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An optimisation model for regional integrated solid waste management I. Model formulation

Increased environmental concerns and the emphasis on material and energy recovery are gradually changing the orientation of MSW management and planning. In this context, the application of optimisation techniques have been introduced to design the least cost solid waste management systems, considering the variety of management processes. This study presents a model that was developed and applied to serve as a solid waste decision support system for MSW management taking into account both socio-economic and environmental considerations. The model accounts for solid waste generation rates, composition, collection, treatment, disposal as well as potential environmental impacts of various MSW management techniques. The model follows a linear programming formulation with the framework of dynamic optimisation. The model can serve as a tool to evaluate various MSW management alternatives and obtain the optimal combination of technologies for the handling, treatment and disposal of MSW in an economic and environmentally sustainable way. The sensitivity of various waste management policies will be also addressed. The work is presented in a series of two papers: (I) model formulation, and (II) model application and sensitivity analysis.

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Introduction

Communities worldwide (particularly in urban areas) are facing increased difficulties in managing their municipal solid waste (MSW) effectively and economically. Increasing waste quantities, diminishing landfill space, growing public environmental awareness, stringent technical requirements on management alternatives, as well as waste prevention policies and recycling goals have led to new trends in MSW management. Considering that demands for proper MSW management increased over the years, the perspective of waste management has gradually changed from open dumping to controlled landfilling to an integrated solid waste management (ISWM) system, which involves a combination of techniques and programs to manage the waste stream.

Decision-makers and technical professionals must consider the key technical, legal, economic, environmental, political, and social issues related to ISWM systems to develop an effective waste management program. As the number and complexity of MSW management alternatives increase, the selection of the best waste management system becomes a more difficult task. Consequently, systems analysis and mathematical modeling techniques have been introduced to waste management (Chang *et al.* 1996). With such techniques, every community can tailor its own unique system to manage various components of the waste stream in an economic and environmentally sound manner. A review of the MSW management and planning literature reveals the growing number and complexity of the avail-

Table 1. A literature review on the use of OR in MSW management

Reference	Description
Nema & Modak 1998	An integer linear programming model was developed as a strategic design approach for the optimisation of regional hazardous waste management systems. The objective was to minimise total costs and risks.
Haith 1998	An Excel spreadsheet, MSWFLOW, was developed as an accounting procedure for the exploration of MSW management decisions.
Daskalopoulos *et al.* 1998	A simple LP model that accounts for both the economic and environmental impacts of an IMSW system, was used. The model optimises the waste management process for a single generation source. Environmental costs are those associated with emissions of greenhouse gases, expressed in terms of equivalent global warning potential (GWP).
Huang *et al.* 1997	A solid waste decision support system (SWDSS) was developed based on an inexact mixed integer linear programming (IMILP) to incorporate different types of uncertainties within its optimisation process.
Sundberg & Ljunggren 1997	A methodology was suggested for the integrated analysis of cost and environmental impacts by linking two modelling approaches for the strategic ISWM planning: the MIMES/ waste model and the LCA model.
Rubinstein 1997	A Multi Attribute Decision System (MADS) was developed. The MADS model is a simulation-planning model that is composed of two modules: screening and evaluation. The screening module assists in selecting feasible MSW management alternatives based on constraints set by decision-makers. The evaluation module builds on the previous module and economic and environmental impacts of MSW management and policy. The model accounts for only environmental transportation costs in terms of vehicle emissions.
Charnpratheep *et al.* 1997	The fuzzy set theory and the analytic hierarchy process (AHP) were coupled into a rasterbased geographic information system (GIS) for the preliminary screening of landfill sites.
Kao *et al.* 1997	A prototype network GIS was developed for landfill siting. Improving the prototype is currently underway through introducing expert systems. That include a fuzzy expert system and a mixed-integer linear optimisation subsytems to implement multi-objective analysis.
Ljunggren & Sunberg 1997	A one period nonlinear programming model (MSW) was developed. This model analysis SWM systems for a single time period and optimises the system for a defined objective function. The objective is to minimise the total cost of MSW management systems. Environmental considerations are addressed through integrating emission constraints and fees.
Chang *et al.* 1996	MIP model was applied with the framework of dynamic optimisation considering economic and environmental factors.
Barlishen & Baetz 1996	A mixed integer linear programming (MILP) was used in the optimisation study with dynamic, multi-period model formulation for facility location, timing and sizing.
Powell 1996	A multi criteria model was developed to evaluate six waste disposal options in a two dimensional matrix. Assessing data was conducted in two ways: numerical or cardinal valuation when numerical data are present, and ordinal ranking method when data are absent or unreliable.
Bhat 1996	A simulation-optimisation model was developed to obtain the optimal allocation of trucks for MSW management by reducing travelling and waiting time costs. The simulation model estimates the waiting time of trucks and the optimisation model uses heuristic approach to fine the optimal allocation of trucks.
Gottinger 1991	A fixed charge mixed integer programming model which views regional waste management systems as network flows was suggested. The mathematical formulation of the long range planning of locations and expansion of facilities for regional waste management was also explored.

able mathematical models. Conventional models usually focus on the economic optimisation with cost minimisation being the sole objective disregarding potential adverse environmental impacts. Since the early 1980's, ISWM planning has gradually changed its orientation with increased environmental concerns and the emphasis on material and energy recovery. At present, proper strategies for ISWM require the optimisation of both socio-economic and environmental considerations. In this respect, deterministic and stochastic mathematical programming models have been applied for ISWM planning. The spectrum of those deterministic models vary widely from direct-calculation to linear programming (LP), mixed integer programming (MIP), dynamic programming, and multi-objective programming. Techniques used for stochastic models involve probability, fuzzy and grey system theory. Various issues of MSW management have been addressed through operations research (OR) methods (Table 1).

Limited suitable land area and resources, growing public opposition, and deterioration of environmental conditions are invariably the main constraints for the proper functioning of an ISWM. In this context, MSW management has often been viewed from the narrow perspective of counties or districts rather than a regional perspective. This study emphasises the latter by developing and applying an optimisation model for ISWM at a regional level, by considering every county or district as a single generation source. The general problem that will be addressed in the model can be described as follows: given the quantities of waste generated at the sources, the locations and capacities of existing facilities, the potential locations and capacities of proposed facilities, and the cost structure (economic and environmental), find out how waste should be routed, processed, and disposed of so that the over all cost (economic and environmental) of the system is minimised. The model is further used to explore the sensitivity of the waste management system to various operational parameters, and to predict the outcome of possible policy changes so that alternative management schemes may be evaluated. The formulation of the model provides a wide range of applications. Depending on data availability and/or the required level of detail, model terms can be modified to provide an optimum path for every scenario. Operational costs considered might simply be the fees paid at the entrance of every waste management facility, or the full costs that cover the "life cycle" of ISWM expenditure. Similarly, environmental costs might be the costs of abatement and remediation of potential pollutants, yet it can extend to include costs of potential health hazards, ecosystem deterioration, and land cost depreciation.

Complications associated with ISWM decisions

Every decision may have its own set of problems, however, there are four basic general sources of difficulty: complexity, uncertainty, multi-objectivity, and subjectivity (Clemen 1996). The level of difficulty for every source vary depending on the case specificity of every problem. The issue of ISWM, which is becoming a critical managerial topic, has its large share of each of the four sources.

First, the decision on ISWM is hard simply because of its complexity. Decision makers must consider many different individual issues: the waste generation stream, the different possible courses of action, the economic load of every waste management alternative, and the environmental impact associated with these alternatives. Simply keeping all these conflicting issues in mind at one time is a challenge.

Second, constituents of the ISWM stream are full of uncertainties. Waste generation is uncertain since it is a function of population distribution and growth, and per capita waste generation rates. Economic estimates are also uncertain being a function of the technology used, economies of scale, land availability, and local labor and equipment prices. Consequently, averaging estimates, that will make the best use of local and international experience, are to be adopted (Daskalopoulos *et al.* 1997).

Third, decision analysis for ISWM is multi-objective. Progress in one direction may impede progress in others. For example, waste dumping is the best waste management alternative in a cost minimisation approach, however, it has the highest potential negative environmental impact, and might conflict with adopted policies. Consequently, decision-makers must trade off benefits in one area against costs in others. In this model, the problem of multi-objectivity was solved by introducing environmental valuation. In this regard, dollar values were assigned to environmental degradation, and the objective function accounts for the minimisation of economic and environmental costs concurrently.

Finally, the problem of ISWM can be viewed from various perspectives depending on the subjectivity of the decision-maker, and thus leading to different conclusions. Depending on the methodology adopted, environmental valuation can be a very subjective field especially if utility functions are encountered. In such a case, every analyst has his own view and consequently his own weighted utility function (Parikh & Parikh 1998; Bartelmus 1998).

Fig. 1 shows a flowchart for an ISWM decision process. It starts with the decision-maker identifying the decision situation and understanding the objectives of the situation. This step is followed by constraint determination, optimisation, selection of the best alternative, and sensitivity analysis. The purpose of this decision process is to help decision makers think systematically about the complex problem of ISWM and to improve the quality of the resulting decisions. There is a difference between a good decision and a lucky outcome. The first is made on the basis of thorough understanding and careful thought of the problem. Outcomes, on the other hand, may be lucky or unlucky, regardless of the decision quality.

In this context, the ISWM optimisation problem can be divided into three main parts. The first part includes the collection of the required information, the second is the development of the model and its optimisation, and the third is the processing and implementation of the model output (Fig. 2).

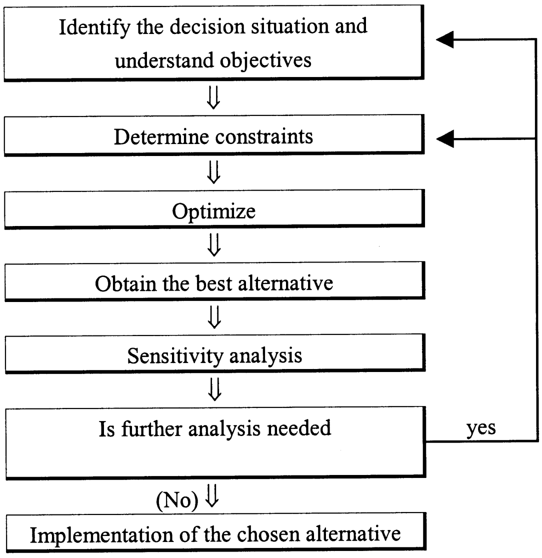

Fig. 1. ISWM decision process

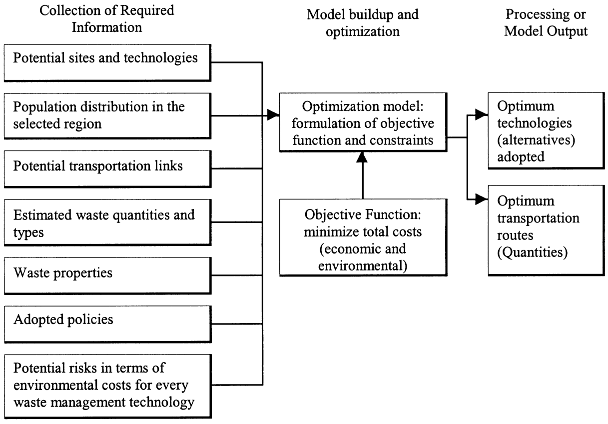

Fig. 2. The three main parts of an ISWM optimisation problem

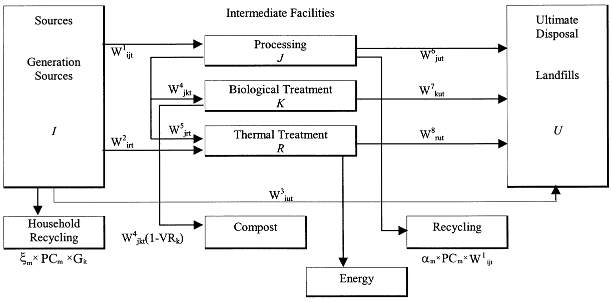

Fig. 3. Waste stream flow network

The model

This section describes the mathematical formulation of the LP model with the frame of dynamic optimisation and detailed illustration of the objective function and model constraints. The flow network of the waste stream is divided into three main sets (Fig. 3). The first set consists of the generation sources (I). The second is the intermediate facilities including the processing facilities (J), the biological treatment facilities (K), and the thermal treatment facilities (R). The last set includes the landfills (U).

Decision variables definition

The total number of generation nodes, processing facilities, biological treatment facilities, thermal treatment facilities, landfills, and time intervals are defined as I, J, K, R, U, and T, respectively. The decision variables in the model are the waste amounts transported from one node, or location, to another. They cover the transport of waste in the 8 possible paths (Fig. 3) as defined in Table 2.

Table2. Model's decision variables

	Waste Transported		
Decision variable	from	to	at
W^1_{ijt}	generation node, i	processing facility, j	time interval, t
W^2_{irt}	generation node, i	thermal treatment facility,r	time interval, t
W^3_{iut}	generation node, i	landfill, u	time interval, t
W^4_{jkt}	processing facility, j	biological treatment facility, k	time interval, t
W^5_{jrt}	processing facility, j	thermal treatment facility, r	time interval, t
W^6_{jut}	processing facility, j	landfill, u	time interval, t
W^7_{kut}	biological treatment facility, k	landfill, u	time interval, t
W^8_{rut}	thermal treatment facility, r	landfill, u	time interval, t

i = I, …., I; j = 1, …., j; k = 1, …., K; r = 1, …., R; u = 1, …, U; t = 1, …, T

All the remaining symbols represent predetermined parameters that can be changed only once for every scenario. For simplicity, the term x was introduced to account for all waste generation nodes and management facilities. Similarly, the term y represents all waste management facilities. Consequently, the term Wdxyt includes any of the following terms: W^1_{ijt}, W^2_{irt}, W^3_{iut}, W^4_{jkt}, W^5_{jrt}, W^6_{jut}, W^7_{kut}, and W^8_{rut}.

Objective function

Depending on the time interval considered, the formulation of the objective function must calculate the discounted cash flow of all quantifiable system costs and benefits over time. For this purpose, the discount factor, βt, accounts for the inflation rate, f, and the nominal interest rate, r as expressed in Equation 1 (Chang *et al.* 1996).

$$\beta_t = \left(\frac{1+f}{1+r}\right)^{t-1} \qquad (1)$$

The general form of the objective function considers the minimisation of the amortised difference between costs and benefits of the whole ISWM system (Equation 2).

$$\text{Minimise} \quad \sum_{t=1}^{T} \beta_t \left(C_t^* - B_t^*\right) \qquad (2)$$

Where: Ct* = cost associated with ISWM stream at time t ($) (with t = 1 , …. , T)

Bt* = benefit associated with ISWM stream at time t ($) (with t = 1 , …. , T)

Table 3. Summary of the conventional and environmental cost component, Ct*

$C_t^* = \sum_{d=1}^{D} \sum_{x=1}^{Xd} \sum_{y=1}^{Yd} \{TC_{xyt} x W^d_{xyt}$	Transportation cost
$+ OC^d_y x \, W^d_{xyt}$	Operational cost
$+ OC^d_y x \, W^d_{xyt} \}$	Environmental cost
$+ \sum_{x=1}^{x} CC_{xt}$	Fixed construction cost
$+ \sum_{x=1}^{x} EC_{xt}$	Fixed expansion cost

with $X_1 = X_2 = X_3 = j$, $X_4 = X_5 = X_6 = j$, $X_7 = k$, $X_8 = r$

$Y_1 = j$,

$Y_2 = Y_5 = r$, $Y_4 = Y_5 = Y_6 = k$

$X = j+K+R+U$

TC_{xyt} = unit cost of waste transported from x to y at time t ($ ton^{-1})

W^d_{xyt} = amount of waste transported form x to y at time t (tons)

OC^d_y = unit operating cost at facility y ($ ton^{-1})

RC^d_y = unit environmental costs (remediation and others) of pollution at facility y at time t ($ ton^{-1})

CC_{xt} = construction cost of a new facility x at time t ($)

EC_{xt} = fixed expansion cost of facility x at time t ($)

i = I, …., I; j = 1, …., j; k = 1, …., k; r = 1, …., R; u =1, …., U; t = 1, …., T

Note: the fixed construction and expansion costs are not decision variables. They are parameters that should be added to the objective function. To consider them as decision variables, Integer Linear Programming (ILP) should be introduced

The cost component of the objective function, Ct*, consists of two major cost categories: conventional and environmental (Table 3). Conventional costs include collection, transportation, construction, operation, and expansion costs. The environmental category indicates the value that society places on environmental damage which was assumed to be equal to the cost of abatement and remediation of potential pollution. Table 3 summarises conventional and environmental cost components.

The benefit components of the objective function, Bt*, consist of the total resource recovery income of waste obtained from selling recyclable materials and compost at the facilities, as well as the total household recycling income (Table 4).

Model constraints

The basic model constraint set consists of mass balance, capacity and material limitations, and policy implementation constraints.

Table 4. Summary of the benefits component, B_t*

$Bt^* = \sum_{m}\sum_{i}\sum_{J}(\alpha_m x PC_m x W^1{}_{iJt}) x UC_m$	Resource recovery (recyclable)
$+ \sum_{J}\sum_{k} W^4_{Jkt}(1-VR_k)C$	Biological treatment revenues
$+ \sum_{i}\sum_{r} W^2_{irt} x Th_{ir} + \sum\sum W^5_{Jrt} x Th_{Jr}$	Thermal treatment revenues
$+ \sum_{m}\sum_{r}(\xi_m x PC_m x G_{it}) x UC_m$	Household recycling income

with m =1, ..., M; i = 1, ..., I; j = 1, ..., J; k = 1, ..., K; r = 1, ..., R; t = 1, ..., T

α_m = percent of material m in waste, sold as recyclable raw material, (% ratio) (model parameter, not variable)
PC_m = percent of material m in solid waste, (% ratio)
UC_m = unit selling price of material m, \$
VR_k = volume reduction ratio at compost facility k
C = revenues from biological treatment facilities , for composting, it is the compost unit price (\$ ton^{-1} of waste)
Th_{ir} = revenues from thermal treatment facilities with waste received directly from generation from one ton of waste (\$ ton^{-1} of waste)
Th_{ir} = revenues from thermal treatment facilities with waste received from processing facilities (i.e. with higher energy content than Th_{ir}) (\$ ton^{-1} of waste)
ξ_m = percent material m sold as recyclable raw material from household, (% ratio) (model parameter, not variable)
RI_m = recycling income for material m (\$ ton^{-1} of waste)
G_{it} = generation amount at source i at time t, (ton)

Note: the household recycling income is not a decision variable. It is a number that should be added to the objective function to obtain the overall network benefits. To consider it as a decision variable, ILP should be introduced

Mass balance constraint

All solid waste generated at a source i, should be shipped either to a processing facility, j, a thermal treatment facility, r, or directly to an ultimate disposal site, u, except for waste sold at the household level (Equation 3).

$$\sum_{j=1}^{J} W^1{}_{ijt} + \sum_{r=1}^{R} W^2{}_{irt} + \sum_{u=1}^{U} W^3{}_{iut} = \sum_{i=1}^{I} G_{it} \times \left(1 - \Sigma_{m=1}^{M}(\xi_m \times PC_m)\right) \quad (3)$$

with i = 1, ... , I, and t = 1, ... , T.

Moreover, all solid waste transported to processing facilities should be either treated or transported to ultimate disposal sites (landfills). In other words, the rate of incoming waste at any facility must equal the rate of outgoing waste plus the amount removed in the process (Equation 4).

$$\sum_{i=1}^{I}\left[W^1{}_{ijt}\left(1 - \sum_{m=1}^{M}(\alpha_m \times PC_m)\right)\right] = \sum_{r=1}^{R} W^5{}_{jrt} + \sum_{k=1}^{K} W^4{}_{jkt} + \sum_{u=1}^{U} W^6{}_{jut} \quad (4)$$

with j = 1, ... , J, and t = 1, ... , T.

Finally, the total amount of solid waste transported to processing facilities in every time period must be greater than or equal to the minimum amounts required to satisfy the recycling policies (Equation 5). For example, to adopt a policy of separating 50% of the paper and cardboard and prepare it for recycling, more than 50% of the waste must be processed if good quality raw material is required since not all the paper portion of the waste is recyclable.

$$\sum_{i=1}^{I}\sum_{m=1}^{M} \alpha_{m,max} G_{it} \le \sum_{i=1}^{I}\sum_{j=1}^{J} W^1{}_{ijt} \quad \textit{with } t = 1, \ldots\ldots, T.$$

with t = 1, …….. , T. (5)

where:

$\alpha_{m,\ max}$ = maximum percent of material m in waste, sold as recyclable raw material at time t, % (model parameter not variable)

Capacity limitation constraint

The planned capacity at each facility should be less than or equal to the maximum allowable capacity, and greater than or equal to the minimum capacity of the facility (Equations 6-9).

$$Cap^1{}_{min,t,j} \le \sum_{i=1}^{I} W^1{}_{ijt} \le Cap^1{}_{max,t,j} \qquad j = 1, \ldots, J \quad t = 1, \ldots, T \quad (6)$$

$$Cap^2{}_{min,t,k} \le \sum_{j=1}^{J} W^4{}_{jkt} \le Cap^2{}_{max,t,k} \qquad k = 1, \ldots, K \quad t = 1, \ldots, T \quad (7)$$

$$Cap^3{}_{min,t,r} \le \sum_{j=1}^{J} W^5{}_{jrt} + \sum_{i=1}^{I} W^2{}_{irt} \le Cap^3{}_{max,t,r} \qquad r = 1, \ldots, R \quad t = 1, \ldots, T \quad (8)$$

$$Cap^4{}_{min,t,u} \le \sum_{i=1}^{I} W^3{}_{iut} + \sum_{j=1}^{J} W^6{}_{jut} + \sum_{r=1}^{R} W^8{}_{rut} + \sum_{k=1}^{K} W^7{}_{kut} \le Cap^4{}_{max,t,u} \quad (9)$$

u= 1, …. , U   t= 1, …. , T

Material limitation constraints

The solid waste is not fully compostable. The model accounts that not all the waste reaching a certain processing facility can be sent to a biological (Equation 10) or thermal treatment plant (Equations 11 and 12). PC_{comp} and PC_{inc}. denote the percentages of compostable or combustible waste.

$$\sum_{k=1}^{K} W^4{}_{jkt} \le PC_{comp} \sum_{i=1}^{I} W^1{}_{ijt}$$

With j = 1, …., J and t = 1, …. , T (10)

$$\sum_{r=1}^{R} W^2{}_{irt} \le PC_{inc.}\, G_{it}$$

With i = 1, …. , I and t = 1, …. , T (11)

$$\sum_{r=1}^{R} W^5{}_{jrt} \le PC_{inc.} \sum_{i=1}^{I} W^1{}_{ijt}$$

with j = 1, …. , J and t = 1, …. , T (12)

The model also accounts for a certain percentage of waste that reaches biological (Equation 13) or thermal (Equation 14) treatment facilities is landfilled (i.e. ash from incinerators and residuals from compost plants). Percentages for materials disposed of in landfills from biological and thermal facilities are referred to as $PC_{ret,b}$ and $PC_{ret,t}$, respectively. Although the amounts of such materials are relatively small, they might affect the optimum solution particularly in the presence of high transportation costs.

$$\sum_{u=1}^{U} W^7{}_{kut} \ge PC_{ret,b} \sum_{i=1}^{J} W^4{}_{jkt}$$

with k = 1, …. ,K and t = 1, …. , T (13)

$$\sum_{u=1}^{U} W^8{}_{rut} \ge PC_{ret,t} \left(\sum_{i=1}^{I} W^2{}_{irt} + \sum_{j=1}^{J} W^5{}_{jrt} \right)$$

With r = 1, …. , R and t = 1, …. , T (14)

Policy implementation constraints

The optimum ISWM plan can be constrained by policy makers through policy-implementation. Separation at the source can be implemented as a policy by imposing some minimum and maximum values for ξ_{xmt} (Equation 15). Similarly, recycling and composting can be encouraged through policies. This can be achieved through setting minimum values for αmt and W^4_{jkt}, respectively (Equations 16 and 17). Consequently, the system will be shifted towards the adoption of more recycling and composting programs using the policy parameters, xmt and amt

$$\xi_{min,m} \le \xi_m \le \xi_{max,m} \qquad (15)$$

$$\alpha_{min,m} \le \alpha_m \le \alpha_{max,m} \qquad (16)$$

$$W^4{}_{jkt,\,min} \le W^4{}_{jkt} \le W^4{}_{jkt,\,max} \qquad (17)$$

Note that the last three sets of equations can be tested through the sensitivity analysis by simulating the optimised solution with the targeted composting quantities, material recycling percentages, and household recycling material percentages, respectively.

Number of variables and equations in the model

The number of decision variables is obtained by the following term:

Total number of decision variables =

T x (IJ + IR + IU + JK + JR + JU + KU + RU)

The number of constraints and number of non-zero terms for every type of constraint equations is briefly summarised in Table 5. Consequently, the total number of constraint equations is:

T x (2I + 5J + 3R + 3K + 2U + 1).

Conclusions

Planning a regional waste management strategy is a critical step that, if not properly addressed, will lead to an inefficient ISWM system. Regional planning affects the design, implementation, and efficiency of the overall ISWM scheme. Consequently, decision-makers search for optimised regional waste management planning to achieve a successful strategy. The optimisation of an ISWM strategy for an area requires the knowledge of

Table 5. Number of equations and non-zero terms for constraints

Equation Number	Number of equations	Number of non-zero terms
3	IxT	J+R+U
4	JxT	I+R+K+U
5	T	IJ
6	2xJxT	I
7	2xKxT	J
8	2xRxT	I+J
9	2xUxT	I+J+R+K
10	JxT	I+K
11	IxT	I
12	JxT	I+J
13	KxT	U+J
14	RxT	I+U+J

available waste management alternatives and technologies, economic and environmental costs associated with these alternatives, and their applicability to the specific area.

The overall objective of the work presented in this paper was to develop a regional LP model that tackles the planning phase of regional ISWM, being the first stage that needs to be addressed. The aim was to assist decision-makers by providing an optimum waste management policy given the available data. It presents the information required for making a factual, analytical decision about the optimum waste management alternative taking into consideration the economic and environmental impacts, all along with the various constraints adopted to account for implemented or suggested policies, mass balance, capacity limitations, operation, finance, and site availability. The model focuses on the macro level ISWM since it is the first level that should be assessed. The model was applied on a regional scale to simulate and optimise MSW management for a specific region. Sensitivity analysis was also conducted to assess major model parameters including the effect of adopting recycling policies and changing operational costs (Abou Najm *et al.* 2002).

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References

Abou Najm, M., El Fadel, M., Ayoub, G., El-Taha, M., and Al-Awar, F. (2002) An optimisation model for regional solid waste management, II. Model application and sensitivity analysis, Paper submitted for possible publication in *Waste Management & Research,* **20.**

Barlishen, K., Baetz, B. (1996) Development of a Decision Support System for Municipal Solid Waste Management Systems Planning, *Waste Management & Research*, vol. **14,** n 1, 71–86.

Bartelmus, P. (1998) "The value of nature: valuation and evaluation in environmental accounting" In Uno, K. and Bartelmus, P. (eds.) *Environmental accounting in theory and practice*, p 263–307, Kluwer Academic Publishers. Printed in Greater Britain.

Bhat, V. (1996) A Model for the Optimal Allocation of Trucks for Solid Waste Management, *Waste Management & Research*, vol. **14,** n **1,** 87–96.

Chang, N., Shoemaker, C., Schuler, R. (1996) Solid Waste Management Analysis with Air Pollution and Leachate Impact Limitations, *Waste Management & Research*, vol. **14,** n **5,** 463–481.

Charnpratheep, K., Zhou, Q., Garner, B. (1997) Preliminary landfill site screening using fuzzy geographic information systems, *Waste Management & Research*, vol. **15,** 197–215.

Clemen, R. (1996) Making hard decisions, an introduction to decision analysis, Second edition, Duxbury Press.

Daskalopoulos, E., Badr, O., Probert, D. (1998) An Integrated Approach to Municipal Solid *Waste Management, Resource, Conservation and Recycling,* vol. **24,** 33-50.

Daskalopoulos, E., Badr, O., Probert, D. (1997) Economic and Environmental Evaluations of Waste Treatment and Disposal Technologies for Municipal Solid *Waste, Applied Energy,* vol. 58 209-255.

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

Haith, D. (1998) Material Balance for Municipal Solid Waste Management, *Journal of Environmental Engineering,* 67–75.

Huang, G., Baetz, B., Patry, G. (1997) SWDSS: *A Decision Support System Based on Inexact Optimisation for Regional Waste Management and Planning Application to the Region of Hamilton-Wentworth,* Air and Waste Management Association, 90th Annual Meeting and Exhibition, 97–RA134A.03, Toronto, Ontario, Canada.

Kao, J., Lin, H., Chen, W. (1997) Network geographic information system for landfill siting, *Waste Management & Research,* vol. **15,** 239–253.

Ljunggren, M., Sundberg, J. (1997) *A Method for Strategic Planning of National Solid Waste Management Systems- Model and Case Study,* Air and Waste Management Association, 90th Annual Meeting and Exhibition, 97–RA134A.04, Toronto, Ontario, Canada.

Nema, A., Modak, P. (1998) A strategic design approach for optimisation of hazardous waste management systems, *Waste Management & Research,* vol. **16,** 210–224.

Parikh, J. and Parikh, K. (1998) "Valuing environment in developing countries: a challenge" In Uno, K. and Bartelmus, P. (eds.) *Environmental accounting in theory and practice,* p 321–335, Kluwer Academic Publishers. Printed in Greater Britain.

Powell, J. (1996) The Evaluation of *Waste Management Option, Waste Management & Research,* vol. **14,** n **6,** 515–526.

Rubenstien, B. (1997) *Multiple Attribute Decision System (MADS): A System Approach to Solid Waste Management Planning,* Air and Waste Management Association, 90th Annual Meeting and Exhibition, 97–RA134A.02, Toronto, Ontario, Canada.

Sundberg, J. and Ljunggren, M. (1997) *Linking Two Modeling Approaches for the Strategic Municipal Waste Management Planning. The MIMES/Waste Model and LCA,* Air and Waste Management Association, 90th Annual Meeting and Exhibition, 97–RA134A.06, Toronto, Ontario, Canada.

Nomenclature

Symbol	Description
α_m	Percent of material m in waste, sold as recyclable raw material at time t (% ratio)
ξ_m	Percent material m sold as recyclable raw material from household at time t (% ratio)
$\alpha_{m,\ max}$	Maximum percent of material m in waste, sold as recyclable raw material (% ratio)
β_t	Discount Factor
AHP	Analytic Hierarchy Process
C	Revenues from biological treatment facilities, for composting, it is the compost unit price ($ ton^{-1} of waste)
Cap_{min} and Cap_{max}	Minimum and maximum facility-capacities
CC_{xt}	Construction cost of a new facility x at time t ($)
EC_{xt}	Fixed expansion cost of facility x at time t ($ ton^{-1})
f	Inflation rate
GIS	Geographic Information System
G_{it}	Generation amount at source i at time t (ton)
GWP	Global Warming Potential
I	Total number of generation sources
IMILP	Inexact Mixed Integer Linear Programming
ISWM	Integrated Solid Waste Management
J	Total number of processing facilities
K	Total number of biological treatment facilities (compost plant)
LP	Linear Programming
MADS	Multiple Attribute Decision System
MILP	Mixed Integer Linear Programming
MIP	Mixed Integer Programming
MSW	Municipal Solid Waste
$OC^d{}_y$	Unit operating cost at facility y ($ ton^{-1})
OR	Operations Research
PC_{comp} and $PC_{inc.}$	Percentages of compostable or combustible waste (% ratio)
PC_m	Percent of material m (% ratio)
$PC_{ret,b}$ and $PC_{ret,t}$	Percentages for returnable materials to landfills from biological and thermal facilities, respectively (% ratio)
R	Total number of thermal treatment facilities (incinerator)
r	Nominal interest rate
$RC^d{}_y$	Unit remediation cost of pollution at facility y ($ ton^{-1})
RI_{mt}	Recycling income for material m ($ ton^{-1} of waste)
SWDSS	Solid Waste Decision Support System
T	Total number of time intervals
TC_{xyt}	Unit cost of waste transported from x to y at time t ($ ton^{-1})
Th_{ir}, Th_{jr}	Revenues from thermal treatment facilities, for incineration, it is the energy recovery revenues from one ton of waste ($ ton^{-1} of waste)
U	Total number of landfills
UC_m	Unit selling price of material m ($)
VR_k	Volume reduction ratio at compost facility k
$W^d{}_{xyt}$	Amount of waste transported for activity d: from x to y at time t (ton)
C*t	Cost associated with ISWM stream at time t ($)
B*t	Benefit associated with ISWM stream at time t ($)