RESEARCH

Comparative Risk Analysis for Metropolitan Solid Waste Management Systems

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ABSTRACT / Conventional solid waste management planning usually focuses on economic optimization, in which the related environmental impacts or risks are rarely considered. The purpose of this paper is to illustrate the methodology of how optimization concepts and techniques can be applied to structure and solve risk management problems such that the impacts of air pollution, leachate, traffic congestion, and noise increments can be regulated in the long-term planning of metropolitan solid waste management systems. Management alternatives are sequentially evaluated by adding several environmental risk control constraints stepwise in an attempt to improve the management strategies and reduce the risk impacts in the long run. Statistics associated with those risk control mechanisms are presented as well. Siting, routing, and financial decision making in such solid waste management systems can also be achieved with respect to various resource limitations and disposal requirements.

The risk problems facing society today have many characteristics that complicate the application of formal analysis (Merkhofer 1987). The responsibility of government is to place risk management policy or regulation into perspective (Merkhofer 1987). Therefore, the recent trend of metropolitan environmental resources management has been placed upon the development and evaluation of sustainable management strategies. Although many strategies of sustainable development and management for a metropolitan region have been discussed on various occasions, the array of hazards or risks corresponding to municipal solid waste management is rarely considered and integrated with respect to the long-term environmental impacts. It is recognized that someone in charge of the public service program should have the responsibility, authority, and knowledge to deal with those environmental risks reduction issues for solid waste management.

The existence of environmental risk sources in a metropolitan solid waste management system does not imply the problems cannot be solved for affected or potentially affected parties, but the situation of managing such a system with multiple risks is considerably more complex in practice. In reality, environmental risk management is not a "zero-tolerance issue" in a sustainable metropolitan region. While the total elimination of environmental risks is impossible, the analytical concern actually rests upon the concept of the least environmental risk and cost to operate an efficient management system, or an optimal strategy to satisfy both environmental and economic requirements in a management system. Hence, to identify the most useful analytical approach, the analyst must clearly understand the decision problem from many aspects, including economic, physical, chemical, biological, financial, health, and even physiological impacts. Different decision alternatives can be linked with various types of issues addressed in the evaluation process, such that a comparative risk assessment and management approach must be applied. One useful approach necessary for the development of such a conceptual long-term solid waste management framework for comparing decision-making alternatives is the use of a mathematical programming technique that may serve as a planning tool to simultaneously reconcile the conflicts among economic, efficiency, equity, and environmental goals.

It can be seen that the current status of solid waste removal, treatment, and disposal practices may generate environmental risks in many areas, including traffic congestion, noise increments, and air and groundwater quality impacts. While those environmental risks simply cannot be eliminated, economic/financial justification for management control alternatives of environmental risks is needed. Hence, the related management factors in decision making may include economic principles, environmental laws, rules, regulations, and other institu-

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tional or physical risk control settings. Overall, the institutions and mechanisms that have evolved for environmental risk management in a metropolitan solid waste management system proposed in this paper are emphasized by first distinguishing various types of risk problems. The framework of risk identification is then prepared in search of the final optimal solution, which is synthesized from a series of sequential combinations with several risk assessment approaches in an optimization modeling process. After the proper integration and analysis, the best control mechanism or alternative for risk sources that do present actual threats to human life quality and/or the environment can finally be selected. In addition, for the purposes of demonstration, the development of systems, methods, and programs to achieve the strategic objective of maximum risk reduction at minimum feasible cost using a mixed integer programming (MIP) model is also described in this study for a typical solid waste management system in the city of Kaohsiung, Taiwan.

Methodology

The overall steps for the implementation of such a proposed methodology are first to determine the risk sources and related impacts so as to fulfill the primary functions of an environmental risk identification. Several uniform methods for the measurement and representation of each type of environmental risk are then built up and integrated into the mathematical programming model to aid in the generation of optimal solid waste management alternatives. The optimal feasible strategies for dealing with assessment and long-term management of environmental risks can finally be demonstrated for those controlling entities that must satisfy both the environmental and economic requirements and reduce risks with technological and managerial capabilities. Such a quantitative and systematic approach may produce a result that allows for comparative analysis of risk management performance and contributes to overall credibility of the environmental risk management program in a metropolitan region.

Risk Identification and Assessment

As Corello and Merkhofer (1993) described, risk assessment is a systematic process for describing and quantifying the risks associated with hazardous substances, processes, actions, or events. In principle, an inventory of environmental risks can be recognized and characterized from six aspects (Wilson 1991): (1) the type of environmental risk; (2) the quantity and extent of the risk sources; (3) the identity of the control mechanisms governing the level of risk; (4) the current and future condition of the control mechanisms; (5) the identification of the transport mechanisms that might operate to move the risk from its present position to a position where environmental damage can occur; and (6) the quantification of the likely damage to the targets of the environmental risk. However, two problems exist in the process of system analysis. First, with respect to the quantitative impacts, more complex issues arise when dealing with the adequate expression of those environmental risks in the modeling process. Second, since environmental risk is substantially influenced by public perceptions, the potential costs of the environmental risk liability and the corresponding benefits are not easily defined. However, if a problem cannot be described with a reasonable degree of accuracy, it cannot be brought under control and managed. A compromise approach should be applied in the analytical procedure.

The environmental risk sources and their distribution constitute a complex framework in a solid waste management system. Of particular concern in the development of a long-term management strategy are the direct and indirect environmental impacts of traffic congestion and noise due to garbage shipping, and air and groundwater pollution associated with incineration and landfilling alternatives. The risk assessment methodology for these environmental risks are approached through the development of an independent submodel related to each type of environmental impact in this analysis. Subjective judgment of the analysts could be focused on the selection of the measurement of risk in quantitative terms, such as exposure level, impact index, assimilative capacity, service quality, etc., in the formulation of those submodels. Overall, the violations of environmental tolerance levels on air quality and noise control are regulated by environmental law, while the limitations of impacts on groundwater and traffic congestion are identified by expert consensus with a selected engineering index and road service level, respectively. Constraints linked with those submodels for characterizing the degree of risk are used in the optimization process to describe and quantify the impacts of each type of risk associated with various waste distribution alternatives. Five criteria are characterized in the modeling process, including logical soundness, completeness, accuracy, practicality, and acceptability in those constraint formulations.

Risk assessment of leachate impact is the most difficult task in this quantitative analysis. Since it is related to probability of failure, dynamic prediction of leachate is necessary in both quantity and quality aspects, as well as its adverse effects on human life or the natural environment. Specifically, the evaluation of all environmental impacts in a conventional solid waste management model could result in an argument of the difference between perceived and actual risks in the mind of public as well as the units used for economic and environmental considerations, because the actual cost borne by the prevention of such public perception of the risk is very difficult to describe. Hence, no assignment of dollar value of these environmental risks is made in this modeling analysis. Only relative trade-offs among various alternatives regarding environmental risk management programs exist in the optimization process.

The relative impacts of these four categories of environmental risks in the final optimal solution can then be evaluated by sequential inclusion of each type of environmental risk in the constraint set of a MIP model, but the priority setting should refer to the public perception of risk in response to those primary concerns in the risk communication process. In this analysis, a simple survey was made to identify such environmental priorities. In general, technological advances may decrease or effectively control the air and leachate impacts, while the influences of traffic congestion and noise increments must be regulated systematically during the planning process. This implies that the adjustment of traffic congestion and noise should be emphasized first in the optimization process. As a result, the inclusion of traffic congestion, noise control, air pollution, and leachate impact considerations in the conventional planning framework is sequentially established in an attempt to improve the environmental quality from a long-term perspective.

Risk Management in the Optimization Framework

A good management plan for environmental risk reduction and control turns out to the key to the success in modern solid waste management systems, but a comparative risk evaluation of decision-making approaches usually requires that alternative approaches first be identified and differentiated. As shown in the literature, a variety of mathematical programming models have been applied for identifying solid waste management alternative approaches. Specifically, the MIP models, formulated for location/allocation analysis, have been widely applied for long-term economic optimization of solid waste management systems. Major contributions were established by Marks and others (1970), Helms and Clark (1974), Fuertes and others (1974), Walker and others (1974), Kühner and Harrington (1975), Hasit and Warner (1981), Jenkins (1982), Gottinger (1986), Kirca and Erkip (1988), and Zhu and ReVelle (1990). Furthermore, the fundamental efforts in combining the environmental impacts into a location/allocation model were also presented by Chang and others (1994, 1995a,b), in which several simulation models were applied for the illustration of different types of environmental risks. This analysis serves as a companion study of Chang's work to present a new and broader point of view for solid waste management. With respect to the environmental risks in such systems, major areas of subjective concern related to environmental quality are identified above as traffic congestion, noise increments, air pollution, and leachate impact in a growing metropolitan region. Environmental risk management strategies are therefore generated by the sequential inclusion of traffic congestion, noise control, air pollution, and leachate impact in the constraint set to regulate those four types of environmental risks explicitly in a MIP model. Once the combination with those risk assessment descriptions is established, the MIP model would become explicitly a disciplined method for economic and environmental thinking through all management alternatives and eventually identify the corresponding optimal alternative approach with respect to the allocation of resources necessary to implement the optimal alternative in a solid waste management system. Detailed descriptions of how optimization concepts and techniques can be applied to structure and solve risk management problems regarding to the control of air pollution, leachate impacts, traffic congestion, and noise increment in the long-term planning of Kaohsiung solid waste management system in Taiwan are provided in the following sections.

Optimization Structure

The MIP model with the framework of dynamic optimization is organized in this study for long-term solid waste management system planning conditional on several types of environmental concerns in the formulation. The inherent benefits and associated costs for possible waste distribution and risk reduction alternatives are systematically evaluated. However, one major feature in the environmental risk management that is substantively different from a regular management plan is that part of the benefits or impacts are measured in units of risk reduction instead of dollars. However, monetary units are still used to evaluate system costs and benefits for the other objectives, but the use of incommensurable risk units simultaneously with the dollar value can only reflect the relative trade-off in a decision-making problem. Nevertheless, this would allow the selection of an optimal strategy for the reduction of a specific environmental risk given the existing disposal demand, economic situation, financial limitations, physical constraints, and other local conditions. In addition, the entire budgeting task associated with environmental risk control can also be optimally established throughout the functional combination between objective function and constraint set. The elements in the modeling framework are delineated in the next sections.

Objective Function

The objective function in this model contains all related cost–benefit expressions that are formulated for calculating the discounted cash flow of all quantifiable system benefits and costs over several specific time periods. In the application, the real discounted factor is defined by the inflation rate and the nominal interest rate simultaneously to form a set of realistic discounted factors in the planning horizon. Hence, to achieve the minimization of net system cost or maximization of net system benefit, the cost elements in the objective function consist of initial cost and long-term control cost, such as total construction cost, total transportation cost, total operating cost, total expansion cost, total recycling cost, and so on, while the benefits are described mainly based on the total resource recovery income at each treatment or disposal facility and total household recycling income. Possible items of recoverable resources considered in this model include paper, glass, metal, plastics, steam, and electricity. However, indirect benefits from resource recovery are not incorporated in this formulation because of the inherent uncertainties and possible incommensurable units involved in such expressions. In the financial sense, investment decisions in a solid waste management system that involve large capital expenditure in the long run can be viewed as a risk evaluation method for determining risk rate of return of both objective and subjective considerations.

Constraint Set

The basic constraint set is composed of the mass balance, capacity limitation, operating, financial, site availability, and conditionality constraints that perform the essential task of site selection, system operation, and tipping fee evaluation in an integrated system planning framework. Those environmental risk constraints emphasized in this model consist of the noise control, traffic congestion, air pollution control, and leachate impact constraints, which are expected to be influential in a risk-neutral planning scenario. The inclusion of the proposed environmental risk constraints make this model advisable in pursuing the goal of multipurpose environmental risk control.

In the basic constraint set, mass balance constraints ensure that all solid waste generated in each collection district should be shipped to some other treatment or disposal components in the system. Furthermore, the waste reduction by household recycling can also be taken into account simultaneously in terms of the participation rate of residents, the recyclable ratio, and the composition of waste, but the recycling potentials in the waste stream must be evaluated in advance. In addition, the mass balance constraint must ensure that the rate of incoming waste equals the rate of outgoing waste plus the amount deducted in the treatment process for every treatment and disposal facility. Any potential site available for transfer, treatment, or disposal can be considered in this dynamic framework. The capacity limitation constraint has to be arranged for compliance with the treatment capacity planned during construction and expansion. The incoming waste stream load should be less than, or equal to, the maximum allowable capacity and greater than, or equal to, the minimum capacity at one site. The maximum allowable capacity associated with each site is limited by the land area, while the minimum capacity is determined by the minimum equipment size and its economy of scale for all new facilities. Except for the above considerations, the operating constraint must be prepared in relation to every existing facility to ensure that the accumulated waste inflow at each site will be less than, or equal to, the available capacity in each planning period. Once the above basic constraints are considered, the intertemporal trade-off of construction and later expansion of a facility can be established by the conditionality constraint, which requires that the initialization of a new site in a system can only occur once in a multistage planning project. On the other hand, the site availability constraint allows a subset of the potential sites be flexibly excluded for 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. For the purpose of financial planning and evaluation, financial constraints provide information regarding the financial balance and possible user charges (tipping fees) for dumping garbage and risk reduction. The evaluation of the possible impact of resource recycling can also be made through variation of prices in the secondary materials market in the financial constraint.

In this study, sequential inclusion of environmental risk considerations is achieved through the combination of traffic congestion, noise control, air pollution control, and leachate impact constraints, along with the above basic constraint set. The degree of traffic congestion is conventionally classified at six different levels in Taiwan, each corresponding to a ratio of the actual traffic flow rate and the original designed flow rate. The allowable traffic flow is thus equal to the multiplication of the selected service level and the designed flow rate at the main entrance road of each facility site, but the condition of background traffic flow rate before the inclusion of the garbage truck stream must be investigated in advance. The traffic impacts imposed by the operation of a solid waste treatment facility can then be evaluated by converting the expected garbage truck stream into a consistent unit (i.e., passenger car unit; PCU) so as to compare with the value of allowable traffic flow rate subtracted by the background traffic flow rate at each site.

The increased noise level from a solid waste management system can be distinguished as the simple source of noise (i.e., from treatment and disposal facilities) and the line source of noise (i.e., increased traffic flow by the garbage trucks). The degree of noise control in a metropolitan region is officially classified at four different levels in Taiwan, in which the unit used for the description of the noise level is decibel. In general, dB(A) is used as the abbreviation of decibel combined with a specific weighted method "A weight." Although several formulas for traffic noise impacts have been evaluated in the modeling process, the formula of Leq, as illustrated by cumulative distribution, was chosen in this analysis. Only the noise impacts from the traffic flow and the background noise level at each facility site are integrated in a representative constraint. Hence, formulation of the noise control constraint by comparing the aggregate noise levels at a target neighboring community close to a facility site with the acceptable noise level, based on the governmental criteria or environmental law, can be achieved.

In Taiwan, the Air Pollutants Emission Standards for Municipal Incinerators limits the emission rates of pollutants from incinerators, while the National Ambient Air Quality Standards controls the ambient pollutant concentration in the surrounding environment. However, once compliance with the Air Pollutants Emission Standards for Municipal Incinerators has been determined, compliance with National Ambient Air Quality Standards must be demonstrated. Hence, this analysis regulates the ambient air quality limitations to evaluate the marginal air pollution impact by the inclusion of the new incinerators. A modified Gaussian diffusion model for long-term planning is selected to determine the value of the transfer coefficient corresponding to the predetermined most sensitive receptor in the surrounding area of a new incinerator. The proposed transfer coefficient is described as a function in terms of wind speed, distance between emitter and receptor, effective stack height, diffusion coefficient in air, and half-life and decay rate for pollutant. The multiplication of flue gas flow rate, emission factor, and transfer coefficient in the constraint therefore assures that the more solid waste handled at an incineration site, the greater the amount of air pollution in a region. This may also yield the maximum allowable emission rate for a specific incinerator, given the maximum, annual average, ground-level, ambient concentrations at a specific receptor. The pollutants considered in this analysis are total suspended solid (TSP) and sulfur dioxide (SO_2) since the impacts of these two pollutants become critical in the Kaohsiung metropolitan region. Other pollutants can also be included in different scenarios.

In a solid waste management system, combustion ash and raw garbage are the two major inflows to sanitary landfills, yet 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 high organics-containing leachate in landfills. In this analysis, the lead impact is selected for the comparative risk assessment. 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, a specific impact index (i.e., the BNR index) is finally selected as the representative index (Short 1986). BNR is the abbreviation of "base numerical rating," which is an analytical index for measuring pollutant penetration ability in an unsaturated zone. This index is a function of pollutant concentration after assimilation in the unsaturated zone under a certain geochemical environment. Thus, the intrinsic meaning of the risk score associated with BNR is defined as an impact index derived for different pollutants p corresponding to each type of incoming waste stream at a specific time period in a designated landfill. Adding such an index here would reflect the associated risk generated by the metal impact of the ash stream and the organics impact of the raw garbage stream in the system. It is thus noted that the waste stream distribution can be altered in the optimization process by such an additional impact consideration in the constraint set. The model formulation is illustrated in the next section and the major variables are defined in Appendix 1.

MIP Model Formulation

The objective function is formulated for calculating the discounted cash flow of all quantifiable system benefits and costs over time. Discounted factors are equivalent to an economic adjustment and provide the net system value for decision making. Hence, the real discounted factor is defined simultaneously by the inflation rate (f) and the nominal interest rate (r), which is denoted as β_t $\{=[(1+f)/(1+r)]^{t-1}\}$. The expression of the objective function is:

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

The cost component (C_t) consists of:

$$\text{total transportation cost} = \sum_{(j,k)\in I, j\neq k} [CT_{jkt} S_{jkt}]$$

$$\text{total construction cost} = \sum_{k\in (J\backslash Y_1)} [CC_{kt} DC_{kt} + F_{kt} Y_{kt}]$$

$$\text{total operating cost} = \sum_{k\in (J\backslash Y_1 \cup K\backslash K_1)} \left[CO_{kt} \sum_{(j,k)\in I_1} S_{jkt} \right]$$

$$\text{total expansion cost} = \sum_{k\in (J\backslash Y_1 \cup K\backslash K_1)} [CE_{kt} TEXP_{kt}]$$

$$\text{total recycling cost} = \sum_{i\in R} TR_{it} CR_{it}$$

The only two benefit components (B_t) considered here are:

$$\text{total resource recovery income at the facilities} = \pm \sum_{i\in R} \sum_{k\in (M\cup K_4 \cup J_4)} \sum_{(j,k)\in I_1} [P_{ikt} T_{ikt} S_{jkt}]$$

$$\text{total household recycling income} = \pm \sum_{i\in (J_1\cup K_1)} \sum_{j\in R} [IR_{ijt}\, \alpha_{ijt}\, G_{it}]$$

In the expression, set subtraction is represented by the notation of a backslash (\). The total transportation costs are expressed as linearly proportional to unit waste loading. As usual, a fixed charge structure is employed in the formulation of total construction cost. The average operating cost is assumed to be a constant. 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. However, part of these recyclables could be picked up directly at households or other places rather than in treatment plants. Thus, a separate term, corresponding to the income from household recycling, is formulated. Since recyclables may not always have economic value in the secondary materials market; the plus/minus sign is therefore used in these benefit expressions. Next the constraints are discussed sequentially.

Mass Balance Constraint

Point source. All solid waste generated in the collection district should be shipped to other treatment or disposal components. 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.

$$\sum_{k\in (J\backslash Y_1 \cup K\backslash K_1)} S_{ikt} = G_{it}(1 - \alpha_{it}) \qquad \forall i \in (J_1 \cup K_1), \forall t \in T'$$

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

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

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

System facility. For any system component, the rate of incoming waste must equal the rate of outgoing waste plus the amount deducted in the treatment process.

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

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.

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.

$$\sum_{y=1}^{T} DC_{ky} \ge MIN_k \sum_{y=1}^{T} Y_{ky} \qquad \forall k \in (J\backslash Y_1)$$

$$DC_{ky} + \sum_{t=y+1}^{T} NEXP_{kyt} \le MAX_k Y_{ky}$$

$$\forall k \in (J\backslash Y_1), \forall y \in (1, T-1)$$

$$\sum_{y=2}^{t} NEXP_{kyt} = TEXP_{kt} \qquad \forall k \in (J\backslash Y_1), \forall t \in T'$$

Old facility.

$$DC_k + \sum_{t=1}^{T} TEXP_{kt} \leq MAX_k \qquad \forall k \in (K \backslash K_1)$$

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.

$$TIME\left(\sum_{y=1}^{t'} (DC_{ky} + \sum_{t=y+1}^{t'} NEXP_{kyt})\right) \geq \sum_{(j,k)\in I_1} S_{jkt}$$

$$\forall k \in (J \backslash J_1),\ \forall t' \in T'$$

Old facility.

$$TIME\left(DC_k + \sum_{t=1}^{t'} TEXP_{kt}\right) \geq \sum_{(j,k)\in I_1} S_{jkt'}$$

$$\forall k \in (K \backslash K_1),\ \forall t' \in T'$$

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.

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

Site Availability Constraint

This constraint can also allow the planner to leave out some of the potential sites.

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

Financial Constraint

The key point in the formulation is the use of an inequality rather than an 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.

$$C_t \leq B_t + TIP_t\left(\sum_{i\in(K_1\cup J_1)} G_{it}\right) \qquad \forall t \in T'$$

Traffic Congestion Constraint

The degree of traffic congestion is conventionally classified at six different levels, each corresponding to a condition of the traffic flow rate relative to the original designed flow rate. Hence, SL_{ijt} represents the selected service level of traffic flow at different facility sites. The allowable traffic flow is thus equal to the multiplication of the selected service level and the designed flow rate at the main entrance road ($\overline{C_{ijt}}$) is the average value of background traffic flowrate before the inclusion of the garbage truck stream. It is known that the unit used to express $\overline{C_{ijt}}$ and $\overline{V_{ijt}}$ is the passenger car unit (PCU). Hence, the traffic impacts created by the operation of solid waste treatment can be expressed by converting the garbage truck stream, as defined in the parentheses below, into a consistent unit (i.e., PCU) by multiplying a conversion factor, CU.

$$CU\left[\sum_{i\in(J_1\cup K_1),\, l\in I} S_{ijt} \div P_1\right] + \overline{V_{ijt}} \leq SL_{ijt}\overline{C_{ijt}}$$

$$\forall j \in (J \backslash J_1 \cup K \backslash K_1),\ \forall t \in T'$$

Noise Control Constraint

The major sources of noise in a typical solid waste management system can be classified as the simple source of noise (i.e., from treatment and disposal facilities) and the line source of noise (i.e., increased traffic flow by the garbage trucks). The former can be properly controlled by engineering technology, but the latter has to be regulated in the optimization process. Although the level of noise, its characteristics, and the criteria used to assess the noise impact differ from one environment to another, the method of doing so is similar. In general, the equivalent noise level (L_{eq}) is the most prevalent approach used for the evaluation of traffic noise impacts. In Taiwan, the degree of noise control in a metropolitan region is classified at four different levels, and the unit used for the description of noise level is dB(A). An empirical model for noise impact assessment is independently developed by the authors, as illustrated below:

$$NL = c_1 + c_2 \ln F - D \quad \text{and}$$

$$F = CU\left[\sum_{i\in(J_1\cup K_1),l\in L} S_{ijt} \div P_1\right] + \overline{V_{ijt}}$$

in which F is the noise impact created by the garbage truck fleet at the main entrance road of each treatment and disposal facility; c_1 and c_2 are regression coefficients; and D is the spatial decay constant, an empirical number based on the local situation. The aggregate noise levels, at the most sensible neighboring community around the facility site, can then be calculated and compared with the acceptable noise level (NL) in the environmental regulations. Background noise level (NB) should be taken into account. Temporal variations of noise are considered and evaluated through the integration of the noise impacts from those additional sources of waste shipping plus the background level around the designated community in each independent noise control area. Therefore, the whole constraint formulation is:

$$c_1 + c_2 \ln\left\{CU\left[\sum_{i\in(J_1\cup K_1),l\in L} S_{ijt} \div P_1\right] + \overline{V_{ijt}}\right\} - D_j$$
$$\leq NL_j - NB_j \qquad \forall j, \forall t \in T'$$

Air Pollution Control Constraint

In Taiwan, air pollution from municipal incinerators is regulated under the Air Pollutants Emission Standards for Municipal Incinerators and National Ambient Air Quality Standards. While the maximum allowable emission rates for criteria pollutants are handled in the former standards, the maximum concentrations (i.e., parts per million or micrograms per cubic meter) of certain pollutants in the surrounding environment are specified in the latter. Hence, this analysis considers ambient air quality limitations for several pollutants at a set of prespecified sensitive area in Kaohsiung City. The constraints formulation are described below:

$$f'\left[\sum_{k\in(K_3\cup J_3)}\ \sum_{(j,k)\in I_1} (S_{jkt} FGR\, EN_p A_{ka})\right] \leq S_{pt} - B_{apt}$$
$$\forall a, \forall p \in P, \forall t \in T'$$

A_{ka} is the transport and transformation factor that is dependent on the stability, wind speed, distance between emitter and receptor, effective stack height, diffusion coefficient in air, and half-life and decay rate of pollutant p (Wang and others, 1979). f' is a conversion factor regarding the time scale difference between the units of emission factor (EN_p) and National Ambient Air Quality Standard (S_{pt}). FGR is the flue gas production ratio, based on burning one ton of solid waste in the incinerator. The multiplication of 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 left-hand side constraint formulation may yield maximum ground-level ambient concentrations at a set of receptors surrounding the municipal waste combustors for air pollution assessment. The variable B_{apt} in the right-hand side of the constraint serves as an input variable to show the background concentration of air pollutant p at the location of a specific receptor a. To determine the value of A_{ka}, the long-term diffusion equation for a decay pollutant (nonconservative pollutant) at ground level and at the centerline of the plume may be arranged as (Wang and others 1979):

$$C(x) = \frac{2q}{\pi u C^2 x^{2-n}} \exp\left(\frac{-\overline{H}_r^2}{C^2 x^{2-n}}\right) \exp(-kt) = qA_{ka}$$

in which $C(x)$ is the aggregate ambient air pollutant concentration (μg/m^3 or ppm); u is the average wind speed; $\overline{H}_r$ is the effective height of plume release corresponding to the wind speed u; $k(t^{-1})$ is the first order reaction rate (=0 if the pollutant is conserved); t is reaction time; q is emission rate of particular air pollutant from the stack of incinerators; C^2 is the isotropic diffusion coefficient; and n is the stability parameter.

Leachate Impact Constraint

The BNR 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 pollutants p corresponding to each type of waste stream distribution in a specific time period. Adding such an index here would reflect the associated risk generated by the metal impact of the 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 indices, 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. Because there is no professional consensus on the impact limitation ($LIMIT_k$), this value could be determined by the simulations.

$$\sum_{t} \sum_{(j,k)\in J_t} \sum_{p} (BNR_{jkpt} S_{jkt}) \leq LIMIT_k \qquad \forall k \in (K_4 \cup J_4)$$

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:

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

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 the dispersion coefficient; μ_a is the first-order degradation constant in the aqueous phase; μ_s is the 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 the volumetric water content of the soil.

Based on the assumption of the equality between μ_a and μ_s, 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}:

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

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:

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

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 the retardation factor; $T_{1/2}$ is half reaction time of pollutant p, and μ is the first-order degradation constant of pollutant p in the unsaturated zone.

Case Study

A significant improvement is anticipated by basing the reduction of risk for a given real-world solid waste management system in which the strategic management plan would actually be associated with the numerical response action of the inclusion of major environmental risks. A case study in Kaohsiung City is thus prepared as a numerical illustration to demonstrate the effectiveness of managing environmental risks in a metropolitan solid waste management system.

Figure 1. The geographical location of the solid waste management system in Kaohsiung City.

System Environment of Kaohsiung City

Kaohsiung City, located beside Kaohsiung harbor, is the largest city in the southern part of Taiwan. The geographical location and its solid waste management system configuration are shown in Figure 1. Twelve garbage collection teams are in charge of the clean-up work in the 11 administrative districts. Only the Sanming district has two collection teams, and the service area is separated east to west divisions. The only existing landfill is the Shichinpu landfill, located at the northern boundary of Kaohsiung. The transportation to Chichin mainly relies on an underground tunnel across the bottom of the harbor connecting with the downtown area of Kaohsiung City. Three candidate sites—Fuhdingjin, Nantzu, and Talinpu—are planned for future resource recovery plants. Three possible sites for two new transfer stations (Tsoying and Chienchen) and one new landfill (Tapindin) were selected in the preliminary screening, but uncertainties still exist in the procurement of the

Table 1. Simulation scenarios

	Base	Case 1	Case 2	Case 3	Case 4	Case 5
Traffic congestion		V[a]				V
Noise control			V			V
Air quality				V		V
Leachate impact					V	V
Total cost (1992–93 billions NT$)	3.98	5.45	4.12	4.16	4.43	5.81

[a] V represents the inclusion of this evaluation option.

Table 2. Optimization results of case 5

	Incinerator	Transfer station	Landfill
New sites included	Nantzu	Tsoying	Tapindin
	Fudingjin	Chienchin	
	Talinpu		
Initialization period	2	2	2
	2	2	
	2		
Design capacity (TPD)	300	122	30
	768	182	
	300		
Total expansion capacity (TPD)	56	110	576
	0	0	
	0		
Tipping fee (NT$/ton)			
period 1		944	
period 2		954	
period 3		0	
period 4		0	
Recycling (ton/period)			
period 1		1072967	
period 2		1196322	
period 3		1345927	
period 4		1507443	

land and the agreement of local residents. The Schichinpu landfill is expected to be closed in 1995, but it was expanded due to the lack of other disposal alternatives in the current solid waste management system.

Analytical Framework

In this analysis, a hypothetical 20-year project with four time periods is conducted. The start-up year is 1993, when the system has only one landfill. The Shichinpu landfill is expected to be expanded and continuously used until the ear 2003 (i.e., the end of second time period). The start-up date of operation of the Tapindin landfill is assumed to be at the beginning of the second time period. The Chichin transfer station, which only serves the Chichin district, is regarded as a point source. Construction or expansion of any facility is to be completed within the previous time period. Hence, the use of any facility in the dynamic optimization process represents the start-up date of its operation, whenever investments are incurred. Therefore, the potential facility of transfer stations and incinerators can be considered in the system operation after the beginning of the second time period. The candidate sites for transfer stations are prepared for shipping raw garbage only.

Data Acquisition and Analysis

In the objective function, the construction cost functions are derived based on a thorough engineering survey in Taiwan. Facility expansion costs are assumed the same as the variable costs in these derived construction cost functions. Furthermore, economic and physical factors, such as the prices of electricity and secondary materials, recycling cost, operating costs, transportation costs, interest rate, inflation rate, waste reduction ratio, conversion efficiency, and so on, need to be determined in advance. On the other hand, a lot of parameter values

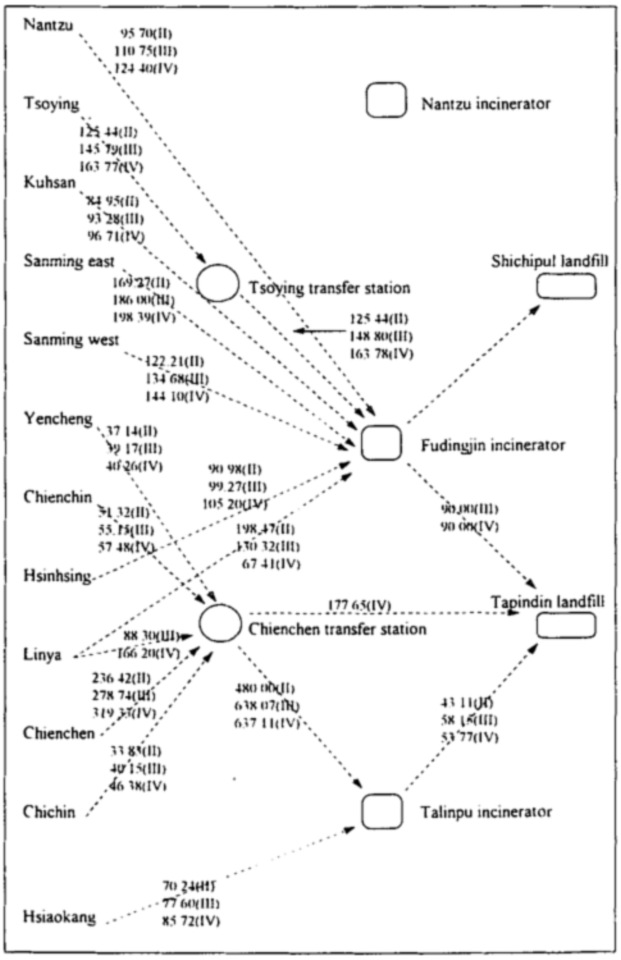

Figure 2. Optimal waste flow pattern in base case (unit: tons per day).

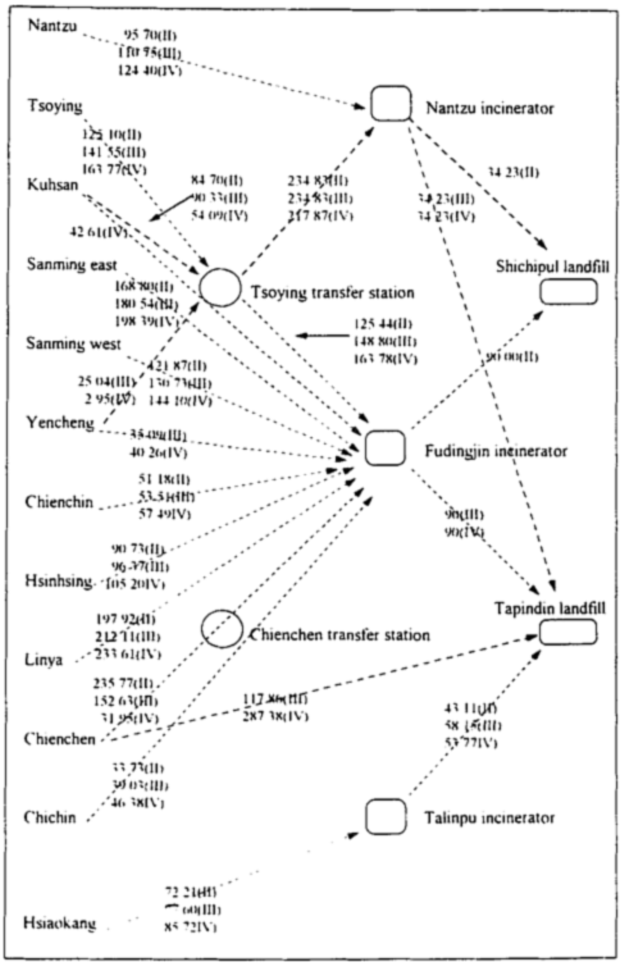

Figure 3. Optimal waste flow pattern in case 1 (unit: tons per day).

in the constraint set also have to be decided in advance. For example, the spatial and time variations in both waste generation and composition have to be investigated and applied in the mass balance constraints. The maximum capacities of incinerators, transfer stations, and landfills must be decided for the capacity limitation constraint. In the traffic congestion constraint, a selection of traffic service level in advance is required. However, different traffic service levels might be selected for different types of case study. Investigations of the background traffic flow over time periods were also assumed. The required noise control level can be determined according to both environmental law and governmental regulation and used as the right-hand side values in the noise control constraint. In addition, parameter values related to meteorological, geochemical, and geographical conditions in both air pollution and leachate impact control constraints also need to be prepared before performing the modeling analysis.

Results and Discussion

The final management scenarios are classified into six cases, which correspond to the base case without considering any risk reduction program, each independent consideration of those four types of environmental risks, and the gross consideration of the whole spectrum of environmental risks. Table 1 explains the simulation scenarios, which shows the effort of the stepwise testing from case 2 to case 5 associated with their risk control costs in the optimal risk control action. Apparently, the control cost for the maximum reduction of environmental risks in case 5 reaches the highest level. The results of case 5 for long-term planning within the 20-year planning horizon are therefore listed in Table 2. It is evident that all of the candidate sites are included in the final optimal solution in order to decentralize the waste distribution as well as result in the minimum extent of corresponding environmental impacts. For the purpose of detailed illustration, Figures 2–7 show the optimal waste

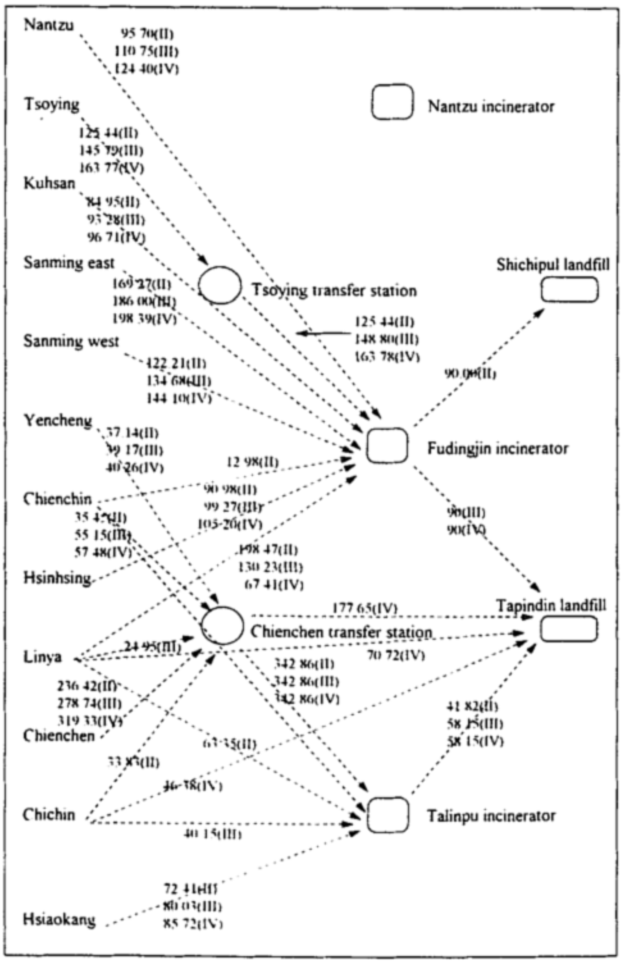

Figure 4. Optimal waste flow pattern in case 2 (unit: tons per day).

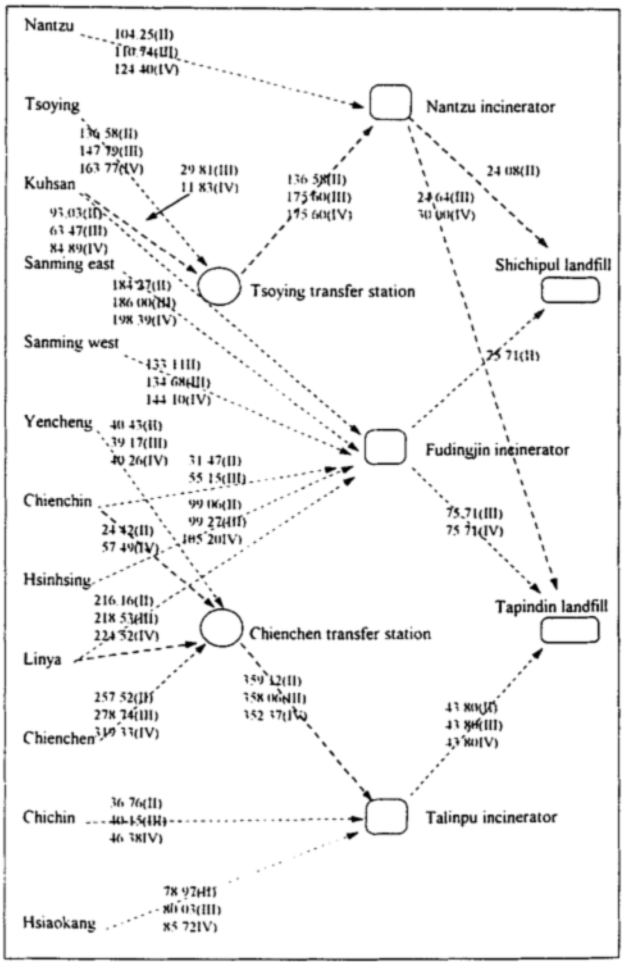

Figure 5. Optimal waste flow pattern in case 3 (unit: tons per day).

management patterns corresponding to the base case and cases 2–5, as defined in Table 1. While only partial sites are included in the optimal solution in several cases, the degree of control of environmental impacts can therefore be calculated compared to the relative performance in the base case. Therefore, Figures 8–10 explain the results of comparative impacts for the environmental risk control associated with traffic, noise, and air pollution impacts at three incineration sites, whereas Figure 11 illustrates the control of leachate impact at landfill sites. It is observed that the depression of traffic flow at the Nantz incineration site is optimized due to its higher background noise level, while the reduction of air quality impact is achieved at the Talinpu incineration site because of the relatively larger background concentration. A relative trade-off between lead and organics impacts exists, as indicated by Figure 11. The information of the effectiveness of each risk control action reveals the intrinsic meaning of cost–benefit analysis.

Final Remarks

Various types of risk management scenarios have already been compared in terms of their underlying environmental impact rationales within the standard procedure of optimization modeling. A useful way of conceptualizing these comparisons is in the form of related figures and tables, as indicated above, that relatively express the potential application to different kinds of risk problems. Although an evaluation of the various approach categories in terms of those four environmental risk constraints may provide some idea of how well each performs in practice from cost–benefit and risk prevention perspectives, it does not explicitly indicate which to choose. All management decisions would result in a distribution of benefits and burdens. It is the responsibility of the decision makers to select a final risk control program. In the decision-making process, a fundamental criticism may arise from several aspects, including the impossibility of finding a socially optimal decision

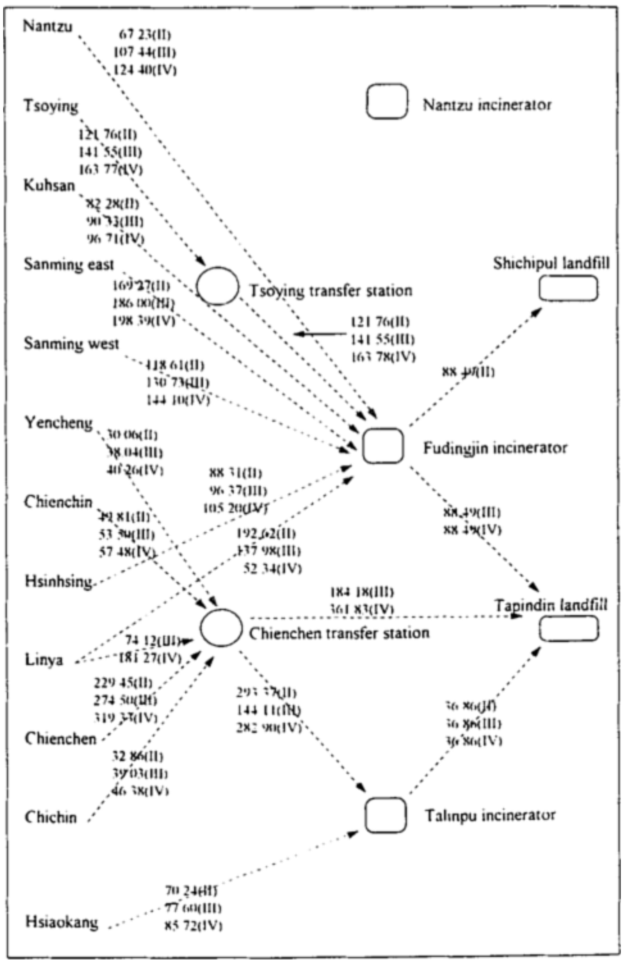

Figure 6. Optimal waste flow pattern in case 4 (unit: tons per day).

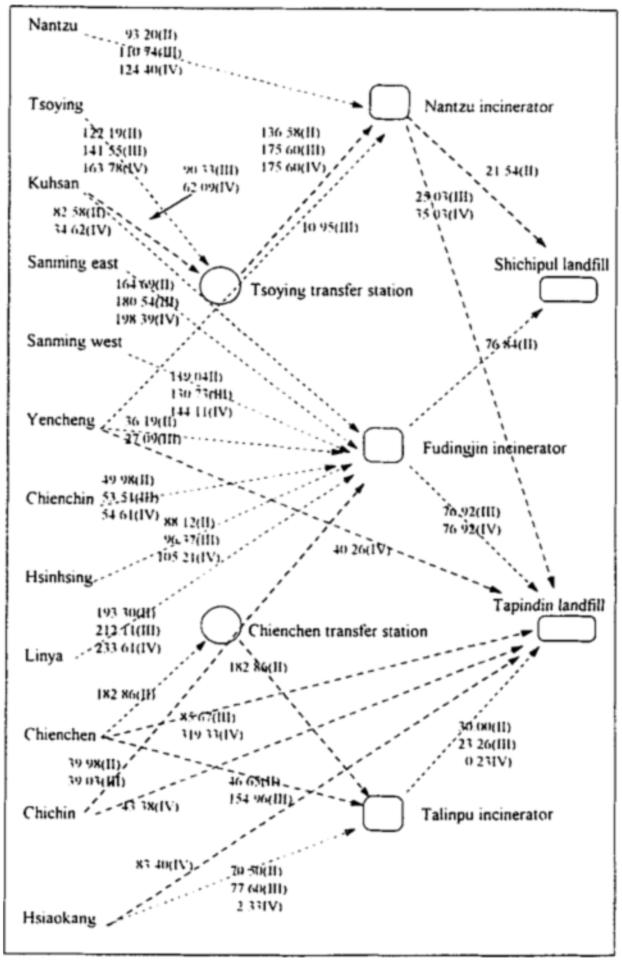

Figure 7. Optimal waste flow pattern in case 5 (unit: tons per day).

rule, decomposition of a large-scale system, inherent incompleteness of modelling, and inability to account for the indirect cost–benefit. In particular, long-term cost–benefit analysis has been most subject to criticism concerning its distributional equity and intergenerational concerns. In addition, susceptibility to manipulation of the assessment procedure, modelling, and analysis, as well as the possible misuse and misinterpretation of analytical results will result in distortion or bias of the final actions for environmental risk management.

Conclusion

This analysis provides guidance to those participating in comparative risk assessment projects for metropolitan solid waste management systems. The comparative risk framework and mechanics have been applied in the city of Kaohsiung, Taiwan. Because of its broad underlying scope to establish an analytical goal for solid waste management, such a problem cannot be solved without addressing other economic and social issues except those environmental concerns. It is shown that the underlying

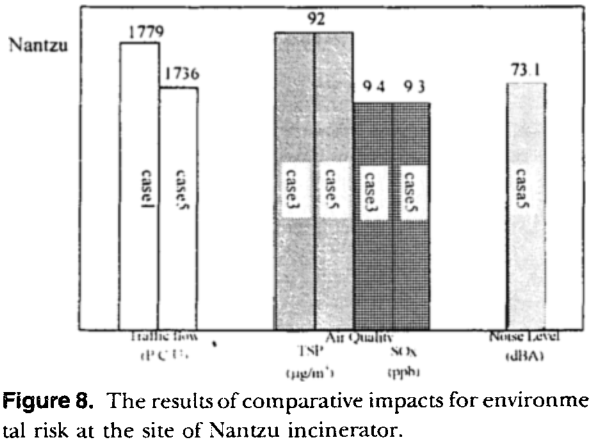

Figure 8. The results of comparative impacts for environmental risk at the site of Nantzu incinerator.

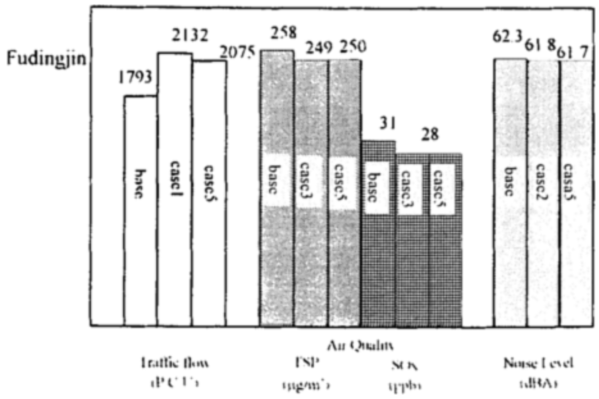

Figure 9. The results of comparative impacts for environmental risk at the site of Fudingjin incinerator.

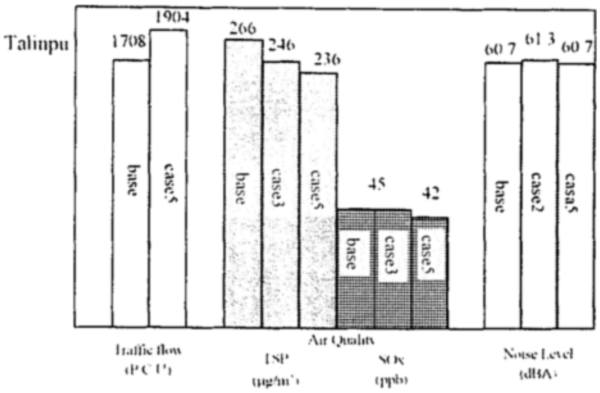

Figure 10. The results of comparative impacts for environmental risk at the site of Talinpu incinerator.

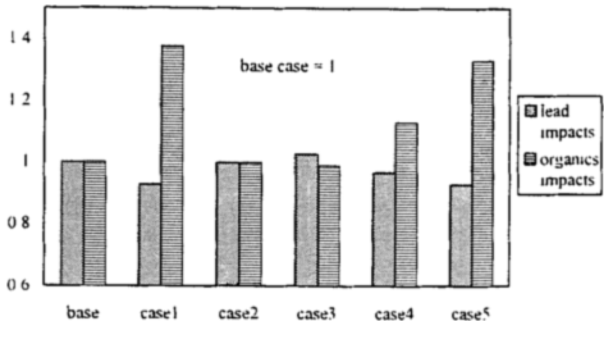

Figure 11. The comparative result of leachate impacts at landfill site.

driving forces in the MIP model can automatically generate the optimal strategy or at least an acceptable alternative for both objectives of economic and environmental optimization. The outcomes can also be used for risk communication with the public to create greater understanding of the size of a risk before and after control actions.

Appendix 1: Notation in the MIP Model

Definition of Sets

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 $(J_1 \cup J_2 \cup J_3 \cup J_4)$ in each period
J_1	set of allnew 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 $(K_1 \cup K_2 \cup K_3 \cup K_4)$ 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

Definition of Input Variable

T	the number of total time periods in the planning horizon
G_{it}	waste generation rate in municipal district i at time t
CT_{jkt}	unit transportation cost among system components at time period t
CO_{kt}	unit operating cost at facility k at time period t
CC_{kt}	variable construction cost at facility k at time period t

CR_{jt}	recycling cost of material i 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 aste destroyed by the processing at site k and time t
MAX_k	the maximum allowable capacity at site k
MIN_k	the minimum required capacity at site k
N_t	the specified number of available potential sites in a time period
$TIME$	the length of time within one time period t (conversion factor)
β_t	discount factor for time period t
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
P_{ikt}	the price of each resource is recovered at site k at time period t
$\alpha_{ijt,\max}$	maximum fraction of recyclables which can be recovered in the waste stream, G_{it}
CU	the conversion factor between the garbage truck unit and passenger car unit
$\overline{C_{ijt}}$	the maximum designed traffic capacity on the main entrance road at each facility at time period t
$\overline{V_{ijt}}$	the average background traffic flow on the main entrance road at each facility at time period t
P_1	the allowable weight loading of different types of trucks
SL_{ijt}	required service level of main road connecting different system components at time period t
BNR_{jkpt}	base numerical rating of pollutant p in the waste stream from j to k at time period t
$LIMIT_k$	total tolerance of pollutant p in the incoming waste stream at landfill k
A_{ka}	the transport and transformation factor corresponding to the linkage between plant k and receptor a
f'	a conversion factor regarding the time scale difference between the units of emission factor (EN_p) and National Ambient Air Quality Standard (S_{pt})
FGR	the flue gas production ratio, based on burning one ton of solid waste in the incinerator
E_{apt}	the background concentration of air pollutant p at the location of a specific receptor a at the time period t
D_j	spatial decay constant at site j, based on the local situation
NL_j	the acceptable noise level of site j in the environmental regulations
NB_j	the background noise level at a specific site j

Definition of Decision Variables

S_{jkt}	optimal waste stream among system components at time period t
Y_{kt}	binary integer variable for the selection of facility at time period t
DC_{kt}	design capacity of a new facility at site k at time period t
$NEXP_{kyt}$	expansion capacity at new site k at time t based on the initialization of facility operation at time period y
$TEXP_{kt}$	total expansion capacity of a new or an old facility at site k at time t
C_t, B_t	the total system costs and benefits respectively at time period t
TIP_t	tipping fee charged per unit amount of waste at time period t
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

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