15 0.1 .75 0.0
.15 0.1 0.0 .75
.15 0.1 0.0 .75

8. 8. 15. 20. *  transportation costs associated with the link between each WSA and each facility
8. 8. 20. 15.    [$/tonne]; may set to 0.0 if a link is not used

10. 0.0 10. 0.0  * waste flows from outside sources (not
10. 10. 10. 0.0  locally collected or contracted out)
10. 10. 10. 0.0  to each facility in the order listed at
10. 10. 0.0 10.  the top of this file, for every time
10. 10. 0.0 10.  period of the modelling time horizon [t/time period]

0. 20. 1000. 4 1 40.
1000000. 30. 20000. 3 4 30.

*  for each landfill (in the order they appear at the top of the file), the: fixed capital cost [PV$];
   operating cost [$/t]; capacity [t]; the set reference number of a backup landfill; the start-up
   year (1=existing); and the collection cost associated with waste transferred from WSAs to
   landfills = garbage collection cost [$/t]

0. 50. .85 .85 0.0 0 50. 4 100.
500000. 40. .9 0.0 .9 0.0 5. 4 200.

*  for processing facilities (in the order they appear in the set specified at the top of the file), the:
   fixed capital cost [PV$]; operating cost [$/t]; residuals factor; recycling factor; composting
   factor; RDF factor; average revenue per processed tonne; a backup landfill; and the collection
   cost associated with waste transferred from WSAs to these facilities (garbage collection cost
   for EFW or mixed MSW processing facilities, recycling collection cost for MRFs, and
   composting collection cost for CCFs)
*  for a system of MRFs or CCFs to handle source separated recyclables or compostables, 15
   should be entered as the backup landfill as this is the default value assumed in the model

30. 30. 100. 100. 100.   * the maximum capacity of processing facilities for each time period
0.0 50. 100. 100. 100.   [t/time period] (design capacity for a periodic analysis, projected
                         operating capacity for a yearly analysis)

.15 0.0  * the fractional flow assignments from processing
.15 0.0  facility 1 (mrfA) to the landfills for each time
.15 0.0  period (representing the flow of residuals for
0.0 .15  disposal)
0.0 .15
```

```
.1 0.0 *  the fractional flow assignments from processing facility 2
.1 0.0
.1 0.0
0.0 .1
0.0 .1

100. 100.   *   transportation costs associated with the flow of waste or materials from WSAs
200. 200.       to each of the processing facilities (mrfA and ccfA) [$/t]
```

* If transfer stations are also specified, the data file would continue with the following entries, in a similar manner as shown above:

1) for each transfer station, the: fixed capital cost [PV$]; operating cost [$/t]; a backup landfill; and the collection cost associated with waste hauled from the WSAs to the transfer station [$/t] (the garbage collection cost);
2) the maximum design or operating capacity for each facility, for each time period [t/time period];
3) the fractional flow assignments for waste flows transferred to landfills;
4) the transportation cost associated with the transfer of waste from each transfer station to each landfill [$/t];
5) the fractional flow assignments for waste flows transferred from each transfer station to processing facilities (for MRFs, and CCFs these should be set to 0.0);
6) and, the transportation cost associated with the transfer of waste from each transfer station to each processing facility [$/t] (for MRFs, and CCFs these should be set to 0.0);

SAMPLE OUTPUT FILE: OUT.DAT -> The waste or material flows to the facilities and the system costs for the simulation study.

```
WASTE GENERATION AT WASTE SOURCE AREAS (t/period)
WASTE SOURCE AREA:  1
    102.   120.  * the total waste or material flows originating from WSA 1 for each
    104.   126.  time period of each year of the study (either echoes the IN.DAT data or
    109.   132.  shows a synthetic waste flow series)
    114.   140.
    120.   149.

WASTE SOURCE AREA:  2
     50.    60.  * the total waste or material flows originating from WSA 2 for each
     52.    61.  time period of each year of the study
     54.    63.
     55.    65.
     60.    69.

TOTAL FLOWS TO THE FACILITIES FOR EACH SIMULATED YEAR

 mrfA   30.   30.    64.    66.    70.
 ccfA    0.   44.    46.    47.    50.
```

```
ldf1    327.  308.   293.   0.     0.
ldf2    0.    0.     0.     305.   324.
```

* If the study investigates the management of recyclables or compostables in isolation of the rest of the mixed MSW management system (using a set of MRFs or CCFs), an additional section of output would follow illustrating any flows assigned to the facilities above the available capacity that will require landfilling (in addition to the processing residuals). This situation is indicated by specifying 15 as the reference number for the backup landfill for the MRFs or CCFs (default value required for modelling purposes).

```
FLOWS TO LANDFILLS IN EACH YEAR AND MAXIMUM CAPACITIES

ldf1    327.  308.   293.   0.     0.     1000.
ldf2    0.    0.     0.     305.   324.   20000.


TOTAL NET OPERATING COST AT THE FACILITIES FOR EACH SIMULATED YEAR
(PV$)

 mrfA   214.  204.   413.   408.   410.
 ccfA   0.    1426.  1405.  1384.  1385.
 ldf1   6219. 5581.  5056.  0.     0.
 ldf2   0.    0.     0.     7532.  7614.


TOTAL ANNUAL COSTS AND REVENUES FOR MSW SYSTEM (PV$)
YEAR O&M    TRANSPORT   COLLECTION  REVENUES    TOTAL COST
 1   7648.  5426.       15493.      1214.       27353.
 2   8548.  5965.       20222.      1337.       33399.
 3   9390.  6348.       20102.      2517.       33323.
 4   11810. 6800.       17692.      2487.       33816.
 5   11906. 6964.       17931.      2497.       34304.


ANNUAL WASTE RECOVERY WITH THE MSW SYSTEM (tonnes)
YEAR WASTE         RECYCLABLES      COMPOSTABLES     RDF
 1   352.          26.              0.               0.
 2   373.          26.              40.              0.
 3   388.          54.              41.              0.
 4   404.          56.              43.              0.
 5   428.          59.              45.              0.

TOTAL COST OF THE MSW SYSTEM (PV$) = $  2662194.
```

APPENDIX G

A complete listing of the names and contact addresses of the waste management professionals consulted for the validation of the prototype decision support system

Susan Alexander, B.Sc.
Recycling Co-ordinator,
Waste Management
The Regional Municipality of Hamilton-Wentworth
Transportation/Environmental Services Group
35 King Street East, 4th Floor,
Hamilton, Ontario
L8N 4A9

Phil Jensen,
Supervisor, Residential Waste Reduction,
Waste Management
The Regional Municipality of Hamilton-Wentworth
Transportation/Environmental Services Group
35 King Street East, 4th Floor,
Hamilton, Ontario
L8N 4A9

Lisa deSoto, P.Eng.
Solid Waste Engineer
The Corporation of the City of Brantford
City Hall,
100 Wellington Square,
Brantford, Ontario
N3T 2M3

Shelley M. Dowhanik, P.Eng.
Waste Reduction Coordinator
The City of Winnipeg
Waterworks, Waste and Disposal Department
1500 Plessis Road
Box 178 Transcona P.O.
Winnipeg, Manitoba
R2C 2Z9

APPENDIX H

A summary of the input data and results of the case study application of the program planning components of the prototype decision support system

MAIN PARAMETERS:	**Selkirk, Manitoba**
Base year	1992
interest rate, inflation rate	0.08, 0.03
population	9815
number of SFD hhlds	2814
people/hhld (SFDs)	2.81
waste generation rate for the SFD sector	2950 tonnes/year
number of MFD hhlds	763
number of MFDs	38
people/hhld (MFDs)	2.5
waste generation rate for the MFD sector	600 tonnes/year
number of ICI sites	294
waste generation rate for the ICI sector	2000 tonnes/year

SOURCE SEPARATION COMPOSTING:	Residential On-site Programs
SFD composter cost, economic life	$50, 10 years
SFD participation rate	40% (75%)
SFD start-up cost, annual cost	$60000, $9500/year ($20000/year)
SFD waste diverted	145 tonnes/year (365 tonnes/year)
Reduction in total SFD stream	5% (12%)
SFD annual cost per tonne	$65/tonne ($55/tonne)
SFD admin., depreciation (% of cost)	23%, 65%
MFD composter cost, economic life	$30, 10 years
MFD participation rate	25% (75%)
MFD start-up cost, annual cost	$10000, $1800/year ($5000/year)
MFD waste diverted	18 tonnes/year (54 tonnes/year)
Reduction in total MFD stream	3% (9%)
MFD annual cost per tonne	$100/tonne ($95/tonne)
MFD admin., depreciation (% of cost)	45%, 45%

SOURCE SEPARATION COMPOSTING:	Drop-off Program
materials accepted:	all yard waste
participation rate	25%
SFD waste diverted	62 tonnes/year
Reduction in total SFD stream	2%
MFD waste diverted	3 tonnes/year
Reduction in total MFD stream	0.5%
ICI waste diverted	6 tonnes/year
Reduction in total ICI stream	0.3%
annual cost	$4000/year
annual cost per tonne	$55/tonne
administration cost	$3000/year (75% of total)
Processing Facility: windrow composting (low technology)	at the current landfill site
start-up cost	$10000
annual operating cost	$2200/year
annual cost per tonne	$30

SOURCE SEPARATION COMPOSTING:	Residential and ICI **Curbside Program**
materials accepted:	all yard waste
participation rate	90%
collection system	weekly, using bags
collection vehicle (capital,O&M,capacity)	dump truck, $80000, $50000, 4 m^3
SFD waste diverted	265 tonnes/year
Reduction in total SFD stream	8%
MFD waste diverted	12 tonnes/year
Reduction in total MFD stream	2%
ICI waste diverted	23 tonnes/year
Reduction in total ICI stream	1%
start-up cost	$170000
annual cost	$73000/year
annual cost per tonne	$245/tonne
Processing Facility: windrow composting (low technology)	at the current landfill site
start-up cost	$30000
annual operating cost	$9000/year
annual cost per tonne	$30

SOURCE SEPARATION RECYCLING:	Residential Drop-off Recycling Program
materials accepted:	metal cans, glass, newspaper, PET
participation rate	25%
depot system, cost	plastic carts, $3500/depot
number of depots, required	13
collection vehicles (#,capital,O&M,capacity)	1 (1 d/wk), stake truck, $40000, $60000, 18m^3
SFD waste diverted	81 tonnes/year
Reduction in total SFD stream	3%
MFD waste diverted	17 tonnes/year
Reduction in total MFD stream	3%
start-up cost	$90000
annual cost	$70000/year
annual cost per tonne	$715/tonne
annual cost (part-time workers)	$17000
annual cost per tonne (part-time workers)	$175/tonne

SOURCE SEPARATION RECYCLING:	Residential Curbside Recycling Program
materials accepted:	metal cans, glass, newspaper, PET
participation rate	90%
container, cost	blue box, $5/unit
collection vehicl. (#,capital,O&M,capacity)	1, stake truck, $40000, $60000, 18 m^3
SFD waste diverted	275 tonnes/year
Reduction in total SFD stream	9%
MFD waste diverted	60 tonnes/year
Reduction in total MFD stream	10%
start-up cost	$70000
annual cost	$66000/year
annual cost per tonne	$200/tonne
annual cost per tonne (part-time workers, bi-weekly collection, bags)	$150/tonne (115 tonnes/year) $17000/year

APPENDIX I

A summary of the input data and results of the case study application of the facility planning components of the prototype decision support system

MAIN PARAMETERS:	Winnipeg, Manitoba
Base year	1991
interest rate, inflation rate	0.08, 0.02
population	616786
number of SFD hhlds	170910
people/hhld (SFDs)	2.79
number of MFD hhlds (complexes < 5 units)	40145
number of MFD hhlds (complexes >= 5 units)	33680
people/hhld (MFDs)	1.895
population growth rate	0.7%/year
growth rate for the ICI sector	1.0%/year
initial waste generation rate for the SFD sector	257000 tonnes/year
initial waste generation rate for the MFD sector	57000 tonnes/year
initial waste generation rate for the ICI sector	257000 tonnes/year
initial waste generation rate for public works	72000 tonnes/year

SOURCE SEPARATION RECYCLING:	Residential drop-off program weekly collection, expanded over time
materials accepted	newspaper, aluminum cans, PET, glass, OCC expanded: mixed and fine paper, ferrous cans, HDPE and LDPE plastic
participation rate	25%
depot system	self-dumping depots (igloos)
depot cost, capacity	\$4250/site, 10 m^3/site
number of depots required	160 (start-up year) to 265 (year 20)
collection vehicle (capital,O&M,capacity)	roll-off truck, \$90000, \$60000, 30.5 m^3
number of vehicles required	4 to 6
Residential waste diverted	10000 tonnes/year to 14000 tonnes/year
Reduction in residential waste stream	3% to 4%
annual cost	\$500000/year to \$700000/year
annual cost per tonne	\$50/tonne
percentage of cost associated with collection activity	75%
total present value program cost (over 20 years)	\$8.7 million

SOURCE SEPARATION RECYCLING:	Residential curbside program weekly collection, expanded over time, container provided (Blue Box), large MFD complexes excluded
materials accepted	newspaper, aluminum cans, PET, glass, OCC expanded: mixed and fine paper, ferrous cans, HDPE and LDPE plastic
participation rate	85%
container cost	$6/unit
collection vehicle (capital,O&M,capacity)	closed-body truck, $75000, $65000, 21 m^3
number of vehicles required	11 to 45
Residential waste diverted	9000 tonnes/year to 48000 tonnes/year
Reduction in residential waste stream	3% to 15%
annual cost	$1 million/year to $3 million/year
annual cost per tonne	$70/tonne
percentage of cost associated with collection activity	85%
total present value program cost (over 20 years)	$35.4 million

PLANNING YEAR	MATERIALS RECOVERY (DROP -OFF PROGRAM) (tonnes/year)	MATERIALS RECOVERY (CURBSIDE PROGRAM) (tonnes/year)
1	9947	8467
2	10005	11866
3	11037	13384
4	11100	13397
5	12814	44104
6	12888	44353
7	12962	44615
8	13037	44879
9	1311	45145
10	13187	45412
11	13258	45661
12	13329	45912
13	13401	46164
14	13473	46417
15	13545	46672
16	13618	46928
17	13691	47185
18	13765	47444
19	13839	47705
20	13914	47967

DATA REQUIRED FOR OPTIMIZATION CASE STUDY APPLICATION:

1. **WASTE GENERATION SOURCE AREA (WSA) DATA:** relative population and material flow levels (tonnes/year) for the DROP-OFF PROGRAM

	WSA 1	WSA 2	WSA 3	WSA 4	WSA 5	WSA 6
% OF TOTAL POPULATION	2.89	7.66	12.40	9.63	13.57	15.60
YEAR 1	287.5	761.9	1233.4	957.9	1349.8	1551.7
YEAR 2	289.1	766.4	1240.6	963.5	1357.7	1560.8
YEAR 3	319.0	845.4	1368.6	1062.9	1497.7	1721.8
YEAR 4	320.8	981.6	1376.4	1068.9	1506.3	1731.6
YEAR 5	370.3	981.6	1588.9	1234.0	1738.9	1999.0
YEAR 6	370.3	981.6	1588.9	1251.7	1738.9	2027.7
YEAR 7	370.3	981.6	1588.9	1269.4	1738.9	2056.4
YEAR 8	370.3	981.6	1588.9	1287.4	1738.9	2085.4
YEAR 9	370.3	981.6	1588.9	1305.1	1738.9	2114.1
YEAR 10	370.3	981.6	1588.9	1323.2	1738.9	2143.6
YEAR 11	370.3	981.6	1588.9	1340.2	1738.9	2171.1
YEAR 12	370.3	981.6	1588.9	1357.2	1738.9	2198.6
YEAR 13	370.3	981.6	1588.9	1374.5	1738.9	2226.5
YEAR 14	370.3	981.6	1588.9	1391.7	1738.9	2254.5
YEAR 15	370.3	981.6	1588.9	1408.9	1738.9	2282.4
YEAR 16	370.3	981.6	1588.9	1426.4	1738.9	2310.7
YEAR 17	370.3	981.6	1588.9	1443.9	1738.9	2339.0
YEAR 18	370.3	981.6	1588.9	1466.4	1738.9	2375.4
YEAR 19	370.3	981.6	1588.9	1479.3	1738.9	2396.4
YEAR 20	370.3	981.6	1588.9	1497.2	1738.9	2425.4

	WSA 7	WSA 8	WSA 9	WSA 10	WSA 11	WSA 12
% OF TOTAL POPULATION	7.09	9.97	4.78	5.55	7.72	3.14
YEAR 1	705.2	991.7	475.5	552.0	767.9	312.3
YEAR 2	709.4	997.5	478.2	555.3	772.4	314.2
YEAR 3	782.5	1100.4	527.6	612.6	852.0	346.6
YEAR 4	787.0	1106.7	530.6	616.0	856.9	348.5
YEAR 5	908.5	1277.6	612.5	711.2	989.2	402.4
YEAR 6	921.6	1277.6	621.3	711.2	989.2	408.1
YEAR 7	934.6	1277.6	630.1	711.2	989.2	413.9
YEAR 8	947.8	1277.6	639.0	711.2	989.2	419.8
YEAR 9	960.8	1277.6	647.8	711.2	989.2	425.5
YEAR 10	974.2	1277.6	656.8	711.2	989.2	431.5
YEAR 11	986.7	1277.6	665.2	711.2	989.2	437.0
YEAR 12	999.2	1277.6	673.7	711.2	989.2	442.5
YEAR 13	1011.9	1277.6	682.2	711.2	989.2	448.2
YEAR 14	1024.6	1277.6	690.8	711.2	989.2	453.8
YEAR 15	1037.3	1277.6	699.3	711.2	989.2	459.4
YEAR 16	1050.2	1277.6	708.0	711.2	989.2	465.1
YEAR 17	1063.0	1277.6	716.7	711.2	989.2	470.8
YEAR 18	1079.6	1277.6	727.8	711.2	989.2	478.1
YEAR 19	1089.1	1277.6	734.3	711.2	989.2	482.3
YEAR 20	1102.3	1277.6	743.2	711.2	989.2	488.2

WASTE GENERATION SOURCE AREA (WSA) DATA: relative population and material flow levels (tonnes/4 years) for the CURBSIDE PROGRAM

NOTE: the maximum flow in each time period was multiplied by 4 to produce the base estimates of waste generation in each period

WSA	% OF TOTAL POP.	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
1	2.89	1549	5188	5188	5188	5188
2	7.66	4105	13751	13751	13751	13751
3	12.40	6645	22260	22260	22260	22260
4	9.63	5160	17287	18276	19248	20258
5	13.57	7272	24360	24360	24360	24360
6	15.60	8360	28004	29606	31182	32793
7	7.09	3799	12728	13456	14172	14904
8	9.97	5342	17898	17898	17898	17898
9	4.78	2562	8581	9072	9555	10049
10	5.55	2974	9963	9963	9963	9963
11	7.72	4137	13859	13859	13859	13859
12	3.14	1683	5637	5959	6276	6600

2. **TRANSPORTATION DISTANCE MATRIX: approximate round trip distances (km) between the waste generation source areas and the processing facility locations**

WSA	FAC 1 (existing)	FAC 2 (existing)	FAC 3 (existing)	FAC 4 (proposed)	FAC 5 (proposed)	FAC 6 (proposed)
1	24.8	27.5	23.4	10.3	24.1	38.5
2	17.9	22.0	17.9	8.2	30.2	32.3
3	11.0	8.2	4.1	21.3	20.6	17.9
4	3.4	15.1	9.6	25.4	32.3	16.5
5	17.9	6.9	9.6	37.8	37.1	7.6
6	17.2	13.1	11.0	22.0	13.1	23.4
7	26.1	20.6	19.2	33.0	13.8	34.4
8	9.6	7.6	2.1	25.4	28.9	16.5
9	23.4	12.4	15.1	37.1	39.9	4.8
10	20.6	5.5	9.6	31.6	27.5	15.8
11	30.2	13.1	21.3	38.5	22.0	17.9
12	32.3	16.5	23.4	41.2	18.6	22.0

3. MILP DECISION VARIABLES:

(a) Drop-off program:

f_{wft} = flow of recyclables from waste source area w (w=1,..,12) to facility f (f=1,..,3) in time period t (t=1,..,20)

(b) Curbside program:

f_{wft} = flow of recyclables from waste source area w (w=1,..,12) to facility f (f=1,4,5,6) in time period t (t=1,..,5)

$IUSE_{ft}$ = do not use (open) or use potential facility f (f=4,5,6) in time period t (1,..,5)
= (0,1)

DCF_{ft} = design capacity of potential facility f (f=4,5,6) in time period t (t=1,..,5) [tonnes/4 years]
= $UNIT_f$ * $ICAP_{ft}$

$ICAP_{ft}$ = number of units of capacity developed in time period t when potential facility f is first opened
= (0,..,4)

EXP_{ft} = capacity expansion of facility f (f=4,5,6) in time period t (t=2,..,5)
= UF_f * IXF_{ft}

IXF_{ft} = number of units of capacity expanded at facility f (f=4,5,6) in time period t
= (0,..,3)

4. MILP MODEL PARAMETERS: model parameter estimates provided for the MILP model formulations

NOTE: all costs are given in present value (time zero) dollars (discounted by a factor of 0.06 to reflect the present value of costs in the various time periods)

NOTE: the objective function cost coefficients are the net cost of assigning one unit of recyclables from a waste source area to a facility in a time period t, i.e, HAUL*DISTANCE+COLL+OMF-(REV*RFACTOR)

NOTE: a capacity utilization factor of 0.8 and 250 operating days per year have been assumed for the calculation of facility development and operating restrictions

$HAUL_{wft}$ = linehaul cost from waste source area w (w=1,..,12) to facility f (f=1,..,6) in time period t (t=1,..,20 for drop-off; t=1,..,5 for curbside) [$/t/km]
= $0.29/tonne/km * travel distance for the drop-off program vehicles
= $0.4/tonne/km * travel distance for the curbside program vehicles

COLL = recycling program collection cost [$/tonne]
= $37.5/tonne for the drop-off program
= $59.5/tonne for the curbside program

OMF_{ft} = operating cost at facility f (f=1,..,6) for time period t, including the residuals disposal (RESFAC * $25/t (f=1,2,3,6) or $20/t (f=4,5)) [$/tonne]
= $43.75/tonne for f=1
= $48.75/tonne for f=2,3
= $57/tonne for f=4,5
= $57.5/tonne for f=6

FCF_{ft} = fixed cost for potential facility f (f=4,5,6) in time period t (t=1,..,5)
= $120000 (curbside program only)

$CEXP_{ft}$ = variable capacity development or expansion cost at facility f (f=4,5,6) in time period t (t=1,..,5) [\$/tonnes/4 years] (curbside program only)
= \$30/tonnes/4 years for f=4,5,6

REV_{ft} = average revenue for materials recovered at facility f (f=1,..,6) in time period t (t=1,..,5) [\$/tonne]
= \$42/tonne

$RFACTOR_f$ = fraction of input recovered as recyclables at facility f (f=1,..,6)
= 0.85 for f=1,2,3
= 0.90 for f=4,5,6

$RESFAC_f$ = fraction of input requiring disposal (residuals) at facility f (f=1,,..,6)
= 0.15 for f=1,2,3
= 0.10 for f=4,5,6

$WASTE_{wt}$ = recyclable materials recovered from waste source area w (w=1,..,12) in time period t (t=1,..,20 for drop-off; t=1,..,5 for curbside) (see Section 1 above)

DCF_f = initial operating capacity of existing facility f (f=1,2,3) [tonnes/x years]
= 10000 tonnes/year for f=1 for drop-off; 32000 tonnes/4 years for f=1 for curbside
= 8000 tonnes/4 years for f=2,3

MCF_f = maximum operating capacity of existing facility f (f=1,2,3) [tonnes/x years]
= 10000 tonnes/year for f=1 for drop-off; 32000 tonnes/4 years for f=1 for curbside
= 8000 tonnes/4 years for f=2,3

$UNIT_f$ = basic unit of installed capacity for potential facility f [tonnes/4 years]
= 40000 tonnes/4 years for f=4,5,6 (i.e., 50 t/day units of design capacity)

UF_f = basic unit of expanded capacity for potential facility f [tonnes/4 years]
= 40000 tonnes/4 years for f=4,5,6 (i.e., 50 t/day units of expanded design capacity)

SUMMARY OF THE RESULTS OF THE OPTIMIZATION STUDIES:

1. OPTIMAL TOTAL SYSTEM COSTS:

RECYCLABLES MANAGEMENT SYSTEM	OPTIMAL TOTAL SYSTEM COST
drop-off collection program	**\$6.3 million**
curbside collection program	**\$43.2 million**

2. FACILITY SIZING AND DEVELOPMENT PATTERNS, AND TOTAL SYSTEM COSTS FOR THE OPTIMAL AND NEAR-OPTIMAL CURBSIDE RECYCLABLE MATERIALS MANAGEMENT SYSTEM SOLUTIONS:

where: t = time period (1,..,5)
DC = design capacity for initial development (tonnes/day)
OC = updated operating capacity (tonnes/year), including expansions
XC = design capacity for expansions (tonnes/day)

SYSTEM SOLUTION	FACILITY 4	FACILITY 5	FACILITY 6
optimal $43.2 million	t=2: DC = 50 t/d OC = 10000 t/yr	t=2: DC = 50 t/d OC = 10000 t/yr	t=1: DC = 50 t/d OC = 10000 t/yr t=2: XC = 50 t/d OC = 20000 t/yr
near-optimal 1 $45.3 million	t=1: DC = 50 t/d OC = 10000 t/yr t=2: XC = 100 t/d OC = 30000 t/yr t=3: XC = 50 t/d OC = 40000 t/yr	t=3: DC = 50 t/d OC = 10000 t/yr	t=2: DC = 50 t/d OC = 10000 t/yr
near-optimal 2 $45.3 million	t=5: DC = 50 t/d OC = 10000 t/yr	t=1: DC = 50 t/d OC = 10000 t/yr t=2: XC = 150 t/d OC = 40000 t/yr	t=3: DC = 50 t/d OC = 10000 t/yr
near-optimal 3 $45.3 million			t=1: DC = 200 t/d OC = 40000 t/d

SUMMARY OF THE OUTPUT FROM THE SIMULATION STUDIES:

1. VERIFICATION OF THE OPTIMIZATION MODELLING APPROACH:

TOTAL ANNUAL COSTS AND REVENUES FOR MSW SYSTEM (PV$)

YEAR	O&M	TRANSPORT	COLLECTION	REVENUES	TOTAL COST
1	2641278.	296202.	3188486.	1958406.	4167561.
2	7800839.	680162.	8460513.	5321668.	11619850.
3	6326724.	558219.	6855770.	4313221.	9427492.
4	5126518.	457340.	5550583.	3492849.	7641592.
5	4154262.	452407.	4494274.	2828720.	6272223.

TOTAL COST OF THE MSW SYSTEM (PV$) = $ 43215920.

2. SIMULATION OF THE OPTIMAL SYSTEM UNDER YEARLY TIME INCREMENTS:

TOTAL ANNUAL COSTS AND REVENUES FOR MSW SYSTEM (PV$)

YEAR	O&M	TRANSPORT	COLLECTION	REVENUES	TOTAL COST
1	417421.	46815.	503912.	309510.	658638.
2	551878.	61895.	666229.	409207.	870795.
3	587245.	65861.	708924.	435431.	926599.
4	554406.	62181.	669446.	411072.	874962.
5	1916537.	167104.	2078603.	1307447.	2854798.
6	1818088.	158441.	1972018.	1240380.	2708166.
7	1720705.	149834.	1871384.	1174120.	2567804.
8	1625850.	141447.	1775903.	1109404.	2433796.
9	1555260.	137218.	1685310.	1060302.	2317488.
10	1475137.	130050.	1598685.	1005776.	2198096.
11	1396172.	123044.	1517064.	952062.	2084219.
12	1319144.	116174.	1439060.	899520.	1974857.
13	1260743.	112464.	1365056.	858995.	1879267.
14	1195777.	106629.	1294846.	814797.	1782455.
15	1131579.	100848.	1228264.	771162.	1689528.
16	1069237.	95235.	1165095.	728653.	1600915.
17	1021505.	111251.	1105166.	695592.	1542330.
18	968700.	105542.	1048332.	659778.	1462796.
19	917472.	99944.	994434.	624866.	1386984.
20	867757.	94478.	943297.	590957.	1314575.

TOTAL COST OF THE MSW SYSTEM (PV$) = $ 39216270.

APPENDIX J

A listing of the references used in the development of the knowledge-based system components of the prototype decision support system

A. GENERAL

ACI/ADI (1989). Westmorland/Albert Region Waste Management Alternatives - Final Report. Prepared for the Westmorland/Albert Solid Waste Provisional Committee, Province of New Brunswick.

BioCycle Magazine.

Chertow, M.R. (1989). Garbage Solutions: A Public Official's Guide to Recycling and Alternative Solid Waste Management Technologies. National Resource Recovery Association, The United States Conference of Mayors, Washington, D.C.

City of Seattle (1989). On the Road to Recovery: Seattle's Solid Waste Management Plan. Seattle Solid Waste Utility, August, 1989.

Environmental Protection Agency (1989). Decision-Makers Guide to Solid Waste Management. Solid Waste and Emergency Response, EPA/530-SW-89-072, Washington, D.C.

Ontario Ministry of the Environment (1990). "Towards a Sustainable Waste Management System." Discussion Paper, 0-7729-7183-8, Queen's Printer for Ontario.

Ontario Recycling Update, Recycling Council of Ontario.

Peavy, H.S., Rowe, D.R., and Tchobanoglous, G. (1985). Environmental Engineering. McGraw-Hill Book Company, Toronto.

Smith, D.G. (1989). "A Comprehensive Costing Methodology for the Assessment of Municipal Solid Waste Management Alternatives." unpublished Master of Engineering Project Report, McMaster University, Hamilton, Ontario.

Zandi, I. (1990). Proceedings of the Sixth International Conference on Solid Waste Management and Secondary Materials. The Journal of Resource Management and Technology, Philadelphia, Pennsylvania, December 4-7,.

Zandi, I. (1989). "Solid Waste Management Strategies - A Question of Priorities." *J. of Resource Management and Technology*, 17(2): 53-60.

B. WASTE GENERATION AND COMPOSITION

Argue, R. (1991). "Rural and Remote Challenges: Blue Box 2000 - Meeting the Challenge in an Urban/Rural Setting." presented at the 12th Annual Recycling Councii of Ontario Conference - Sharing the Challenge, Toronto, Ontario, October 8-11, 1991.

City of Guelph (1991). "Wet/Dry Pilot Project: Summary of Preliminary Findings." April, 1991.

City of Guelph (1990). unpublished report, June 1990.

Evans, B.W., and Paine, R.L. (1984). "Composition Analysis of Refuse by Land Use in the Core of the City of Toronto." Prepared for The Toronto Recycling Committee.

GIRDUS/GRAIGE (1988). "Le programme de Collecte Selective a Ville La Salle: Composition des Dechets, Potentiel de Resources Secondaires et Taux de Recuperation." L'Universite du Quebec, Montreal, Quebec.

Gore & Storrie Limited (1991). Residential Waste Composition Study, Volume I of the Ontario Waste Composition Study. Prepared for the Waste Management Branch of the Ontario Ministry of the Environment, Queen's Printer for Ontario, PIBS 1415.

Gore & Storrie Limited (1991). Commercial Waste Composition Study: Volume II of the Ontario Waste Composition Study. Prepared for the Waste Management Branch of the Ontario of the Environment, Queen's Printer for Ontario, PIBS 1608.

Hickman, L. (1991). "Canada's Green Plan." *Municipal Solid Waste News*, 13(3): 2.

Krogmann, U. (1991). "Separate Collection of Biowaste." in Proceedings of the Sixth International Conference on Solid Waste Management and Secondary Materials. Philadelphia, Pennsylvania, December 4-7, The Journal of Resource Management and Technology, Paper no. 42, 8 p.

Perks, G. (1988). Waste Less Now. Final Report. Pollution Probe Foundation, Toronto, Ontario.

SWEAP (1990). "Your Guide to SWEAP." brochure, Metropolitan Works Department, Toronto, Ontario.

United States Environmental Protection Agency (1990). "Characterization of Municipal Solid Waste in the United States: 1990 Update - Executive Summary." EPA/530-SW-90-042A.

Vesilind, P.A., and Rimer, A.E. (1981). Unit Operations in Resource Recovery Engineering. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

C. COMPOSTING

Airite Environmental Industries (1990). Report on a Pilot Project for the Collection and Composting of Source Separated Food and Yard Waste. aei, Richmond Hill, Ontario.

BioCycle (1989). The BioCycle Guide to Yard Waste Composting. The JG Press Inc., Emmaus, Pennsylvania.

Diaz, L.F., Eggerth, L.L., and Goleuke, C.L. (1991). "Managing Yard Waste Composting's Major Budget Items." *Solid Waste & Power*, April, 1991: 50-58.

Krogmann, U. (1990). "Separate Collection of Biowaste." in Proceedings of the Sixth International Conference on Solid Waste Management and Secondary Materials, The Journal of Resource Management and Technology, December 4-7, Philadelphia, Pennsylvania, Paper no. 42, 8p.

Kuniholm, P.F. (1990). "Assessing the Opportunities for Solid Waste Composting." in Proceedings of the Sixth International Conference on Solid Waste Management and Secondary Materials, The Journal of Resource Management and Technology, December 4-7, Philadelphia, Pennsylvania, Paper no. 14, 13p.

M.M. Dillon Limited, and Cal Recovery Systems Incorporated (1990). Composting: A Literature Study, 1989. Prepared for the Ontario Ministry of the Environment, Queen's Printer for Ontario.

Scheinberg, A., and Smoler, D. (1990). "European Food Waste Collection and Composting Programs." *Resource Recycling*, **12**: 76-81.

D. RECYCLING

Argue, R. (1991). "Rural and Remote Challenges: Blue Box 2000 - Meeting the Challenge in an Urban/Rural Setting." presented at the 12th Annual Recycling Council of Ontario Conference - Sharing the Challenge, Toronto, Ontario, October 8-11, 1991.

BioCycle (1990). The BioCycle Guide to Collecting, Processing and Marketing Recyclables. The J.G. Press, Inc., Emmaus, Pennsylvania.

City of New York (1990). New York City Recycles: Preliminary Recycling Plan, Fiscal Year 1991. Office of Operations Planning, Department of Sanitation.

Energy Pathways Inc. (1990). How-to Manual for Planning and Implementing Recycling Programs for Apartment Buildings. Prepared for the Recycling Advisory Committee, Province of Ontario, April, 1990.

Institute for Local Self-Reliance (1991). Beyond 40 Percent: Record Setting Recycling and Composting Programs. Island Press, Washington, D.C.

Resource Integration Systems Ltd. (1987). Recycling Technology Manual. Prepared for the Recycling Advisory Committee, Hamilton, Ontario, January, 1987.

Resource Integration Systems Ltd. (1989). Addendum: Recycling Technology Manual. Prepared for the Recycling Advisory Committee, Hamilton, Ontario, March, 1989.

Resource Integration Systems Ltd. (1989) Industrial, Commercial, and Institutional Recycling in Ontario: Operator's Handbook. Prepared for Ontario Multi-Material Recycling Incorporated (OMMRI) and Recycling Advisory Committee.

E. OPTIMIZATION MODELLING

Baetz, B.W. (1990). "Optimization/Simulation Modeling for Waste Management Capacity Planning." *J. of Urban Planning and Development (ASCE)*, **116**(2): 59-79.

Brill, E.D. Jr. (1979). "The Use of Optimization Models in Public-Sector Planning." *Management Science*, **25**(5): 413-422.

Chang, S-Y, Brill, E.D. Jr., and Hopkins, L.D. (1982). "Use of Mathematical Models to Generated Alternative Solutions to Water Resources Planning Problems." *Water Resources Research*, **18**(1): 58-64.

Gottinger, H-W. (1991). Economic Models and Applications of Solid Waste Management. Gordon and Breach Science Publishers, New York.

Harrington, J.J., and Gidley, J.S. (1985). "The Variability of Alternative Decisions in a Water Resources Planning Problem." *Water Resources Research*, 21(12): 1831-1840.

Harvey, D.J., and O'Flaherty, T.G. (1973). "An Analysis of Solid Waste Transportation and Disposal Alternatives." *INFOR*, 11(3): 187-201.

Jenkins, L. (1982). "Developing a Solid Waste Management Model for Toronto." *INFOR*, 20(3): 237-247.

Jenkins, A.L. (1979). "Optimal Location of Facilities for Recycling Municipal Solid Waste." unpublished PhD Dissertation, University of Toronto, Toronto, Ontario.

Kuhner, J., and Harrington, J.J. (1975). "Mathematical Models for Developing Regional Solid Waste Management Policies." *Engineering Optimization*, 1(4): 237-256.

Kuhner, J., and Heiler, B. (1973). "Regional Planning Models for Solid Waste Management." in Models for Environmental Pollution Control, R.A. Deininger (ed.), Ann Arbor Science Publishing Inc., Michigan, pp. 327-357.

Wagner, H.M. (1975). Principles of Operations Research. Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Wilson, D.C. (1981). Waste Management: Planning, Evaluation, Technologies. Oxford University Press, New York.

F. TRANSPORTATION COSTING

Homburger, W.S. (ed.) (1982). Transportation and Traffic Engineering Handbook. Institute of Transportation Engineers, Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Hutchinson, B.G., and Mallett, J.J.L. (1990). "Line Haul Transport Cost and Pavement Damage Characteristics of Some Ontario Trucks." *Canadian J. of Civil Engineering*, 17(1): 28-35.

Kneafsey, J.T. (1975). Transportation Economic Analysis. Lexington Books, Toronto.

Marino, K.V. (1991). "Analyzing the Economics of a Regional Solid Waste Project." *Solid Waste & Power*, V(1): 30-35.

G. MSW MANAGEMENT FACILITIES - GENERAL

Gottinger, H-W. (1991). Economic Models and Applications of Solid Waste Management. Gordon and Breach Science Publishers, New York.

G1. TRANSFER STATIONS

Harvey, D.J., and O'Flaherty, T.G. (1973). "An Analysis of Solid Waste Transportation and Disposal Alternatives." *INFOR*, 11(3): 187-200.

Proctor & Redfern Limited (1976). Solid Waste Management Study: Report on Final Recommendations and Response to Public Input. Prepared for the Regional Municipality of Hamilton-Wentworth, Ontario, February, 1976.

G2. MIXED MSW PROCESSING FACILITIES

BioCycle (1989). The BioCycle Guide to Yard Waste Composting. The JG Press Inc., Emmaus, Pennsylvania.

M.M. Dillon Limited, and Cal Recovery Systems Incorporated (1990). Composting: A Literature Study, 1989. Prepared for the Ontario Ministry of the Environment, Queen's Printer for Ontario.

G3. EFW FACILITIES

Carlson, R.L. (1986). "The Impact of Materials Recycling Programs on Energy Recovery Facility Economics." *J. of Resource Management and Technology*, 15(1): 28-36.

Felago, R.T., and Stoller, P.J. (1979). Resource Recovery Management Model Overview. The MITRE Corporation, Metrek Division, Bedford, Massachusetts, September, 1979.

Levinson, A. (1990). "A System for Managing Solid Waste." *J. of Resource Management and Technology*, 18(1): 17-20.

G4. LANDFILLS

Anon. (1991). "Landfill Gas." *Warmer Bulletin*, 30: 31-33.

Glebs, R.T. (1988). "Landfill Costs Continue to Rise." *Waste Age*, 19(3): 84-93.

Smith, B.D., Cox, G.D., and Quick, P.G. (1990). "Technical Issues in Siting and Design of Municipal Solid Waste Landfills in the 90's." in Proceedings of the Sixth International Conference on Solid Waste Management and Secondary Materials, The Journal of Resource Management and Technology, December 4-7, Philadelphia, Pennsylvania, Paper no. 18, 15p.

H. SIMULATION

Baetz, B.W. (1990). "Optimization/Simulation Modeling for Waste Management Capacity Planning." *J. of Urban Planning and Development (ASCE)*, 116(2): 59-79.

Brill, E.D., Jr. (1979). "The Use of Optimization Models in Public-Sector Planning." *Management Science*, 25(5): 413-422.

Wilson, D.C. (1981). Waste Management: Planning, Evaluation, Technologies. Oxford University Press, New York.