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SOLID WASTE MANAGEMENT SYSTEM ANALYSIS WITH AIR POLLUTION AND LEACHATE IMPACT LIMITATIONS

Ni-Bin Chang[1], Christine A. Shoemaker[2] and Richard E. Schuler[2]

[1]*Department of Environmental Engineering, National Cheng-Kung University, Tainan, Taiwan, Republic of China, and* [2]*School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, 14853, U.S.A.*

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Conventional location/allocation models for solid waste management usually focus on the economic optimization. However, the siting of important facilities, such as landfills, incinerators and transfer stations, in the solid waste management system still encounters several other limitations which must be considered through the use of optimization techniques. This paper presents sustainable waste management strategies in which the decision makers may put forward their views on material recycling and the assimilative capacity of the environment for two major factors; air pollution control and leachate impact. A mixed integer programming model with the framework of dynamic optimization is applied to achieve such a goal.

Key Words—Solid waste management, optimization, system analysis, modelling, materials recycling.

1. Introduction

Economic optimization in the system planning of solid waste management was first emphasized in the late 1960s by Anderson (1968). Since then, most of the waste-related planning models have been focused on the cost minimization in system analysis. Until the early 1980s, the planning of an integrated solid waste management system gradually changed its orientation with the increasing environmental concerns and the emphasis on material and energy recovery. As a consequence, public scrutiny of siting new facilities, rising pressure of tipping fees, and legislatively mandated recycling require greater sophistication of system analysis techniques. It is believed that the sustainable waste management strategies needed in many countries today require the optimization of both socio-economic and environmental considerations. Such strategies provide the best dynamic combination of waste recycling, facilities siting and system operation.

Various deterministic and stochastic mathematical programming models have been applied for planning solid waste management systems. The spectrum of those deterministic models include linear programming (LP), mixed integer programming (MIP), dynamic programming (DP), and multi-objective programming, while the techniques used in stochastic expressions consist of probability, fuzzy and grey systems theory. Location/allocation models (i.e. MIP models) have mainly been used in site selection and capacity expansion. In the literature, the applications of MIP models for economic optimization of solid waste management systems include Marks *et al.* (1970), Helms & Clark (1974), Fuertes *et al.* (1974), Walker *et al.* (1974), Kühner & Harrington (1975), Hasit & Warner (1981), Jenkins (1982), Gottinger (1986), Kirca & Erkip (1988) and

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Zhu & ReVelle (1990). In addition, Baetz (1990) employed a DP model to determine the optimal capacity expansion patterns for waste-to-energy and landfill facilities. Perlack & Willis (1985) and Koo *et al.* (1991) used the multi-objective programming models in siting waste treatment facilities. The grey fuzzy linear programming (GFLP) and the grey chance-constrained programming (GCCP) approaches were used by Huang & Baetz (1993) and Huang *et al.* (1993), respectively, for solid waste management planning. Thomas *et al.* (1990) announced the development of an expert system for municipal solid waste management.

This paper represents a specific effort in which the environmental impacts, including air pollution and leachate impacts, are integrated into a location/allocation model. In addition, material recycling and energy recovery is also emphasized in the screening process of siting management facilities in a growing metropolitan region. Numerical illustration of Broome County, New York, U.S.A., demonstrates this methodology. It shows that the incorporation of these two environmental factors can alter the conventional waste management pattern in metropolitan solid waste management systems.

2. Model formulation

The MIP model with the framework of dynamic optimization can still be used efficiently for site selection once the environmental concerns and the material recycling are incorporated. The nomenclature of this model is listed in Appendix 1.

2.1 Objective function

The objective function in this model is formulated for calculating the discounted cash flow of all quantifiable system benefits and costs over time. Discounted factors are prepared economically for the dynamic adjustment. In the application, the real discounted factor is defined simultaneously by the inflation rate (f) and the nominal interest rate (r), which is denoted as $\beta_t(=[(1+f)/(1+r)]^{t-1})$. The mathematical expressions of the objective function are defined as in equations 1–10:

$$\text{Minimize} \sum_{t=1}^{T} \beta_t(C_t - B_t) \qquad [1]$$

The cost components (C_t) consist of:

$$\text{Total transportation cost} = \sum_{(j,k) \mathrm{v} I, j \ \mathrm{r} \ \mathrm{k}} [CT_{jkt} \times S_{jkt}] \qquad [2]$$

$$\text{Total construction cost} = \sum_{k \mathrm{v} (J \backslash J_1)} [CC_{kt} \times DC_{kt} + F_{kt} \times Y_{kt}] \qquad [3]$$

$$\text{Total operating cost} = \sum_{k \mathrm{v} (J \backslash J_1 \ \mathrm{j} \ K \backslash K_1)} \left[CO_{kt} \times \sum_{(j,k) \mathrm{v} \mathrm{I}1} S_{jkt} \right] \qquad [4]$$

$$\text{Total expansion cost} = \sum_{k\text{v}(J\backslash J_1 \text{ j } K\backslash K_1)} [CE_{kt} \times TEXP_{kt}] \quad [5]$$

$$\text{Total recycling cost} = \sum_{i\text{v}R} TR_{it} \times CR_{it} \quad [6]$$

$$\text{Total cost for additional air pollution control} = \sum_{k\text{v}(K_3 \text{ j } J_3)} \sum_{p\text{v}P} \{CA_{kpt} \times E1_{kpt}\} \quad [7]$$

Only three benefit components (B_t) are considered in this model; these are:

$$\text{Total resource recovery income at the facilities} = \pm \sum_{i\text{v}R} \sum_{k\text{v}(M \text{ j } K_4 J_4)} \sum_{(j,k)\text{v}I1} [P_{ikt} \times T_{ikt} \times S_{jkt}] \quad [8]$$

$$\text{Total household recycling income} = \pm \sum_{i\text{v}(J_1 \text{ j } K_1)} \sum_{j\text{v}R} [IR_{ijt} \times \alpha_{ijt} \times G_{it}] \quad [9]$$

$$\text{Total residual values of new facilities at the end of planning horizon} = \sum_{k\text{v}(J\backslash J_1)} RV_{kt} \quad [10]$$

In these mathematical expressions, set subtraction is represented by the notation of a backslash (\). A fixed charge structure is still employed in the formulation of total construction cost. The term of facilities expansion cost does not have a fixed charge; hence, only the variable cost is included. The possible recoverable resources (i.e. material and energy) consist of paper, glass, metal, plastics, steam and electricity, and the net market prices of these resources recovered at processing plants and transfer stations can then be estimated. However, these secondary materials could be picked up directly at households or other places, instead of in treatment or sorting facilities. Thus, a separate term, corresponding to the income from household recycling, is defined. Since recyclables may not always have positive economic value in the secondary material market, the plus/minus sign is therefore formulated in this benefit term.

The residual values for those facilities at the end of planning horizon assure that the benefit of old facilities may exceed their salvage value. The logic of expressing residual value here is that it may be assumed that the total construction or expansion investment should be no more than the summation of all net benefits in each time period, discounted to the present value. In the last time period, the benefit should include salvage value. Then, with a fixed length of operating period, the residual value is defined as the residual benefit left beyond the end of the planning horizon. The later the facility is built, the greater the benefit that remains. The summation of individual benefits at different years, discounted to the present value, must at least equal the total construction cost or else the facility would never be built. If the yearly benefit is assumed to be identical as B, and salvage value is assumed to be equal to a proportion (γ) of total construction cost by estimation, the minimum net present value or total expected benefit is the project's construction cost. To consider a multistage process, the residual value can be derived below (Chang 1989):

$$TC_{kt}=\gamma TC_{kt}\times\left(\frac{1+f}{1+r}\right)^{T}+B\times\sum_{i=t}^{T+t}\left(\frac{1+f}{1+r}\right)^{i} \quad [11]$$

in which t is the initialization period of a facility. Hence, the benefit can be expressed as:

$$B=\left\{\left[1-\gamma\left(\frac{1+f}{1+r}\right)^{T}\right]\div\left[\sum_{i=t}^{T+t}\left(\frac{1+f}{1+r}\right)^{i}\right]\right\}\times TC_{kt} \quad [12]$$

and the residual value is therefore defined as:

$$RV_{kt}=B\times\sum_{i=T}^{T+t}\left(\frac{1+f}{1+r}\right)^{i}+\gamma\left(\frac{1+f}{1+r}\right)^{T}\times TC_{kt} \quad [13]$$

then, the residual value represents a fraction of the total construction cost as below:

$$RV_{kt}=\delta\times TC_{kt}=\delta\times F_{kt}\times Y_{kt}+\delta\times CC_{kt}\times DC_{kt} \quad [14]$$

where:

$$\delta=\left[1-\gamma\times\left(\frac{1+f}{1+r}\right)^{T}\right]\div\left[\sum_{i=t}^{T+t}\left(\frac{1+f}{1+r}\right)^{i}\right]\times\left[\sum_{i=T}^{T+t}\left(\frac{1+f}{1+r}\right)^{i}\right]+\gamma\times\left(\frac{1+f}{1+r}\right)^{T} \quad [15]$$

2.2 Constraint set

The basic constraint set in Chang's study (1989), consisting of the mass balance, capacity limitation, operating, financial, site availability and conditionality constraints, is still retained, which performs the fundamental function of site selection, system operation and tipping fees evaluation. The special constraints emphasized in this paper are air pollution control, leachate impact and material recycling constraints that are expected to be influential in the metropolitan solid waste management system planning. The configuration of the proposed constraint set in this model is illustrated as follows:

2.2.1 Mass balance constraint

Point sources

All solid waste generated in the collection district should be shipped to other treatment or disposal sites. Furthermore, the waste reduction by household recycling can be taken into account in terms of the participation rate of residents, the recyclable ratio and the composition of waste. Recycling potential must be evaluated in advance, and the impact on system operations can be shown by including the following constraints:

$$\sum_{k\in(J\setminus J_1\cup K\setminus K_1)} S_{ikt}=G_{it}\times(1-\alpha_{it}) \qquad \forall i\in(J_1\cup K_1),\ \forall t\in T' \tag{16}$$

$$\alpha_{it}=\sum_{j\in R}\alpha_{ijt} \qquad \forall i\in(J_1\cup K_1),\ \forall t\in T' \tag{17}$$

$$0\le\alpha_{ijt}\le\alpha_{ijt,\max} \qquad \forall i\in(J_1\cup K_1),\ \forall j\in R,\ \forall t\in T' \tag{18}$$

$$TR_{it}=\sum_{i\in(J_1\cup K_1)} G_{it}\times\alpha_{it} \qquad \forall t\in T' \tag{19}$$

System facility

For any system facility, the rate of incoming waste must equal the rate of outgoing waste plus the amount deducted in the treatment process. This deduction could be zero in the transfer stations and landfills. Any potential site available for transfer, treatment or disposal can be included in this constraint.

$$\sum_{(j,k)\in I_1} S_{jkt}\times(1-R_k)=\sum_{(k,j)\in I_2} S_{kjt} \qquad \forall k\in M,\ \forall t\in T' \tag{20}$$

2.2.2 Capacity limitation constraint

The treatment capacity planned during the procedure of construction and expansion should be less than, or equal to, the maximum allowable capacity, and greater than, or equal to, the minimum capacity on one site. The maximum allowable capacity is limited by the area of land, while the minimum capacity is determined by the minimum equipment size and its economy of scale.

New facility

In the following expression, the binary integer variable is combined with the upper or lower bound of capacity such that the site selection can be performed by the binary choice of its value "one or zero", which corresponds to the "inclusion or exclusion" of design capacities in the constraint and related cost/benefit terms in the objective function. The period of facility initialization is denoted by the symbol y that can avoid distortion of the later expansion schedule.

$$\sum_{y=1}^{T} DC_{ky}\ge MIN_k\times\sum_{y=1}^{T} Y_{ky} \qquad \forall k\in(J\setminus J_1) \tag{21}$$

$$DC_{ky} + \sum_{t=y+1}^{T} NEXP_{kyt} \leq MAX_k \times Y_{ky} \qquad \forall k v (J \backslash J_1), \forall y v (1, T-1) \qquad [22]$$

$$\sum_{y=2}^{t} NEXP_{kyt} = TEXP_{kt} \qquad \forall k v (J \backslash J_1), \forall t v T' \qquad [23]$$

Old facility

$$DC_k + \sum_{t=1}^{T} TEMP_{kt} \leq MAX_k \qquad \forall k v (K \backslash K_1) \qquad [24]$$

2.2.3 Operating constraint

The accumulated waste inflow at each site should be less than, or equal to, the available capacity in each planning period.

New facility

$$TIME \times \left[\sum_{y=1}^{t'} \left(DC_{ky} + \sum_{t=y+1}^{t'} NEXP_{kyt} \right) \right] \geq \sum_{(j,k) v I_1} S_{jkt} \qquad \forall k v (J \backslash J_1), \forall t' v T' \qquad [25]$$

Old facility

$$TIME \times \left(DC_k + \sum_{t=1}^{t'} TEXP_{kt} \right) \geq \sum_{(j,k) v I_1} S_{jkt'} \qquad \forall k v (K \backslash K_1), \forall t' v T' \qquad [26]$$

2.2.4 Conditionality constraint

The conditional constraint ensures that the initialization of a new site in a system can only occur once in a multistage planning project. The intertemporal trade-off of construction and later expansion of a facility can then be established.

$$\sum_{t=1}^{T} Y_{kt} \leq 1 \qquad \forall k v (J \backslash J_1) \qquad [27]$$

2.2.5 Site availability constraint

The subset of the potential sites may be excluded by social or political reasons in a specific time period. Hence, this constraint can also allow the planner to leave out some of the potential sites.

$$\sum_{k v (J \backslash J_1)} Y_{kt} \leq N_t \qquad \forall t v T' \qquad [28]$$

2.2.6 Financial constraint

This constraint provides information about financial balance and possible users' charge (tipping fee) for waste management. The evaluation of resource recycling can also be made by varying the price of secondary materials and electricity generated in the system. The key point in the formulation is the use of an inequality, rather than equality, constraint. If the equality constraint holds, the solution will show that there will never be profits in operating these facilities in each period, and the accumulated income will be used up through the building of extra treatment capacity which is of no use in that period.

$$C_t \leq B_t + TIP_t \times \left[\sum_{i \mathrm{v} (K_1 \mathrm{~j~} J_1)} G_{it} \right] \qquad \forall t \mathrm{v} T' \tag{29}$$

2.2.7 Air pollution control constraints

In the U.S.A., air pollution is regulated under the Clean Air Act in various ways. The National Ambient Air Quality Standards (NAAQS) imposed by the Federal Government specify maximum concentrations (i.e. ppm or μg m^{-3}) of certain pollutants in the surrounding environment, while the Prevention of Significant Deterioration (PSD) and New Source Performance Standards (NSPS) limit mass emission rates (i.e. tonnes year^{-1}) of pollutants from specific sources. Generally, PSD constraints are more stringent than NAAQS constraints. However, once compliance with PSD increments has been determined, compliance with NAAQS must be demonstrated. Hence, this analysis considers both PSD and NAAQS limitations, but only the deduction rate of pre-determined air pollutant $p(E1_{kpt})$ described in the PSD constraint is included in the objective function during the cost minimization process. The constraint formulations are described as below:

PSD constraints

$$f1 \times \left[\sum_{(j,k) \mathrm{v} I_1} (S_{jkt} \times EP_p) \right] \leq S1_{kpt} + E1_{kpt} \qquad \forall k \mathrm{v} (K_3 \mathrm{~j~} J_3),\ \forall p \mathrm{v} P,\ \forall t \mathrm{v} T' \tag{30}$$

$f1$ is a conversion factor on yearly basis between the units of emission factor (EP_p) and air quality standard ($S1_{kpt}$). The required removal efficiency for additional air quality improvement can be obtained by $E1_{kpt}/(S1_{kpt} + E1_{kpt})$. However, removal efficiency would technologically encounter an upper bound by:

$$E1_{kpt}/(S1_{kpt} + E1_{kpt}) \leq U_{kpt} \qquad \forall p \mathrm{v} P,\ \forall t \mathrm{v} T' \tag{31}$$

NAAQS constraints

$$f2 \times \left[\sum_{k \mathrm{v} (K_3 \mathrm{~j~} J_3)} \sum_{(j,k) \mathrm{v} I_1} (S_{jkt} \times FGR \times EN_p \times A_{ka}) \right] \leq S2_{pt} + E2_{apt} \qquad \forall a,\ \forall p \mathrm{v} P,\ \forall t \mathrm{v} T' \tag{32}$$

*f*2 is a conversion factor on yearly basis between the units of emission factor (EN_p) and air quality standard ($S2_{pt}$). A_{ka} is the dispersion factor which is dependent on the frequency distribution of wind, wind speed category, distance between emitter and receptor, effective stack height, diffusion coefficient in air, and half life and decay rate for pollutant *p* (Bruce 1970). A modified Gaussian diffusion model for long-term planning is selected to determine the value of A_{ka}. As shown below, the long-term diffusion equation for a decay pollutant at ground level (i.e. $z=0$) and at centre line of plume (i.e. $y=0$) may be simplified to (Bruce 1970; Lancour 1975; Guldman & Shefer 1980):

$$C(x,\theta)=q\times\sum_s\sum_n\left[\frac{2.03f}{\sigma_{z_s}u_n x}\times EXP\left(\frac{-\bar{H}^2}{2\sigma_z^2}\right)\right]\times EXP(-kt)=q\times A_{ka} \qquad [33]$$

in which $C(x,\theta)$ is aggregate ambient air pollutant concentration ($\mu\mathrm{g\,m}^{-3}$); $f=f(\theta,s,n)$ is the frequency during the period of interest that the wind is from the direction θ, for the stability condition *s*, and wind speed class *n*; σ_{z_s} is the vertical dispersion parameter (standard deviation) evaluated at the distance *x* for the stability condition *s*; u_n is the representative wind speed for class *n*; *H* is the effective height of plume release corresponding to the wind speed u_n; $k(t^{-1})$ is first-order reaction rate ($=$ 0 if the pollutant is conserved); *t* is reaction time; and *q* is emission rate of particular air pollutant.

To fulfil this calculation, seasonal or annual wind distribution data by Pasquill stability classes is needed. For each of the various stability classes, wind distribution data are combined and presented as relative frequency distribution of wind speed vs. wind direction. The dispersion model may yield maximum, annual average, ground level, ambient concentrations at a set of receptors surrounding the municipal waste combustors. Only the highest level of receptor impact (the largest A_{ka}) in the receptor grid is chosen for air pollution assessment in this constraint. The value of $S2_{pt}$ is determined by both the measured background concentration and the non-controlled sources. The multiplication of flue gas flow rate (*FGR*), EN_p, and A_{ka} assures that the more solid waste handled at an incineration site, the greater the amount of air pollution in a region. The variable $E2_{apt}$ serves as a decision variable to show whether region *a* is in "attainment" or "non-attainment" of air pollutant *p* with NAAQS.

2.2.8 Leachate impact constraints

In a solid waste management system, combustion ash and raw garbage are two major waste inflows toward sanitary landfills. However, they produce different impacts due to different leachate characteristics. Residue ash contains a more concentrated mix of metals per unit weight, a by-product of high temperature combustion, while the raw garbage produces leachate with high concentrations of organic compounds in landfill. The difficulties in formulating such a constraint with higher parameter uncertainties and the lack of a comprehensive impact index make this constraint only advisable for risk assessment. In search of several related impact indices in the literature, the *BNR* index was finally selected as the impact index. *BNR* is the abbreviation of "base numerical rating" which is an analytical index for measuring pollutant penetration ability in an unsaturated zone (Short 1986). This index is a function of pollutant concentration after assimilation in the unsaturated zone under a certain geochemical environment. Thus, BNR_{jkpt} is defined as the impact index derived for different pollutant p corresponding to each type of waste stream at a specific time period. Adding such an index here would reflect the associated risk generated by the metal impact of an ash stream, and by the organics impact of the raw garbage stream in the system. It is worthwhile to observe that the waste stream distribution could be altered in the optimization process by such an additional impact consideration. Therefore, in the constraint formulation, these BNR indexes, multiplied by corresponding waste stream in the network, constitute the total impact at landfill over the project life. The right hand side value of $LIMIT_k$ represents the limited tolerance of all pollutants from leachate considered at landfill site k in the planning horizon in case the leaking event occurs. Since there is no professional consensus on the impact limitation ($LIMIT_k$), this value could be determined by simulations.

$$\sum_{t} \sum_{(j,k) v I1} \sum_{p} (BNR_{jkpt} \times S_{jkt}) \leq LIMIT_k \qquad \forall k \text{v}(K_4 \text{ j } J_4) \tag{34}$$

The BNR index, as formulated in the above constraint formulation, is derived from a general transport equation (i.e. a differential material balance equation), describing the concentration of the pollutant as a function of both depth in the soil and time (Short 1986). That is:

$$\frac{\partial C_a}{\partial t} = D_a \times \frac{\partial^2 C_a}{\partial x^2} - V_a \times \frac{\partial C_a}{\partial x} - \frac{\rho}{\theta} \times \frac{\partial C_a}{\partial t} - \mu_a \times C_a - \frac{\rho}{\theta} \times \mu_s \times C_s \tag{35}$$

where V_a is the constant speed of flow through the soil; C_a is the concentration of pollutant in leachate through the soil; C_s is the concentration of pollutant in the soil phase; D_a is dispersion coefficient; μ_a is first-order degradation constant in the aqueous phase; μ_s is first-order degradation constant in the soil phase; x is the vertical depth from the bottom of the landfill site; ρ is the bulk density of soil; and θ is volumetric water content of the soil.

Based on the assumption of the equality between μ_a and μ_s in Equation 35, Short (1986) computed an estimate of X, the depth the chemical will penetrate below a landfill at concentration in excess of the detection limit C_{DL}:

$$X = \left(\frac{V_a}{\mu \times R} \right) \times \ln \left(\frac{C_p}{C_{DL}} \right) \tag{36}$$

The BNR is defined in terms of the depth of penetration X during the assimilation process such that when X equals the depth of unsaturated zone Z, the BNR equals 100. Thus for each pollutant p considered in the corresponding waste stream from place j to k at time period t, it yields:

$$BNR_{jkpt} = \left(\frac{100}{Z} \right) = \frac{144.3 \times V_a \times T_{1/2}}{R \times Z} \times \ln \left(\frac{C_p}{C_{DL}} \right) \tag{37}$$

in which C_{DL} is the analytical detection limit for the pollutant; C_p is the steady-state concentration of pollutant p in the leachate; R is retardation factor; $T_{1/2}$ is half reaction time of pollutant p; and μ is first-order degradation constant of pollutant p in the unsaturated zone.

By the above derivations, two major types of pollutant impacts, heavy metal and BOD_5, in the leachate can be included in the constraint such that the environmental balance between ash and municipal solid waste stream is anticipated in the optimization process.

2.2.9 Non-negativity constraints

All decision variables should be non-negative.

3. Case study: dynamic planning of the Broome County solid waste management system

This case study has been prepared specifically to illustrate this model. The final optimal planning alternatives may provide better insight into the Broome County solid waste management system. The practical use of the methodology described above consists of four stages: (1) specify a schematic for a proposed solid waste management system; (2) collect basic data describing system configurations, including public regulation, waste generation, recycling potentials, efficiency of processing, parameters in air and groundwater environment, and other economic parameters; (3) build a mixed integer programming model and search for the optimal solution; and (4) conduct sensitivity analysis for testing system uncertainties.

3.1 Background of Broome County solid waste management system

Broome County, located in the southern part of New York State (U.S.A.), is a county in which the solid waste management system is identified by 19 waste generation districts, four candidate sites of incinerators (Brickyard, Phelps Street, Stratmill and Airport Road), and one currently existing landfill (Nanticoke), as shown in Fig. 1. The waste generation rate is approximately 430 tons day^{-1} (390 tonnes day^{-1}) by a population of over 200,000 (HDR 1984). The major goals in this solid waste management system are to select the appropriate sites for future incineration project and to decide the expansion schedule of the existing landfill (HDR 1984).

3.2 Analytical framework

In this analysis, a hypothetical 24-year project with six time periods is conducted. The cash flow for each year within each of the six 4-year time periods is assumed to be identical, although it is different between periods. Construction or expansion of any facility is completed within the time period during which it is initiated. That is, if a facility is to be used in period t, then it must be constructed in time period $t-1$ or before, and all investments are assumed to be incurred at the midpoint of the construction or expansion time period regardless of its real cash flow pattern. In the first time period, the whole amount of waste is handled by all existing facilities. The operation of a new facility starts at the beginning of the second or later time period if it is selected by the planning model.

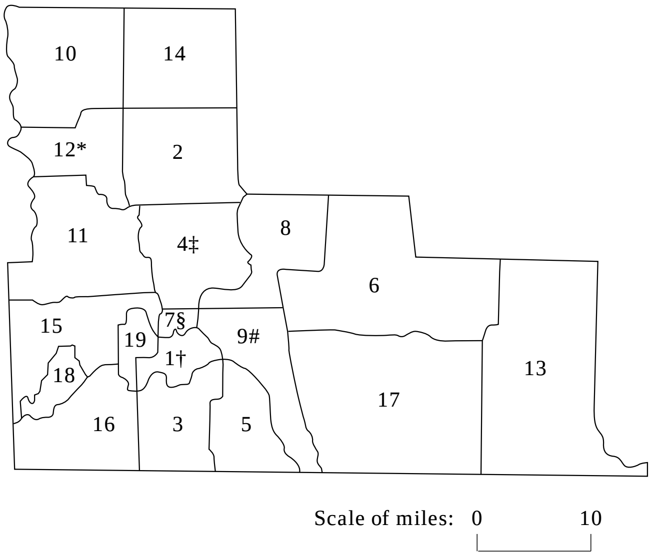

Fig. 1. The configuration of Broome County solid waste management system. * Nanticoke, † Brickyard, ‡ Airport Road, § Phelps Street, # Stratmill. 1, City of Binghamton; 2, Town of Barker; 3, Town of Binghamton; 4, Town of Chenango; 5, Town of Conklin; 6, Town of Colesville; 7, Town of Dickinson; 8, Town of Fenton; 9, Town of Kirkwood; 10, Town of Lisle; 11, Town of Maine; 12, Town of Nanticoke; 13, Town of Sandford; 14, Town of Triangle; 15, Town of Union; 16, Town of Vestal; 17, Town of Windsor; 18, Village of Endicott; 19, Johnson City.

3.3 Data acquisition and analysis

Several cost parameters, mainly including the fixed and variable costs in the construction cost functions, transportation costs and operating costs, serve as the driving forces in the optimization process. Construction cost functions can be identified by linear regression analysis. These cost data must be calibrated by construction cost indexes before the regression analysis is performed. Specifically, the major report used as the database of construction and operating costs was the *1986–87 Resource Recovery Yearbook*. Facility expansion costs were assumed to be the same as the variable costs in these construction cost functions. The New York State Electricity & Gas Corporation had expressed a willingness to purchase the electricity output of the incinerator at reasonably increasing prices over time. The cost data regarding to the landfills was found in the *Broome County Resource Recovery Project* (HDR 1984, 1988). The prices of recyclables were 5 U.S.\$ ton^{-1}* for metal, 2 U.S.\$ ton^{-1} for paper, 0.5 U.S.\$ ton^{-1} for glass, and 3 U.S.\$ ton^{-1} for plastics in this analysis. The upper limits of recyclability were imposed by 20% to paper, 8% to plastics, 5% to glass and 6% to metal as well, according to the investigated waste composition. The residual values of a new incinerator were pre-determined by 3.1, 12.7, 21, 27.2 and 32.6% of the total investment, corresponding to the second, third, fourth, fifth and sixth time periods. Values of 9 and 3.8% were selected as the interest rate (r) and inflation rate (f) to account for economic variations in the dynamic planning process. The waste reduction ratio (R_k) was assumed by 75% in the incineration project. The conversion efficiency of energy recovery was chosen as 520 kWh by burning 1 ton of municipal solid waste. All the related cost/

* Note: 1 U.S. ton is equivalent to 0·907 tonnes.

TABLE 1
Planning scenario of each case in the optimization analysis

Parameter	Base case	Case 1	Case 2	Case 3	Case 4
Tipping fees evaluation	O	O	O	O	O
Curbside recycling			O		
Residual value	O	O	O	O	O
Higher expansion cost		O			
Air pollution control	O	O	O	O	O
Leachate impact control	O			O	
10% waste growth rate	O	O	O	O	
40% waste growth rate					O
No. of decision variables	641	639	1135	639	639
No. of constraints	251	249	730	251	249

O, inclusion of this option.

benefit information in the above would constitute the fundamental framework of the objective function.

Many parameter values in the constraint set have to be decided in advance. For example, 1000 tons day^{-1} (907 tonnes day^{-1}) was chosen as the maximum capacity of incinerators, while 630 tons day^{-1} (571 tonnes day^{-1}) was used as the maximum capacity of Nanticoke landfill. On the other hand, 350 tons day^{-1} (317 tonnes day^{-1}) was selected as the minimum capacity of all incinerators. In the air pollution control constraints, SO_2, NOx, CO, HC and particulates were considered as the criteria pollutants. The FGR and the emission factors of refuse burning were taken from O'Connell's study (1982). Waste generation, composition and meteorological data were adapted from the *Broome County Resource Recovery Project* (HDR 1984). Waste generation rate was assumed to increase by one-tenth linearly over periods. The computerized diffusion model was developed independently in conjunction with the local meteorological data to translate the pollutant emissions from the incinerators into predictions of ground level concentration on a 50 receptor system around the City of Birmingham Area. Thus, long-term average transfer coefficients were computed by a separate Pascal code. Only the receptor with the biggest transfer coefficient corresponding to each potential incinerator site had to be included in NAAQS constraints. To determine the leachate impact index (*BNR*), some geochemical and environmental data were selected (Change 1989), and leachate characteristics of municipal solid waste (MSW) and ash were evaluated and compared by its potential BOD_5 concentrations and limitations of heavy metal in the TCLP test. It is observed that the metal impact of incineration ash was generally higher than that of raw garbage. Conversely, the organics impact from MSW was higher than that of incineration ash. Hence, environmental weights between these two factors could be simulated in search of various types of waste flow patterns toward either incinerators or landfills in the transportation network.

3.4 Optimization results and discussions

Five planning scenarios were chosen to illustrate the model. These are described in Table 1. The base case represented the case of dynamic planning by temporarily excluding the effect of curbside recycling, while both air pollution and leachate impact constraints were included. Due to the uncertainties of expansion costs of incineration facility and the leachate impact, Case 1 temporarily removed leachate impact constraints and specifically illustrated the effect of the inclusion of higher expansion cost. Case 3 simulated the impacts by varying the right hand side values of the leachate impact constraint. An independent screening criteria was applied. In order to test the robustness of this model, Case 4 arranged 40% linear growth rate of waste generation to verify the planning capability of multiple site selection of this MIP model, while leachate impact and curbside recycling were removed temporarily.

The optimization results are listed in Table 2. The LINDO software package was employed as a computer solver in this analysis. These optimization programs were run in the VAX5 system. The computational costs varied from 37 to 229 resource units in the VAX5 system, while the CPU elapse time was less than 25 mins.

In the base case, it was observed that the energy recovery income dominated the optimization decision making, and the option of earlier construction of the incinerator caused the tipping fees decrease to zero in the third time period. The expansion schedule was uniformly distributed to meet the growing demand of solid waste management. Residual values of the capacities of both construction and expansion did not alter the waste management pattern significantly. In Case 1, however, the optimal management pattern remained almost unchanged, compared to that in the base case. Since the consideration of curbside recycling was included in Case 2, and the driving forces existing in the system therefore consisted of recycling income, the benefit of energy recovery, as well as the residual value of new facilities, simultaneously. It was observed that the initialization of the smallest size of incinerator in the system was still needed because the recycling program was limited by its upper bound. As the waste generation increased over time, the incinerator planned in the earlier periods required a higher expansion capacity in the last two time periods. Detailed results showed that a higher proportion of recycling only occurred in those remote districts, while most of the MSW generated in the districts close to the incinerator were planned to be shipped to the incinerator initialized in the optimization process. Moreover, the attractiveness of the recycling programme in such a system could be evident by both the lower objective function value and tipping fees in several cases.

In Case 3, a slightly complicated screening criteria for MSW distribution was imposed. According to the considerations of different environmental weights associated with ash and MSW streams in the dynamic planning framework, the waste management pattern could be regulated to minimize the environmental impacts during operation. Assuming that $S = x + y$, S is total amount of MSW stream generated in the system in the entire planning horizon; y is the total amount of MSW destined to the incinerator in the entire planning horizon; and x is the total amount of MSW destined to the landfill in the entire planning horizon.

Then, the value of lead impact index, defined by BNR_{jk1t}, could be estimated by 1.5 and 0.06 associated with incineration ash and MSW, respectively (Chang 1989). On the other hand, the value of organics impact index, defined by BNR_{jk2t}, were predicted by 6.24 and 393 associated with incineration ash and MSW, respectively (Chang 1989). Thus, the following inequality relationships were derived:

$$1.5 \times 0.25 \times y + 0.06 \times x \leq LIMIT_1 \times C_1 \qquad [38]$$

$$6.24 \times 0.25 \times y + 393 \times x \leq LIMIT_2 \times C_2 \qquad [39]$$

TABLE 2
Optimization results from the system analysis

	Base case	Case 1	Case 2	Case 3	Case 4	
Objective function value (1986–87 million U.S.$)	56.3	57.2	45.6	73	59.2	
New incinerator sites selected	Brickyard	Brickyard	Brickyard	Brickyard	Brickyard +	Airport
Initialization period	2	2	2	3	2	6
Design capacity (tons day^{-1})*	469	469	350	350	601	350
Expansion capacity						
Period 3	43	43	0	—	168	—
Period 4	43	43	0	126	171	—
Period 5	43	43	167	85	61	—
Period 6	43	43	124	80	0	—
Ash stream (tons period^{-1})*						
Period 2	171,345	171,345	107,947	0	219,309	—
Period 3	186,925	186,925	127,750	127,750	280,387	—
Period 4	202,502	202,502	127,750	173,414	342,696	—
Period 5	217,691	217,691	188,418	204,514	365,000	—
Period 6	233,656	233,656	233,656	233,656	365,000	101,220
Raw garbage stream at Nanticoke landfill (tons period^{-1})*						
Period 1	all	all	all	all	all	
Period 2	0	0	0	all	0	
Period 3	0	0	0	236,698	0	
Period 4	0	0	0	116,349	0	
Period 5	0	0	0	52,704	160,003	
Period 6	0	0	0	0	0	
Tipping fee (U.S.$ ton^{-1})*						
Period 1	51	51	51	51	51	
Period 2	65	66	51	40	62	
Period 3	0	0	0	37	0	
Period 4	0	0	0	0	0	
Period 5	0	0	0	0	0	
Period 6	0	0	0	0	0	
Recycling (ton period^{-1})*						
Period 2	—	—	253,589	—	—	
Period 3	—	—	233,302	—	—	
Period 4	—	—	297,649	—	—	
Period 5	—	—	116,549	—	—	
Period 6	—	—	0	—	—	
Max. air pollution Control %						
SO_2	60	60	60	60	80	20
NO_x	3	3	3	3	20	0

* 1 U.S. ton is equivalent to 0.907 tonnes.

The first inequality constraint represented the metal impact constrained by C_1, while the second inequality constraint stood for the organics impact constrained by C_2. Applying the above two inequality constraints and the equation of $S=x+y$, produced:

$$y \leq \frac{LIMIT_1 \times C_1 - 0.06 \times S}{1.5 \times 0.25 - 0.06} \quad \text{and} \quad y \geq \frac{393S - LIMIT_2 \times C_2}{396.24 \times 0.25} \qquad [40]$$

It was noticed that the values of $LIMIT_1$ and $LIMIT_2$ could be simulated in the base case, and S was the input parameter in the model. Hence, the feasible region of y could be simulated and risk assessments of those two environmental impacts could be performed through the assignment of the values of C_1 and C_2. It showed that the value of C_1 increases as the value of C_2 decreases. The optimal solution was then determined based on the pre-determined values of C_1 and C_2. In Case 3, due to the assumption that metal impact was much more concerned than the impact of organics in the leachate, the dynamic planning pattern revealed that metal impact caused the Brickyard site to become less favoured. Hence, both the construction and expansion schedules of the incinerator at the Brickyard site were obviously delayed due to the smaller metal impact requirement.

In Case 4, the Brickyard site was initialized at the beginning and the Airport site was subsequently included when the waste generation was increased dramatically. Partial solid waste streams in several administrative districts nearby Nanticoke Landfill were planned to be handled by landfilling in the fifth time period before the Airport incinerator was due to be operated.

Overall, the Brickyard site was selected as the preferred incinerator site in all cases because it was located close to the highly populated region (i.e. Binghamton City) geographically in the sense that the lower transportation costs dominated part of the optimal waste distribution patterns. The zero tipping fees in the later time periods would verify the economic feasibility of the incineration project, once both limitations of air pollution and leachate impact were confirmed. In addition, the impact of non-point-source air pollution generated by the shipping trucks vs. the point-source air pollution at incinerator sites were also evaluated in this analysis. It was verified that the air pollution impact generated by the former was much less than that by the latter (Chang 1989). Hence, only the air pollution impact at each incinerator site must be considered in this model. Risk management and risk communication of solid waste management projects could also be achieved through such applications.

4. Conclusions

The analysis presented is an extension of a conventional framework used in the system analysis of solid waste management. Both air pollution and leachate impacts are regulated successfully through the optimization process. Moreover, it proves that the efforts of material recycling may save a large amount of system expenditures. For the purpose of environmental quality evaluation, a data-intensive process is inevitably required. The inclusion of air quality and leachate impacts in such a multipurpose solid waste management model does alter the waste distribution pattern based on the economic-oriented planning scenario.

Overall, this study has demonstrated an intellectually appealing approach by an integrated evaluation of solid waste management strategy. Social, physical, economic, environmental and institutional considerations are tied together to find the comprehensive solutions and support guidelines of sustainable management and risk analysis in the metropolitan area. Based on such a methodology, in order to maintain the essential environmental quality and achieve regional development target, a decision maker could manage solid waste distribution optimally so that waste generation, air quality and leachate impacts can be reduced to required levels simultaneously, while tipping fees and government expenditures can be minimized. However, the uncertainties of these environmental or economic parameters in the MIP model are still difficult to express by such a deterministic mechanism. Subsequent research should be focused upon fuzzy or grey fuzzy multi-objective analysis and the inclusion of more types of environmental concerns, such as traffic congestion and noise control.

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Appendix 1

Definition of set

I	Set of linkages between system components in the transportation network in each period.
I_1	Set of incoming waste stream at a specific site in each period.
I_2	Set of outgoing waste stream at a specific site in each period.
J	Set of all new system components (J_1 j J_2 j J_3 j J_4) in each period.
J_1	Set of all new waste generation districts (point sources) in the system.
J_2	Set of all new waste transfer stations in the system in each period.
J_3	Set of all new waste treatment plants in the system in each period.
J_4	Set of all new waste landfills in the system in each period.
K	Set of all old system components (K_1 j K_2 j K_3 j K_4) in each period.
K_1	Set of all old waste generation districts (point sources) in the system in each period.
K_2	Set of all old waste transfer stations in the system in each period.
K_3	Set of all old waste treatment plants in the system in each period.
K_4	Set of all old waste landfills in the system in each period.
L	Set of types of trucks used for shipping waste in the system.
R	Set of resources recovered at facilities and households.
T'	Set of time period ($\{1, \ldots, T\}$).
M	Set of all intermediate facilities in each period.
P	Set of air pollutants considered in air pollution control constraints.

Definition of input variables

T	The number of total time periods in the planning horizon (no unit).
G_{it}	Waste generation rate in municipal district i at time t (tons day^{-1}).
CT_{jkt}	Unit transportation cost among system components at time period t (\$ ton^{-1}).
CO_{kt}	Unit operating cost at facility k at time period t (\$ ton^{-1}).
CC_{kt}	Variable construction cost at facility k at time period t (\$ ton^{-1}).

CR_{jt}	Recycling cost of material i at time period t (\$).
CA_{kt}	Unit cost for additional air pollution control at facility k at time period t (\$).
F_{kt}	Fixed cost for building new facility at site k at time period t (\$).
T_{ikt}	Recovery factor of resource i per unit waste processed at facility k at time period t (%).
R_k	Reduction ratio of waste destroyed by the processing at site k and time t (%).
EP_p	Uncontrolled emission factor with respect to PSD (mg ton^{-1}).
EN_p	Uncontrolled emission factor with respect to NAAQS (mg m^{-3}).
$S1_{kpt}$	Emission standards of pollutant p in PSD standards (tons $year^{-1}$).
$S2_{pt}$	Emission standards of pollutant p in NAAQS (mg m^{-3}).
MAX_k	The maximum allowable capacity at site k (tons day^{-1}).
MIN_k	The minimum required capacity at site k (tons day^{-1}).
U_{kpt}	Upper bound of removal efficiency of pollutant p at site k and time period t (%).
A_{ka}	Dispersion factor or transfer coefficient between incinerator k and receptor (no unit).
FGR	Conversion factor between the waste burning rate and flue gas flow rate (m^3 ton^{-1}).
N_t	The specified number of available potential sites in a time period (no unit).
$TIME$	The length of time within one time period t (days $period^{-1}$).
β_t	Discount factor for time period t (no unit).
r	Nominal interest rate (%).
f	Estimated inflation rate (%).
IR_{ijt}	Net income per unit weight of secondary material j by household recycling in district i and at time period t (\$ ton^{-1}).
P_{ikt}	The price of each resource i recovered at site k at time period t (\$ ton^{-1} or \$ KWh^{-1}).
$\alpha_{ijt,max}$	Maximum fraction of recyclables which can be recovered in the waste stream G_{it} (%).
$f1$, $f2$	Conversion factors of time scale between emissions and emission standards (period $years^{-1}$, period hr^{-1}).
BNR_{jkpt}	Base numerical rating of pollutant p in the waste stream from j *to* k at time period t (no unit).
$LIMIT_k$	Total tolerance of pollutant p in the incoming waste stream at landfill k (no unit).

Definition of decision variables

S_{jkt}	Optimal waste stream among system components at time period t (tons $period^{-1}$).
Y_{kt}	Binary integer variable for the selection of facility at time period t (no unit).
DC_{kt}	Design capacity of a new facility at site k at time period t (tons day^{-1}).
$NEXP_{kyt}$	Expansion capacity at new site k at time t based on the initialization of facility operation at time period y (tons day^{-1}).

$TEXP_{kt}$	Total expansion capacity of a new or an old facility at site k at time t (tons day^{-1}).
C_t	The total system costs at time period t (\$ period^{-1}).
B_t	The total system benefits at time period t (\$ period^{-1}).
TIP_t	Tipping fee charged per unit amount of waste at time period t (\$ ton^{-1}).
α_{it}	Total recycling fraction corresponding to waste inflow G_{it} (%).
α_{ijt}	Recycling fraction of material j corresponding to waste G_{it} (%).
TR_t	Total amount of household recycling at time period t (tons period^{-1}).
RV_{kt}	Residual value of new facility at the end of planning horizon ($).

Note: "Tons" refers to U.S. tons. One U.S. ton is equivalent to 0.907 tonnes.