OPTIMAL PLANNING OF SOLID WASTE COLLECTION, RECYCLING AND INCINERATION SYSTEM

NI-BIN CHANG AND S. F. WANG
Department of Environmental Engineering
National Cheng-Kung University,
Tainan, Taiwan

ABSTRACT

The combustion temperature control for the potential emissions of trace organic compounds during incineration and the possible decrease of heating values by waste recycling have created a mutually influenced infrastructure in the current integrated solid waste management system. This paper illustrates the problem of the compatibility between waste recycling and incineration by a nonlinear goal programming model. The optimal strategies of various planning scenarios and related economic impacts on waste management agencies can then be evaluated. The new management disciplines to be mastered by this model exists for both public and private sectors. From engineering and management perspectives, it shows that such linkage is feasible and essential to facilitate the decision makers for achieving the goals of economic efficiency and environmental protection simultaneously in a multipurpose solid waste management system.

INTRODUCTION

The proposed 25% waste reduction requirement prior to incineration by the U.S. Environmental Protection Agency (EPA) has created a great impact on solid waste management (US EPA, 1989, and MDEP, 1989). But the promulgation (40 CFR Parts 51, 52, and 60) for the Good Combustion Practice (GCP) related to the combustion temperature requirement for controlling potential emissions of trace organic compounds and the energy recovery by electric power generation also become the major focus in assessing new incineration projects. However, these issues have resulted in a mutually influenced infrastructure because of the possible negative impacts on the combustion temperature by waste recycling. In addition, the inherent complexity of refuse composition and the stability of secondary material market may cause more uncertainties in various types of solid waste management system. To contemplate the scope of such dilemmas, as exist in many countries, the effort of pursuing an integrated optimal planning becomes critical. The most significant questions include: How well is the compatibility of recycling and incineration? and What are the subsequent economic impacts for private or public sectors if they are operating waste collection businesses and incineration facilities simultaneously or separately?

This analysis develops the optimal strategies for a regional solid waste management system by a nonlinear goal programming (GP) model. System benefits, recycling targets, and required combustion temperatures are considered as the major goals to be achieved simultaneously. Nonlinear characteristics occur from the interaction of the degree of recycling and the impact on heating value after recycling. The practical implementation is assessed by a case study of the solid waste management system in Tainan City, Taiwan. Further evaluation of reasonable tipping fees and subsidy can also be established according to various private/public management scenarios. GINO software package serves as a solver in this analysis.

BACKGROUND INFORMATION

It has been noted that the central focus of the debate on the municipal solid waste (MSW) incineration has shifted from its apparent management advantages to the unresolved risk issues and the impacts of material recovery (Environment Canada — NITEP, 1985; Hasselriis, 1988; Allan, 1989 and MDEP, 1989 *et al.*). Especially the emissions of a full range of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) have become the most controversial issue in siting and building new municipal incinerators. Various famous testing programs, such as the National Incineration Testing and Evaluation Program (NITEP) in Canada, were instituted to find out how much they could be reduced by optimizing combustion condition, and by add-on control technology (NITEP, 1985). Miller (1989) explained that PCDDs isomers can be completely destroyed at a temperature of 950°C, a residence time of 1.0 sec, and an oxygen concentration no greater than 7%. Many other researchers (Clark, 1988; Schindler, 1989; *et al.*) also presented similar conclusions. Hence, the control of dioxin and furan formation is generally considered to require flame temperature exceeding 982°C (1800°F) for residence time in excess of 1 sec, and minimum excess air level must exceed 50–60% in the proposed Good Combustion Practice (GCP) criteria (Clark, 1988, and Schindler, 1989). Due to the interdependent relationship between combustion temperature and gas residence time, the German criteria requires slightly lower flame temperature and longer gas residence time. The minimum flame temperature in German criteria is 850°C for at least 2 sec of gas residence time which has been adopted as the design standard in the European Economic Community (EEC standards). In addition, energy recovery by burning the trash has been emphasized since the energy crisis, although incineration only contributes a minor fraction of total energy production in many industrialized countries.

However, recycling plastics and paper from the waste stream can significantly reduce the magnitude of heating value, and thereby decreases the combustion temperature in the furnace when not using auxiliary fuel. This situation is phenomenal, especially in some developing countries where the moisture content in the garbage is much higher but the percentage of combustibles is relatively lower, compared with the municipal waste in the industrial world. While the task of waste incineration and collection could be performed by private or public sectors in a management system, trade-offs among waste recycling, hauling distance, combustion temperature, and other economic factors exist in the optimization process. GP is an efficient tool for such optimization analysis rather than any single objective optimization technique.

MODEL FORMULATION

In regional solid waste management planning, an incinerator is usually assigned as the treatment facility for several prespecified administrative districts by adequate system analysis (Chang and Wang, 1993). Due to the varieties of management alternatives in such a system, this model considers that either hauling vehicles or incinerators can be owned and/or operated by various management agencies. Different management alternatives can then be assessed by setting up the corresponding configuration in the model. Within such a service area, the waste generation rate and composition, and related hauling distance are usually differently associated with each district. Paper and plastics are two major items in the waste stream that have resale values in the secondary material market and also may influence the combustion temperature directly. In addition, system benefits are characterized by the income from recycling, the tipping fee charged on the residents, the subsidy from the municipality, and the income from selling electricity. The system costs primarily include the transportation costs of hauling waste and the operating costs for handling the incineration facility. From an integrated management perspective, the system goals considered in this analysis thereby consist of: (a) system benefits should be greater than or at least equal to system costs for the private operators, while system benefits should be as close as possible to system costs for the public operators; (b) combustion temperature should be close to the required level in engineering design criteria, although being higher than the level is also acceptable; (c) paper and plastics should be recovered as close as possible to the prescribed recycling limits. Nonlinear characteristics may occur from the interaction of the degree of recycling and the impact on heating value after recycling. Only the recycling goal, which is bounded by the recyclable ratio and resident participation rate, is formulated as a one-sided goal. The GP model can be formulated as below:

$$\text{Min } z = P_1 d_1^- + P_2(w_{22}^- d_2^- - w_{22}^+ d_2^+)$$

$$+ P_2(w_{23}^- d_3^- - w_{23}^+ d_3^+) + \sum_{i=1}^{N} P_3(a_i^- + b_i^-)$$

subject to:

$$T_f - d_1^+ + d_1^- = \text{MIN}\, T$$

$$TB1 - d_2^+ + d_2^- = TC1$$

$$TB2 - d_3^- + d_3^+ = TC2$$

$$PA_i + a_i^- = \text{MAX}\, PA_i \qquad \forall i \in J$$

$$PL_i + b_i^- = \text{MAX}\, PL_i \qquad \forall i \in J$$

$$\sum_{i=1}^{N} G_i \le CAP$$

$$T_f, TB, TC, d_1^+, d_1^-, d_2^+, d_2^- \ge 0$$

$$PA_i, PL_i, G_i, a_i^-, b_i^- \ge 0 \qquad \forall i$$

$$d_1^+ \times d_1^- = 0; \quad d_2^+ \times d_2^- = 0; \quad a_i^+ \times a_i^- = 0; \quad b_i^+ \times b_i^- = 0$$

Submodel Formulation

T_f (°F) = 0.108 HHV + 3467K − 4.554 M + 0.59 (Ta − 77) − 287 (i.e., Tillman, 1989). HHV (kcal/kg) = 1587 + 7.63 P′ + 13.66 R′ (i.e., based on Taiwan solid waste). E (kWh/ton) = 0.2 HHV (kcal/kg) (i.e., based on Taiwan solid waste).

$$G_1' = \sum_{i=1}^{N} [T_i - T_i \times R_i' \times PL_i - T_i \times P_i' \times PA_i]$$

$$G_i = \sum_{i=1}^{N} [S_i - S_i \times R_i' \times PL_i - S_i \times P_i' \times PA_i]$$

$$M = [S_i W_i - (S_i \times R_i' \times PL_i - S_i \times P_i' \times PA_i) \times f]/G_i$$

$$P' = 100 \times \left[\sum_{i=1}^{n} T_i \times P_i' \times (1 - PA_i)/G_i' \right]$$

$$R' = 100 \times \left[\sum_{i=1}^{n} T_i \times R_i' \times (1 - PL_i)/G_i' \right]$$

$$P = 100 \times \left[\sum_{i=1}^{N} S_i \times P_i' \times (1 - PA_i)/G_i \right]$$

$$R = 100 \times \left[\sum_{i=1}^{N} S_i \times R_i' \times (1 - PL_i)/G_i \right]$$

$$TB1 = \left[SU \times \sum_{i=1}^{N} G_i \right] + \left[PE \times E \times \sum_{i=1}^{N} G_i \right]$$

$$TB2 = \left[PPA \times \sum_{i=1}^{N} S_i \times PA_i + PPL \times \sum_{i=1}^{N} S_i \times PL_i \right]$$

$$+ \left[TIP \times \sum_{i=1}^{N} G_i \right]$$

$$TC1 = \left[\sum_{i=1}^{N} G_i \times CO \right]$$

$$TC2 = \left[\sum_{i=1}^{N} G_i \times CT_i \right]$$

Deviational Variables in GP

d_1^-, d_1^+: deviational variables of combustion temperature.

d_2^-, d_2^+: deviational variables of system benefits obtained from waste incineration.

d_3^-, d_3^+: deviational variables of system benefits obtained from waste collection.

a_i^-, a_i^+: deviational variables of paper recycling (%) in district i.

b_i^-, b_i^+: deviational variables of plastics recycling (%) in district i.

Input Variables in GP

P_1, P_2, P_3: priority of these three goals.

w_{22}^-, w_{22}^+: management weights corresponding to the goal of cost/benefit of collection agency.

w_{23}^-, w_{23}^+: management weights corresponding to the goal of cost/benefit of incineration agency.

J: the set of administrative districts.

CAP: design capacity of incinerator.

TIP: tipping fees charged on the citizens (if any).

MAX PL_i, MAX PA_i: maximum possible recycling rate of plastics and paper in district i respectively.

MIN T: required minimum combustion temperature.

N: the total number of the administrative districts in service area.

Decision Variables in GP

$TB1$ and $TB2$: system benefits obtained from operating collection team and incinerator respectively.

$TC1$ and $TC2$: system costs by operating collection team and incinerator respectively.

G_i: solid waste generation rate after recycling in district i (ton/day, on wet basis).

PA_i and PL_i: paper and plastics actual recycling rate in district i respectively (on wet basis %).

T_f: actual combustion temperature after recycling.

Decision Variables in Submodels

G_i': solid waste generation rate after recycling in district i (ton/day, on dry basis).

M: moisture content of solid waste after recycling.

HHV: high heating value of solid waste after recycling (kcal/kg or Btu/lb).

P', R': paper and plastics content in solid waste after recycling respectively (on dry basis %).

P, R: paper and plastics content in solid waste after recycling respectively (on wet basis %).

Input Variables in Submodels

K: equivalence ratio of combustion.

Ta (°F): preheated temperature of auxiliary air in combustion (assume ambient air temperature is 77°F).

P'_i, R'_i: paper and plastics content in solid waste before recycling in district i respectively (on dry basis %).

W_i: the original water content in the solid waste in district i (on wet basis %).

PE: price of electricity (NT$/kwh).

E: conversion factor between heating value and unit power generated (kWh/ton).

CT_i: unit transportation cost from district i to incinerator (NT$/ton).

CO: unit operation cost of incineration (NT$/ton).

SU: government subsidy for the treatment of waste (per ton basis).

S_i: solid waste generation rate before recycling in district i (wet basis).

T_i: solid waste generation rate before recycling in district i (dry basis).

f: average water content of paper and plastics.

PPL, PPA: prices of paper and plastics in the secondary material market respectively.

Solution Techniques

The priorities of these three goals considered in the model formulation can be assumed to be roughly comparable to decision makers initially. However, it is noted that the goals making up the model are measured in different units such that the aggregate deviational variables in the objective function is meaningless. In other words, when the targets associated with each goal have very different numerical values (i.e., the order of magnitude), the solution provided by this model can be biased as more important (i.e., artificial extraweight) and is given to the goals with higher target values than those with lower ones. In this situation, the artificial extraweight which does not reflect the actual preference of the decision maker to these goals distorts the solution output inevitably.

To overcome such problems which do not correspond to the initial non-preemptive condition, scaling (i.e., normalization) of each goal should be performed before solving for the satisfying solution. Hence, the right-hand-side values, such as the target values of combustion temperature, recycling ratio and the estimated total cost (decision variable), are selected as the scaling factors (Romero, 1991, pp. 38–39). Furthermore, the third term in the objective function should be divided by $2 * \mathrm{N}$ in order to avoid the inherent exaggeration of recycling weight unexpectedly. However, a specific type of problem encountered in this analysis, which has never been discussed in the literature, is that a deterministic goal programming may have mixed types of goals. This means some of the goals could not have a fixed target value and can only be expressed by the degree of satisfaction or aspiration while the others have predetermined target values. Overall, although the conventional scaling procedure intends to make the numerical values of all deviational variables associated with different targets become of like magnitude in the objectives equal which makes the optimum solution unbiased, the issue of artificial extraweight still cannot be completely eliminated in such a specific type of problem. In this situation, relatively higher importance is still given to these imprecise goals without fixed target values than to those with fixed ones if the associated right-hand-side value of the imprecise goal constraint is higher than the others. This type of structure, unlike general non-preemptive GP, cannot accept the reasonable trade-offs among these incommensurable deviational variables in the objective function after scaling.

In this analysis, it should be noted that we have to deal with this sort of specific problem. Three incommensurable goals using temperature, recycling ratio, and the dollar sign as units are considered, but no target values related to benefit/cost have been determined in advance. The expected achievement of benefit in the system is based on the preference of decision makers in the sense that the satisfaction of the degree of profit maximization in public agencies may not be equal to the aspiration of that in private agencies in this solid waste management system. Further, the extra weights are implicitly attached to the goal of benefit/cost, since the possible variations of scaled total benefit or cost are still expected to be very large while the possible changes of temperature or recycling ratio could be relatively trivial in the objective after scaling. Hence, such implicit preemptive priorities may generate the satisfying solutions in favor of the goal of economic efficiency (i.e., benefit/cost) rather than the goal of environmental protection (i.e., recycling and combustion efficiency) in such a superficially nonpreemptive structure. But it is not clear yet how the severity of this problem is in practice since scaling procedure has already improved partial bias condition tremendously. Therefore, according to the solution output of nonpreemptive structure in the first run, several cases are prepared for the direct testing of preemptive GP in the second run in this analysis. Streamlined solution procedure is then used for solving these models. It is expected that the results obtained from the superficially nonpreemptive model and truly preemptive model specifying the benefit/cost goal by first priority will have the obvious differences in this analysis.

Besides, it is noted that because GP was not invented with the purpose of obtaining nondominated solutions, only satisfying solutions can be found. Hence, the solutions obtained via the deterministic nonpreemptive GP are not necessarily Pareto optimal solution (Romero, 1991, Chapter 2). If this is the case, an additional check of solution efficiency (i.e., noninferior solution) is needed to increase the soundness of the GP approach. A simple test or procedure to check if the solution provided by a GP model satisfies the Paretian condition of efficiency or noninferiority has already been prepared in the literature (Romero, 1991). However, there is no such a problem of Paretian condition between fixed goals with predetermined target values and imprecise goals with only the degree of aspiration or satisfaction since such trade-offs are meaningless. Since this analytical framework has already inherently created the preemptive priority for the goal of benefit/cost due to the imperfect theoretical scaling procedure, the Paretian condition is only valid with the goals of recycling and combustion temperature. It is to be verified that the set of satisfying solutions related to each selected recycling profile and achieved combustion temperature in different management alternatives is unique and efficient because combustion temperature can no longer be improved once the recycling program has been selected in the final solution.

Because of the theoretical limitation in scaling procedure (Romero, 1991), it is known that the trade-off between economic and environmental goals is not exact in this nonpreemptive GP. The emphasis of this research is therefore placed upon illustrating a prototype screening methodology for solid waste management to facilitate the decision makers working for profit maximization by optimization techniques with respect to environmental protection implicitly. Satisfying solutions from this nonpreemptive GP models associated with proposed management alternatives are reviewed for the final suggestion of this analysis. These related models can be solved by several optimization software packages, such as GINO, MINOS, GAMS, and so forth. The GINO software package is finally used as a solver. The hardware required is the IBM PC or a machine compatible with 486 CPU and microprocessor.

Model Structures and Related Waste Management Alternatives

In the above model formulation, various management alternatives can be expressed without difficulties because the cost/benefit terms corresponding to private and public sectors are defined separately in the objective and goal constraints. For instance, if the system is only operated by a single agency, the cost/benefit terms defined for different sectors in the objective and goal constraints can be combined together. The inclusion of different deviational variables are also related to the different types of management alternatives and even the intention of decision makers. For instance, it is necessary to include both deviational variables — the slack and surplus one — in the objective when the decision maker intends to achieve an exact satisfaction of a goal (i.e., an exact achievement of the target). In this analysis, if the operating agency, either performing collection or the incineration task, is a public sector, the objective or achievement function associated with benefit/cost expressions should minimize the slack and surplus deviational variables at the same time. This means the total benefit is expected to be equal to the total cost. On the other hand, if the operating agency is a private sector, the goal of profit maximization can be established by the inclusion of only the slack deviational variable with a positive sign and/or the surplus deviational variable with a negative sign in the objective. If only a slack deviational variable with positive sign is considered while the goal constraint is formulated by a format of a two-sided goal, it is then guaranteed mathematically that the total benefit is optimized to reach the total cost as closely as possible while a total benefit is higher than the total cost would be desirable. Further, if the surplus deviational variable with a negative sign is also included in the objective, the total benefit is to be maximized by all means in the trade-off process.

It is considered that if an incineration facility is operated by a private sector, the local municipality should subsidize such an operation, and the residents' tipping fee charged may support financially all or part of such a subsidy in a system. If the system components — incineration and collection equipment — are operated by a single public agency, the consideration of such a subsidy could be excluded in the model. In this situation, to compensate the government expenditure for solid waste management, the tipping fee can be defined as a decision variable in the initial model formulation. In the case of having an incinerator run by a private sector only, both the tipping fee and the subsidy can be defined as decision variables in the model and the management policy of privatization can then be evaluated. If the system is operated by a single private agency, a reasonable or minimum subsidy might be an important message to a decision maker. For this purpose, it can be calculated easily through the inclusion of a subsidy as a decision variable in the model. Overall, whether the tipping fees and/or subsidies should be defined as decision variables actually depends on the management alternatives, strategies and policies selected by the decision maker in advance. It is believed that different degrees of tradeoffs among different goals exist in various management alternatives, although we have perceived that the goal of benefit/cost may have a higher weight potentially.

CASE STUDY

Application Background

Tainan City, located in the southern part of Taiwan, is a city in which the administrative area is divided into seven districts. Each district owns one waste collection team which is currently operated by the Bureau of Environmental Protection of City Government. But privatization of the business of garbage collection is anticipated in the future. Only one incinerator, which is planned to be operated by a private sector (i.e., the turnkey bidder), is sited in this city and the construction is now in progress. However, various waste recycling programs have been conducted for several years, and the ROC EPA will subsidize the City Government continuously for promoting such activities. On the other hand, the potential hazard of trace organic emissions from incineration also results in much concern for the public. The current and future management planning alternatives can be fully coordinated, expressed and evaluated by the aforementioned analytical framework of the GP model.

The background information of waste generation and composition in Tainan City is collected (Chang, 1993). Figure 1 illustrates the geographical location and the configuration of solid waste management system in Tainan City. The required minimum combustion temperature used in this analysis is 982°C (1800°F). The average value of unit transportation costs is obtained and adjusted for each district according to the hauling distance from the district to the incinerator. Due to the consideration of equity in the efforts of recycling, the maximum recycling ratios of paper and plastics attainable in the goal constraints are defined by the same numerical values (i.e., 50% for plastics and 70% for paper) for all districts.

In the submodel for estimating the combustion temperature, the equivalence ratio is assumed by 1 : 1.8 (i.e., 80% excess air), and there is no preheating consideration. As reported by the government agency, the current tipping fee is 840NT$/ton which only constitutes 40% of the total expense for solid waste management, and the average operating cost for handling an incinerator is 1000 NT$ per ton waste. One notices that both heating value and water content would be changed after recycling. 0.32 is thus chosen as the average water content of paper and plastics for the subsequent evaluation of the resultant water content and combustion temperature after recycling. Based on the market investigation of secondary material, 1.2 NT$/kg and 2 NT$/kg are selected as the prices of paper and plastics respectively. Besides, the selling price of electricity is 1.5 NT$/kWh. Hence, the trade-off relationship exists because plastic is regarded as a valuable item in both waste combustion and recycling by having higher heating value and price simultaneously. However, the final recycling profile should also be dependent upon several more factors in the optimization process, including waste generation and composition, heating value and water content after recycling, the level of subsidy for operating an incinerator, the price of selling electricity, and the required hauling distance.

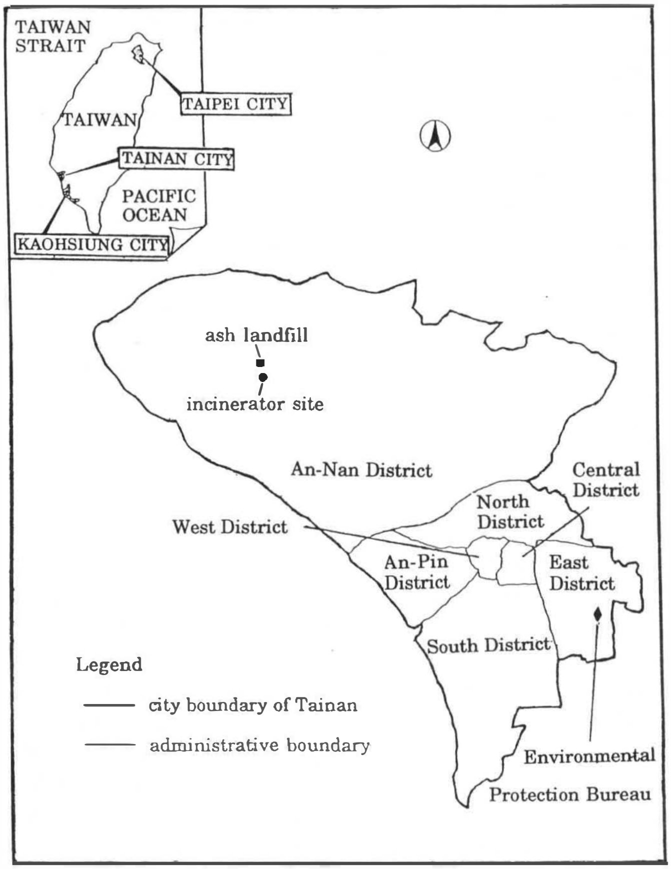

FIG. 1 THE GEOGRAPHICAL LOCATION AND CONFIGURATION OF SOLID WASTE MANAGEMENT SYSTEM IN TAINAN CITY

Results and Discussions

Table 1 illustrates the management alternatives tested in this analysis. Only one set of deviational variable (i.e., d_2^- and d_2^+) associated with the cost/benefit expressions in the objective and goal constraints is included in cases 3–8 because the entire collection, the recycling and incineration system is operated by one public or private sector. The budget balance and privatization may become the major focus in the evaluation process if the tipping fee and subsidy are defined as decision variables in these cases. The situation in base case, case 1 and case 2 are prepared to simulate the current condition, while the testing of cases 5–8 are organized for the better understanding of the future situation in Tainan City. Although case 1 is organized for the situation in which the incinerator is operated by the private sector while the collection duty is performed by the government agency, the minimum level of tipping fee and

TABLE 1 TESTED MANAGEMENT ALTERNATIVES IN THIS ANALYSIS

condition	base	case 1	case 2	case 3	case 4	case 5	case 6	case 7	case8
collection is operated by private sector						•	•	•	•
incinerator is operaed by private sector	•	•	•			•	•	•	•
system is operated by a single company						•	•	•	•
collection is operated by public sector	•	•	•	•	•				
incinerator is operaed by public sector				•	•				
fixed subsidy for incinerator(1500NT$/t)	•					•	•		
subsidy is defined as decision variable		•	•					•	•
fixed tipping fee for resident (840NT$/ton)	•		•		•				
tipping fee is defined as decision variable		•		•					
+ d_2^+ included in the objectives		•	•	•	•			•	
- d_2^+ included in the objectives						•			•
+ d_2^- included in the objectives	•	•	•	•	•	•	•	•	•
+ d_3^+ included in the objectives	•	•	•						
+ d_3^- included in the objectives	•	•	•						

TABLE 2 SATISFYING SOLUTION OF CASE STUDY BASED ON VARIOUS MANAGEMENT ALTERNATIVES

	base case		case 1		case 2		case 3	
combustion temperature(°C)	962 (1763°F)		977 (1790°F)		981 (1799°F)		982 (1800°F)	
recycling rate (%)	PL_i	PA_i	PL_i	PA_i	PL_i	PA_i	PL_i	PA_i
East District	50	70	50	0	50	70	17.9	0
South District	50	70	50	0	50	0	0	70
West District	50	70	50	0	0	0	50	70
North District	50	70	50	70	0	0	50	70
An-Pin District	50	70	50	0	0	0	50	70
An-Nan District	50	70	50	70	50	0	0	70
Central District	50	70	0	70	20	0	50	70
total recycling	32.3%		19.6%		14.9%		18.9%	
total recycling rate of paper	70%		30.8%		19.8%		50.2%	
total recycling rate of plastics	50%		43.1%		36.7%		19.5%	
system benefits for collection (NT$/day)	704,548		809,965		603,083		1,110,631	
system costs for collection (NT$/day)	1,202,034		809,965		813,161		1,110,631	
net system benefits for collection (NT$/day)	-497,486		0		-210,078		0	
system benefits for incineration (NT$/day)	933,577		503,046		523,235		----	
system costs for incineration (NT$/day)	448,451		503,046		523,235		----	
net benefits for incineration (NT$/day)	485,126		0		0		----	
net system benefits (NT$/day)	-12,360		0		-210,078		0	
tipping fee (NT$/t)	----		1,141		----		1,161	
subsidy (NT$/t)	----		395		386		----	

subsidy for keeping the system in operation economically can also be evaluated by the same framework in case the collection business is operated by another independent private sector. The management patterns described in cases 3 and 4 are exactly the same as the current situation in Taipei City, and therefore are also applied for Tainan City.

The satisfying solutions for these nine cases in the nonpreemptive GP model can be obtained from GINO output directly and are listed in Table 2. It is known that the goals of the required combustion temperature (982°C or 1800°F) and recycling cannot be satisfied simultaneously in most of the cases because recycling may generate higher benefits, including direct income from secondary material market and indirect saving from hauling and treatment. Several cases also show that system benefits are nonpositive unless the private sectors participate in both the collection and the incineration business in the sense that privatization is encouraged in such a system. In cases 3, 4, 5 and 6, the predetermined subsidy (1,500NT$/ton) represents the major income in the benefit profile, while the income from power generation is the second most important source of total benefit for private sector operating an incinerator. This implies that contract price is sensitive to a private sector in the process of negotiation with local government. It is worthwhile to mention that the benefit can be specifically maximized as shown in case 8 due to the inclusion of "$-d_2^+$" in the objective whenever subsidy is defined as a decision variable. Overall, the examination in Table 2 shows that the total recycling ratio of paper and plastics cannot reach the target values due to the negative impact on the heating value. However, differ-

TABLE 2 SATISFYING SOLUTION OF CASE STUDY BASED ON VARIOUS MANAGEMENT ALTERNATIVES (CONTINUED)

	case 4		case 5		case 6		case 7		case 8	
combustion temperature(°C)	978 (1792°F)		962 (1763°F)		994 (1821°F)		962 (1763°F)		977 (1791°F)	
recycling rate (%)	PL_i	PA_i	PL_i	PA_i	PL_i	PA_i	PL_i	PA_i	PL_i	PA_i
East District	50	0	50	70	0	0	50	70	50	70
South District	50	0	50	70	50	0	50	70	50	70
West District	0	0	50	70	0	0	50	70	50	70
North District	0	70	50	70	0	0	50	70	50	70
An-Pin District	0	0	50	70	50	0	50	70	50	70
An-Nan District	50	70	50	70	0	0	50	70	50	0
Central District	50	70	50	70	0	42.2	50	70	50	70
total recycling	19%		32.3%		4.3%		32.3%		21.1%	
total recycling rate of paper	30.8%		70%		12.5%		70%		45.8%	
total recycling rate of plastics	40.9%		50%		3.9%		50%		32.9%	
system benefits (NT$/day)	934,924		1,144,598		1,248,611		977,810		6.8×10^{22}	
system costs (NT$/day)	1,118,254		977,810		1,235,277		977,810		1,055,713	
net system benefits (NT$/ton)	-183,330		166,788		13,334		0		very large	
subsidy (NT$/ton)	----		----		----		1,128		1.4×10^{17}	

TABLE 3 SATISFYING SOLUTION BY VARYING THE WEIGHT ASSOCIATED WITH REQUIRED COMBUSTION TEMPERATURE IN THE BASE CASE

weight of the goal of temperature	15		100		210		300	
achieved combustion temperature(°C)	982 (1799°F)		982 (1799°F)		998 (1829°F)		998 (1829°F)	
recycling rate (%)	PL$_i$	PA$_i$	PL$_i$	PA$_i$	PL$_i$	PA$_i$	PL$_i$	PA$_i$
East District	0	70	0	26.4	0	2.4	0	2.4
South District	50	70	0	70	0	1.2	0	1.2
West District	5.9	0	50	70	0	0	0	0
North District	0	70	50	70	0	1.8	0	1.8
An-Pin District	50	0	50	70	0	0	0	0
An-Nan District	0	70	0	70	0	2.3	0	2.3
Central District	0	70	50	70	0	2.3	0	2.3
total recycling	20.9%		20.1%		0.5%		0.5%	
total recycling rate of paper	63.2%		57.6%		1.8%		1.8%	
total recycling rate of plastics	12.9%		16.0%		0%		0%	
system benefits for collection (NT$/day)	613,041		611,821		496,143		496,143	
system costs for collection (NT$/day)	1,326,055		1,348,224		1,571,601		1,571,601	
net system benefits for collection (NT$/day)	-713,014		-736,403		-1,075,458		-1,075,458	
system benefits for incineration (NT$/day)	1,055,225		1,061,677		1,255,239		1,255,239	
system costs for incineration (NT$/day)	497,467		500,741		585,354		585,354	
net benefits for incineration (NT$/day)	557,757		560,936		669,885		669,885	
net system benefits (NT$/day)	-155,257		-175,465		-405,873		-405,873	

TABLE 4 SATISFYING SOLUTION BY VARYING THE WEIGHT ASSOCIATED WITH REQUIRED COMBUSTION TEMPERATURE IN CASE 5

weight of the goal of temperature	1000		1200		1300		1500		1700	
combustion temperature(°C)	962 (1763°F)		982 (1781°F)		962 (1763°F)		981 (1797°F)		962 (1763°F)	
recycling rate (%)	PL$_i$	PA$_i$	PL$_i$	PA$_i$	PL$_i$	PA$_i$	PL$_i$	PA$_i$	PL$_i$	PA$_i$
East District	50	70	50	70	50	70	50	0	50	70
South District	50	70	50	0	50	70	50	0	50	70
West District	50	70	50	0	50	70	0	0	50	70
North District	50	70	50	0	50	70	0	0	50	70
An-Pin District	50	70	50	0	50	70	0	0	50	70
An-Nan District	50	70	50	70	50	70	50	70	50	70
Central District	50	70	50	70	50	70	50	70	50	70
total recycling	32.3%		23.2%		32.3%		15.3%		32.3%	
total recycling rate of paper	70%		37.3%		70%		17.5%		70%	
total recycling rate of plastics	50%		50%		50%		40.9%		50%	
system benefits (NT$/day)	1,144,598		1,186,230		1,144,598		1,216,381		1,144,598	
system costs (NT$/day)	977,810		1,066,916		977,810		1,146,909		1,066,916	
net system benefits (NT$/ton)	166,788		119,314		166,788		69,472		166,788	

ent weight distribution among various incommensurable goals are existing empirically. The economic value of recyclables in the secondary material market and potential saving from hauling and treatment do drive the system into a full recycling scenario, as shown in the base case, case 5 and case 7. This causes the base case minimizes the debt and the case 5 maximizes its profit.

A preemptive structure has to be tested with respect to the decision maker's preference in order to compare the results with those obtained from above. In a preemptive structure, two different level of goals can be clearly distinguished. As mentioned above, the goal of cost/benefit can be regarded as the economic goal while the combustion temperature and recycling are the goals for environmental protection or conservation. The priority of combustion temperature and recycling should be arranged in the same level because they are interdependent. In other words, once the recycling program is selected in the satisfying solution, the combustion temperature achieved in this analytical framework has no chance to be further changed in this case study. In the situation encountered here, the goal of cost/benefit must become a redundant goal if we emphasize the other goal first since the total cost/benefit should be fixed once the recycling program has been determined by the higher priority. Therefore, the goal of cost/benefit is always arranged by the higher priority and the achievement of the goals of temperature and recycling are thus subsequently determined subsequently. It is verified that such preemptive setting does generate the same satisfying solution as shown in Table 2 as expected. But theoretical proof of this phenomenon is left to those mathematicians who are interested in the field of goal programming.

Sensitivity Analysis

Based on the satisfying solution as shown in Table 2, sensitivity analysis can be performed and shown by the following tables and diagrams. Table 3 shows various satisfying solutions by varying the weight associated with the required combustion temperature in the base case. It is observed that the more emphasis placed upon the combustion temperature, the less the material is allowed to be recycled in the management scenarios. In order to understand the impact of varying the relative weight of temperature goal on total recycling ratio in case 5, which might be consistent to the future management pattern in Tainan City, additional sensitivity analysis is performed and the results are listed in Table 3. However, they are quite different from the results as shown in Table 2.

Overall, the actual impact from setting up an imprecise goal in this model can be detected and evaluated by this sensitivity analysis while the system is assumed to be operated by a single agency as arranged in case 5. Furthermore, the Paretian condition for checking the solution efficiency is not necessary here because the unique solution, as shown in Table 4, can never be improved once the trade-off between two major goals with equivalent weight is finished and the third one with relatively lower weight is omitted during the competing process.

CONCLUSIONS

This analysis is significant because of the association between engineering considerations and management targets within various types of solid waste management alternatives. The satisfying solution and subsequent sensitivity analysis account substantially for the interaction of combustion temperature and recycling goals in a regional solid waste management system. Finally, this case study is prepared for the illustration of this model and therefore should not be used as a final recommended plan for Tainan City.

REFERENCES

Allan, T., Platt, B. and Morris, D., "Beyond 25 Percent: Material Recovery Comes of Age," The Institute for Local Self-Reliance, Washington D. C., U.S.A., 1989.

Clark, M. J., "Improving Environmental Performance of MSW Incinerators," *Industrial Gas Cleaning Institute Forum*. 1988.

Chang, Juu-En, "Sampling and Analysis of Tainan Solid Waste in 1992," Technical Report, Department of Environmental Engineering, National Cheng-Kung University, Feb., 1993.

Chang, N. B. and Wang, S. F., "A Locational Model for the Site Selection of Solid Waste Management Facilities with Traffic Congestion Constraints," Civil Engineering Systems, accepted, Nov., 1993.

Environment Canada, "The National Incinerator Testing and Evaluation Program (NITEP)," 1991.

Environment Canada, "The National Incinerator Testing and Evaluation Program: Two-stage Combustion (Prince Edward Island)," Sep., 1985.

Environment Canada, "The National Incinerator Testing and Evaluation Program: Environmental Characterization of Mass Burning Incinerator Technology at Quebec City," Summary Report, June, 1988.

Environment Canada, "The National Incinerator Testing and Evaluation Program: Air Pollution Control Technology," Summary Report, Sep., 1986.

Environment Canada, "The National Incinerator Testing and Evaluation Program: the Environmental Characteristics of Refuse-derived-fuel Combustion Technology," Summary Report, June, 1992.

Federal Register, U. S., "40 CFR Parts 51, 52, and 60, Standards of Performance for New Stationary Sources and Final Emission Guidelines; Final Rules," Feb. 11, 1991.

Hasselriis, Floyd, "The Effect of Recycling on Waste-to-Energy Plants," Gershman, Brickner and Bratton, Inc., Falls Church, Virginia, U.S.A., 1988.

Massachusetts Department of Environmental Protection (MDEP), "Toward a System of Integrated Solid Waste Management," Commonwealth's Master Plan for solid waste management, MA, U.S.A., 1989.

Miller, H. et al., "Correlation of Incineration Parameters for the Destruction of Polychlorinated Dibenzo-p-dioxins," *Chemosphere*, 18 (7–8):1485–1494, 1989.

Romero, C., "Handbook of Critical Issues in Goal Programming," Pergamon Press, 1991.

Schindler, P. J., "Municipal Waste Combustion Assessment Combustion Control at New Facilities," *EPA-600/8-89-057*. 1989.

Tillman, D. A., Rossi, A. J., and Vick, K. M., "Incineration of Municipal and Hazardous Solid Wastes, Academic Press, 1989.

U.S. EPA, "Environmental News: EPA proposes air emissions standards for municipal waste incinerators," R233, pp. 1–4, 1989.

Key Words: solid waste management, waste recycling, waste incineration, privatization, system analysis, nonlinear goal programming