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Environmental Modeling & Assessment; Dec 2001; 6, 4; ProQuest
pg. 297

Environmental Modeling and Assessment **6:** 297–306, 2001.

Strategic management decision support system: An analysis of the environmental policy issues

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In this paper we present a new approach for modeling environmental problem as a bilevel programming problem. To the authors best knowledge, this is the first attempt to use bilivel techniques to tackle such problems. We derive at solution to help decision makers to cope with environmental policy issues. San Francisco, Bay Area is used as a real world example with the solution to their environmental problem.

California is presently faced with a serious deficit of solid waste treatment and disposal facilities. Federal legislation has sought to compel the States to assure the capacity to treat and dispose of their own wastes and the California Legislature has enacted laws requiring the counties to initiate programs so that they can treat and dispose of their own wastes. Neither the federal nor the State programs have met with success in California. California continues to ship greater and greater amounts of waste out-of-state, and the majority of California counties have not instituted plans acceptable to the State government regarding the treatment and disposal of their own wastes.

In the few cases where sitting and licensing programs have been proposed, the policy-makers charged with their evaluation have proceeded with largely intuitive, non-quantitative evaluation of policy options, often ignoring most of the financial and environmental implication of their decisions.

We have developed a strategic management decision model that can evaluate multiple solid waste management options from both economic and environmental standpoints. Examples of problems a quantitative model might evaluate include the economic and environmental impacts of multiple treatment or disposal facilities as opposed to only one site; the environmental impact of taxing “dirty” waste streams, thus encouraging waste treatment and/or minimization on-site; and the social risk resulting from transportation risks assuming one or more multiple treatment or disposal sites or the use of alternative transportation routes.

Because of extensive information presently available for the San Francisco Bay region, we have investigated the regional waste management problem there under several different treatment and disposal scenarios. As appropriate, results from this regional model and from authors earlier work [1] will be applied to California as a whole.

1. Introduction

Solid and hazardous waste management is widely recognized as one of the most serious issues confronting industrialized society. At a great risk are public health, environmental quality, and economic competitiveness of industry. For example, in 1990, about 30,000 firms generated and shipped off-site over 2 million tons of solid and hazardous waste in California alone. In Northern California, the nine counties (Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma), that have formed the Association of Bay Area Governments (ABAG), generate 400,000 tons of incinerable solid and hazardous waste each year.

The rapid production of solid and hazardous waste combined with the increase in disposal costs, the decrease in the available number of landfill sites, changes in legislation, and more public awareness have dramatically altered the way in which we can deal with solid and hazardous waste management and have posed major scientific, social and political question which can best be answered by better sitting of new waste treatment, recycling, and disposal facilities. We are a proposing a mathematical modeling technique to allow governmental agencies to more fully analyze the financial and environmental impact of alternative waste management plans in their deliberations.

The importance of this issue for California policy makers lies in the need for tools for decision-makers to address waste sitting issues in a more quantitative manner. Many of the hazardous waste sitting processes in California are presently at a standstill, even while the volumes of waste generated continue to rise. Between 1998 and 1999, for example, the amount of waste manifested off-site grew nearly 25 percent, to approximately 3 million tons.

The need for treatment and disposal sites within California is underscored by the fact that out-of-state shipments are growing at alarming rates; between 1986 and 1989 exports of hazardous waste from California increased from about 40,000 tons per year to at least 300,000 tons per year according to a July 5, 1991 *Wall Street Journal* article. Should the importing states achieve their goal of obtaining Congressionally mandated restrictions or prohibitions on waste exportation, California would be faced with a crisis of unparalleled proportions: an inability to handle the waste that industry – and the population at large – generates.

Rather than allow the continued long-distance shipping of waste, legislation has already been enacted at both the federal and state level promoting treatment and disposal on a more local level. The Congress, in enacting section 104(k) of the Superfund Amendments and Reauthorization Act of 1986 (P.L. 99-49, 100 Stat. 1613, 42 USC 9604(c)(9)) sought to require the states to assure that they could handle their own wastes either individually or through the use of interstate agreements. If any state fails to assure the capacity to treat and dispose of its own waste, then the Administrator of the Environmental Protection Agency (EPA) is authorized to withhold Superfund clean-up funds from that state. The use of this enforcement penalty was considered by EPA Administrator William K. Reilly against the State of North Carolina which had failed to site regional incinerator [11,12].

The State of California has enacted similar legislation, seeking to force the counties (or regions) of the state to assure their ability to safely treat and dispose of their own waste (AB 2948, Tanner; Stats. 1986, ch. 1509; California Health and Safety Code 25179.1 et. Seq.) [30].

Within this context, the Association of Bay Area Governments (ABAG) in the San Francisco Bay Region [2], and the eight-county Southern California Hazardous Waste Management Authority [28] have both adopted regional hazardous waste management plans under the concepts that each county within the region would site some sort of waste treatment and disposal facility, each county accepting some responsibility for a "fair share" of waste treatment and disposal.

While Southern California has only begun the deliberative process, the Association of Bay Area Governments is actually more advanced in its decision-making process. Indeed, at its July 26, 1991 meeting ABAG's Facility Allocation Committee actually allocated sitting responsibilities to each country within ABAG.

Unfortunately, ABAG's decision-making methodology strikes us a largely intuitive, and is semi-quantitative at best. ABAG's methodology essentially relies on one number to determine sitting responsibility: total waste generated within a county is subtracted from that county's treatment and disposal capacity; the county with the largest deficit gets the most "undesirable" (a subjective judgment on the part of the ABAG staff) facility. The county with the second largest deficit gets the next most undesirable facility, and so on.

It must be pointed out here that ABAG has made virtually no attempt to determine the actual feasibility or environmental impact of any "allocated" facility. For example, the potential placement of an incinerator in the South Bay (in or near San Jose) might violate air quality standards in that part of ABAG; placement in unincorporated area of eastern Alameda or Contra Costa counties might be more desirable from an air quality standpoint. Similarly, the existence of only incinerator within ABAG might increase transportation risk due to shipments have to travel fifty miles or more; in this case, more than one incinerator, each sited near an area of high generation, might be more appropriate. Other decision-making criteria, such as treatment and disposal costs or the costs (both financial and environmental) of implementing on-site recycling should also be examined.

An optimization modeling approach, implemented into a management decision support system, taking into account the various decision-making criteria that both government agencies as well as industry are faced with, would provide a more proper approach in attempting to develop the sitting process within the Bay Area specifically and California generally.

In the core of the DSS, optimization modeling represents a set of tools and procedures of system engineering and analysis that are designed, in the context of a large-scale problem area such as solid waste control, to quantify in an organized manner a complex set of date. The main benefit of optimization models is not the selection of the "best" solutions, but rather the ability of performing sensitivity studies, which are extremely important for identifying those system components, which have relatively large impacts upon the system. For example, minor changes in the composition of the waste feed to incineration can lead to greater emissions of waste undesirable components; a correctly structured model may answer such questions as the amount of tax to levy against firms that manifest untreated waste containing high level of these undesirable components.

In order to fully understand the fundamental characteristic of hazardous waste management, we must introduce two important agents in the economy: The central authority and the firms. The central authority (CA) is defined as any agent in the economy which has the authority to regulate the other agents' activity.

We define a firm as any organization that, through its activity produces some goods, not necessarily identical, in order to maximize its own profit. As a by product of the firm's activity, hazardous waste is also generated which needs to be managed.

In this paper, we present an analytical model for hazardous waste capacity planning and treatment facility location. The behavior of private firms is modeled to assess the effect of central planning decisions and price signals on hazardous waste generation and demand for treatment and disposal. In short, we are mainly concerned with the interaction between the two agents: the CA seeking to regulate the firms in order to maximize the social welfare and the firms responding to these regulations. Furthermore, we have focused our attention on a group of wastes classified as incinerable hazardous wastes since it constitute the largest nonnuclear waste group in the US.

The management of incinerable wastes are divided into four major categories:

1. Source reduction: The elimination or reduction of waste at the source.
2. Recycling: The recycling or reuse of waste material both on-site and off-site (regional level). Recycling is not 100%, and some residuals need to be sent for incineration and disposal.
3. Incineration: Thermal destruction of waste at off-site facilities.
4. Disposal: Releasing material into air, water and land. This option is assumed to be a joint process with the incineration.

Among all the technique of waste management, source reduction is favored due to its lower risk to the environment, and thus is the common sense solution to the prevention of future hazardous waste problems. But due to lack of proper environmental regulation and/or economic consideration, recycling and incineration are part of today's waste management options. The latter processes bring with them certain damage (or externalities) to the environment which we will call pollution damage.

The model, intended as a decision support tool for a regional hazardous waste management authority, is necessarily a simplification of the actual conditions and subject to constraints and assumptions which are described below. Still, it provides a framework for qualitatively comparing the effects of different planning options.

2. Analytical approach

Many authors have attempted optimization techniques in the pollution abatement problem (e.g., [13,14,16,25]). Graves et al. [14] used a large scale nonlinear programming in a pollution abatement model for West Fork White River in Indiana in order to minimize the total cost of pollution abatement structure subject to water quality in each section of the river. Haimes et al. [15] and Hass [18] approached the abatement of water pollution through decomposition techniques of Dantzig and Wolfe [8]. Their goal was to simultaneously compute an optimal waste water treatment configuration and to determine optimal pollution taxes to achieve this configuration.

Models of Haime et al. [15] and Hass [18] depend crucially upon the assumption that the system is (i) centralized, and (ii) the centralized system is capable of decentralization. Jacobsen [20] showed that once revenue sensitivities and appropriate benefit measures are introduced, usually *both* of the above assumptions do not hold. Hall and Jacobsen [16] highlighted the importance of response functions due to specific regulatory policies. They developed an optimization model based on consumers' surplus, profit loss, and changes in tax revenues; and concluded that, when information costs are too high, it is most efficient to tax the solid wastes directly rather than the tax the goods that produced such wastes.

In most of these models, the solution is derived from a microeconomic approach, in the sense that it is found by locating the point where the marginal treatment cost equals to the marginal damage cost from the perspective of a particular individual polluter (some noted exceptions are Jacobsen [20], Hall and Jacobsen [16], and Kolstad [21]). However, a serious shortcoming of these models is that complete information on the production and damage cost functions of each and every firm is assumed to be known. Although, each firm may know its own production cost functions, there is no reason to believe that this information will be readily available to the central authority.

Some researcher have conceptualized the problem in terms of a multilevel frame work [3,15,18,21]. Although Hass [18] seemed to realize the existence of two levels, he did not formulate his model as such. Instead, he modeled the problem as a single level and solved it by using Dantzig–Wolfe nonlinear decomposition.

Haimes et al. [15] also recognized the need to consider the problem from a multilevel modeling viewpoint. They proposed a formulation consisting of three level: a central authority, a regional treatment plant, and the individual polluter. Their solution method decomposed the optimization problem into a set of hierarchically ordered subproblems. The solutions of these subproblems were then coordinated to obtain an optimal solution to the original problem. More specifically, once the central authority determines the tax schedule, it send this information down to the lower levels. The lower levels then process the tax structure and pass results back up to the central authority as optimal treatment levels. Using these treatment levels, the central authority checks the quality constraints to determine if the previous taxing structure is too high (no binding constraints), too low (some constraint violated), or optimal(no constraints violated, some binding constraint). If the previous tax structure is not optimal, a new tax structure is developed. The iterative nature of this solution technique is necessary since there is no mechanism, inherent in the model, which assumes that central authority has any knowledge of the lower level optimization problems. The obvious difficulty with such iterative tax setting is that the lower level (firms) assumes the initial taxes are substantially correct, and they plan their pollution control program which may take several years to complete, and it is largely irreversible once in place.

Kolstad [21] formulated his Four Corner case study in terms of a stochastic bilevel problem, but his interest was to derive some empirical properties for various air pollution regulations.

2.1. Hierarchical decision making

The aim of this paper is to go beyond a location/allocation model and to develop a strategic DSS model that considers the interaction of the governing agency and the firms. It is assumed that the Central Authority (CA) in order to encourage source reduction, may adopt a policy of rewarding firms for each unit of source reduction beyond its specified lower limit. At the same time, the CA desires to regulate firms who fail to meet the minimum source reduction standard and for shipping hazardous waste to offsite incinerators. The economic approach to hazardous waste control is based on the regulation of the behavior of the firms. Hence, a tax system induces the polluters to reduce their discharge to a level where their marginal cost of a proper treatment (i.e., recycling or source reduction) equals the marginal cost of pollution damage (taxes can be used as a surrogate measure of pollution damage). Beyond this level, it is cheaper to pay the tax than continue the treatment process and at optimal tax rate, the cost of any pollution related damage is totally internalized.

The firms, of course, incur other costs other than the penalty (tax) set by the CA. The firms, in planning their waste management policy, need to consider such costs as the onsite recycling cost (including the setup and operation costs), offsite recycling costs, and incineration costs.

This type of model leads to an Hierarchical decision making where the CA assumes the role of the leader that makes decision on prices and taxes. On the other hand, the firms observing the decision made by the CA set their own allocation policies. This type of interaction between the two agents when formulated, is commonly referred to as a Stackelberg Game [29] or in mathematical programming terminology, a *Bilevel Programming Problem* (BLPP). The next section briefly introduces BLPP and its mathematical foundation of the underlying technique which forms the bases of our DSS model.

3. Linear bilevel programming problems

Consider a two-level hierarchical system where the higher-level decision maker, the leader, controls the decision vector $x \in X \subset \mathbb{R}^{n_1}$, and the lower-level decision maker, the follower, controls $y \in Y \subset \mathbb{R}^{n_2}$. The leader makes his decision first, and the follower observing the leader's decision, responds by selecting a decision vector $y \in Y$. The lower linear optimization problem, L(x), can be described as follows. Let $\psi(x)$ denote the optimal value of the lower problem and

$$\mathrm{L}(x):\quad \psi(x) = \min\{d_2^\top y \mid Ax + By \leqslant b,\ y \geqslant 0\},$$

where $d_2^\top y$ is the objective function of the lower problem, A, and B are matrices of size $(m \times n_1)$, and $(m \times n_2)$, respectively; and $b \in \mathbb{R}^m$ is a vector of resources. The bilevel programming problem is then formulated as

$$\min\{c_1^\top x + d_1^\top y \mid \psi(x) \geqslant d_2^\top y,\ (x, y) \in \Omega\}, \tag{P}$$

where $\Omega = \{(x, y) \mid Ax + By \leqslant b,\ x \geqslant 0,\ y \geqslant 0\}$, and $c_1^\top x + d_1^\top y$ is the objective function of the upper-level problem. Given that $\psi(x)$ is a convex function, problem (P) is called a *linear program with an additional reverse convex constraint* or more appropriately, a *linear program with a facially reverse convex constraint.* Bilevel Programming Problem (BLPP) is sometimes denoted by

$$\begin{array}{ll} \min\ c_1^\top x + d_1^\top y & \\ \text{where } y \text{ solves} & \min\ d_2^\top y, \quad (x, y) \in \Omega. \end{array} \tag{Q}$$

Clearly problems (P) and (Q) are equivalent. In order to facilitate further discussion of the properties of BLPP, the following definitions are introduced. The notation follows Bard [5].

Let

$$\Omega(X) = \{x \in X \mid \exists y \ni (x, y) \in \Omega\}$$

be *the projection of* Ω *onto the leader's decision space* X, and let $M(x)$ be the followers *rational reaction set* to a given x.

$$M(x) = \{y \mid y \in \operatorname{argmin}\{d_2^\top z \mid z \in \Omega(x)\}\},$$

where $\Omega(x)$ is the follower's feasible region for fixed x.

The rational reaction set is an implicit mapping which takes a point, $x \in X$, into a subset of the follower's feasible region on which the lower objective is minimized with respect to $y \in Y$. It should be noted that the followers problem may be infeasible for certain values of $x \in X$. Therefore, the rational reaction set may be empty for some values of x.

The leader, by its various choices of x, elicits different rational reactions from the follower. The union of all possible vectors that the leader may select, x, and the corresponding rational reaction, $y \in M(x)$, is called *the Inducible Region.* Let *IR* denote the inducible region defined by

$$IR = \{(x, y) \mid x \in \Omega(X),\ y \in M(x)\}.$$

The leader's problem is then to optimize its objective function over the inducible region.

$$\min\{c_1^\top x + d_1^\top y \mid (x, y) \in IR\}.$$

Proposition 1. If *(P)* is solvable then an optimal solution is achieved at a vertex of the polyhedron Ω.

Proof. See [27]. It is interesting to note that the follower is indifferent to any two strategies, y' and y, if $d_2^\top(y' - y) = 0$. In other words, there could be an equivalent class of follower's response to a given leader's strategy, x. On the other hand, any two strategies x', and x of the leader such that $A(x' - x) = 0$ will cause the same response from the follower since $\psi(x) = \psi(x')$. Consequently, two strategies (x, y), and (x', y') are equivalent if $A(x' - x) = 0$ and $d_2^\top(y' - y) = 0$. That is, there may be an equivalent class of optimal strategies. ☐

3.1. The DSS Model

The following notation is used to describe the model under investigation:

Indices and sets:

i	Index of nine ABAG regions, $i \in I = \{1, \dots, 9\}$.
f	Index of types of firms, $f \in F = \{1, \dots, n_f\}$.
r	Index of types of recycling facilities, $r \in R = \{1, \dots, q_r\}$.

d	Index of types of incinerator facilities, $d \in D = \{1, \ldots, m_d\}$.
t	Index of types of disposal sites, $t \in T = \{1, \ldots, D_t\}$.
w	Index of types of hazardous wastes, $w \in W = \{1, \ldots, p_w\}$.
$R(w)$	Subset of wastes that can be recycled.
$S(i)$	Subset of possible disposal sites due to geography and political considerations.

Parameters:

A_{wi}	Amount of waste w generated at region i (in ton).
α_{wfi}	Fraction of waste w generated by firm f at region i.
β_{wr}	Efficiency of recycler type r on waste type w.
γ_{wd}	Efficiency of incinerator type d on waste type w.
$Rcap_r$	Capacity of on-site recycling type r (in ton).
$Icap_d$	Capacity of incinerator type d (in ton).
$Dcap_t$	Capacity of disposal site t (in ton).
$Ocap_r$	Capacity of off-site recycling facility of type r (in ton).
M_{ij}	Distance between the counties. $i, j \in I$ (in miles).
IC_{wd}	Cost of incineration of waste type w in incinerator type d (per ton).
DC_{wt}	Cost of disposal of waste type w at site t (per ton).
RC_{wr}	Cost of recycling of waste type w at recycling facility type r (per ton).
FR_r	Setup cost of recycling facility type r.
FI_d	Setup cost of incineration facility type d.
FD_t	Setup cost of disposal site t.
TC_{ij}	Transportation cost of waste streams from region i to j (\$/mile).
TR_{ij}	Transportation cost of waste residual from region i to j (\$/mile).

Leader's decision variables

μ_{wd}	Unit price charged by the incinerator facility d for waste type w.
ν_{wr}	Unit price charged by the off-site recycling facility r for waste type w.
τ_w	Tax charged by the Central Authority on waste type w.
yo_{wijd}	Amount of off-site recycling residual from waste w sent to incinerator d from region i to j.
o_{ir}	Number of off-site recycling facilities type r built in region i.
q_{id}	Set to one if region i has an incinerator type d.

Follower's decision variables

xn_{wifr}	Amount of on-site recycling of waste w in region i by firm f using recycling type r.
xo_{wifjr}	Amount of waste w sent from i to j by firm f to recycling type r.
y_{wifjd}	Amount of waste w sent to d type incinerator in region j from firm f in region i.
yn_{wifjd}	Amount of waste w recycling residual sent to incinerator d by firm f (region i to j).
p_{ifr}	Number of recycling facilities type r built in region i by firm f.

The Model may now be represented as an BLPP which forms the foundation for the DSS Model.

Central Authority Model (leader)

$$\begin{aligned} \text{Min} \sum_{i\in I}\sum_{f\in F}\Bigg\{ & \sum_{k\in I}\sum_{d\in D}\Bigg[\sum_{w\in W}(TC_{ik}+IC_{wd})\cdot y_{wifkd} + \sum_{w\in R(w)}(TC_{ik}+IC_{wd})\cdot yn_{wifkd}\Bigg] \\ & + \sum_{w\in R(w)}\sum_{r\in R}\sum_{j\in I}(TC_{ij}+RC_{wr})\cdot xo_{wifjr}\Bigg\} + \sum_{i\in I}\sum_{f\in F}\sum_{r\in R} FR_r\cdot p_{ifr} \end{aligned}$$

$$+\sum_{i\in I}\sum_{r\in R} FR_r\cdot o_{ir}+\sum_{i\in I}\sum_{d\in D} FI_d\cdot q_{id}+\sum_{w\in R(w)}\sum_{i\in I}\sum_{f\in F}\sum_{r\in R} RC_{wr}\cdot xn_{wifr}$$
$$+\sum_{w\in R(w)}\sum_{j\in I}\sum_{k\in I}\sum_{d\in D}(TC_{jk}+IC_{wd})\cdot yo_{wjkd}$$

subject to:

Firms' Model (follower)

$$\text{Min}\sum_{w\in R(w)}\sum_{i\in I}\sum_{f\in F}\Bigg[\sum_{r\in R} RC_{wr}\cdot xn_{wifr}+\sum_{j\in I}\sum_{d\in D}(\mu_w+\tau_w+TC_{ij})\cdot y_{wifjd}$$
$$+\sum_{j\in I}\bigg(\sum_{d\in D}(\mu_w+TC_{ij})\cdot yn_{wifjd}+(\nu_w+TC_{ij})\sum_{r\in R} xo_{wifjr}\bigg)\Bigg]+\sum_{i\in I}\sum_{f\in F}\sum_{r\in R} FR_r\cdot p_{ifr}$$

subject to:

$$\sum_{r\in R}\bigg(\sum_{w\in R(w)} xn_{wifr}-p_{ifr}\cdot Rcap_r\bigg)\leqslant 0\quad \forall i\in I,\ f\in F, \tag{1}$$

$$\sum_{w\in R(w)}\sum_{i\in I}\sum_{f\in F} xo_{wifjr}\leqslant o_{jr}\cdot Ocap_r\quad \forall j\in I,\ r\in R, \tag{2}$$

$$\sum_{i\in I}\Bigg[\sum_{w\in R(w)}\Big(yo_{wijd}+\sum_{f\in F} yn_{wifjd}\Big)+\sum_{w\in W}\sum_{f\in F} y_{wifjd}\Bigg]\leqslant q_{jd}\cdot Icap_d\quad \forall j\in I,\ d\in D, \tag{3}$$

$$\sum_{k\in I}\sum_{d\in D} yo_{wjkd}-\sum_{i\in I}\sum_{f\in F}\sum_{r\in R}\beta_{wr}\cdot xo_{wifjr}=0\quad \forall w\in R(w),\ j\in I, \tag{4}$$

$$\sum_{k\in I}\sum_{d\in D} yn_{wifkd}-\sum_{r\in R}\beta_{wr}\cdot xn_{wifr}=0\quad \forall w\in R(w),\ i\in I,\ f\in F, \tag{5}$$

$$\sum_{r\in R}\bigg(xn_{wifr}+\sum_{j\in I} xo_{wifjr}\bigg)+\sum_{k\in I}\sum_{d\in D} y_{wifkd}=\alpha_{wif}\cdot A_{wi}\quad \forall w\in R(w),\ i\in I,\ f\in F, \tag{6}$$

$$q\ \text{binary},\quad p,o\ \text{integer}. \tag{7}$$

3.2. Model complexity

The above model portrays a scenario where the Central Authority will attempt to minimize the total local and regional costs to the system. The CA will set prices that can be charged from the firms for the use of the off-site facilities as well as determine the level of taxes on the incineration of the particular waste streams. Note that the off-site facility setup and transportation costs are assumed to be borne entirely by the Central Authority. In total, the CA will be responsible for the costs of off-site recycling and incineration. Furthermore, we have assumed that the central authority will pay the average per unit cost under full capacity assumption. The firms after observing the prices and taxes set by the CA will attempt to optimize their collective location/allocation problem. It should be noted that the objective of the lower problem becomes linear since the variables μ_w, ν_w, and τ_w for $w\in R(w)$ are set by the CA. The firms don't have control over the location of the off-site facilities but can decide on the size and number of on-site recycling facilities.

Although the above model is linear in the leader's objective and bilinear in the follower's objective, the problem is still classified as an NP-hard problem. In fact, Hansen et al. [17] have shown that a linear bilevel programming problem is *strongly* NP-hard.

The data set that we are working on contains 20 waste streams (appendix contains a listing of the waste streams) partitioned into two sets: recyclable and non-recyclable with an incineration option for all types of wastes. Three sizes of incinerators and recycling facilities are made available with about 27 waste generators. Even with the deletion of the disposal option the leader has to deal with about 500 continuous and 54 discrete decision variables and the follower's problem has about 5,000 continuous and 81 discrete decision variables. Although the number of decision variables seems small for a traditional single level optimization problem, it is immense for a nonconvex optimization problem such as the above model.

Presently about a half-dozen computer codes exist for solving the linear bilevel programming problem (e.g., see [4,6,17]). To the best of our knowledge, they can handle about 100 leader variables and 100 follower variables and 50 constraints. When discrete variables are added, the manageable problem size shrinks by nearly an order of magnitude.

Although the penalty method [4] can handle a larger size

Table 1
Hazardous waste generation and capacity for ABAG counties (tons).

County	Hazardous waste generation				Treatment capacity
	1988	1989	1990	1991	
Alameda	97,502	89,599	86,400	88,282	80,520
Contra Costa	65,306	95,172	135,287	63,733	0
Marin	1,993	3,253	2,983	3,463	2,430
Napa	1,200	1,801	1,323	1,663	0
San Francisco	44,167	64,679	50,787	39,551	76,000
San Mateo	69,645	90,919	113,828	114,983	78,900
Santa Clara	92,449	83,804	95,308	111,041	68,773
Solano	14,668	25,108	38,587	32,049	0
Sonoma	7,603	8,743	36,108	8,648	0
Total	394,533	462,808	560,611	463,413	306,643

Source: Waste generation computed from summary tapes of Hazardous Waste Manifest Data from Department of Toxic Substances Control [22].

follower's problem, it's leader size is still restricted to about 100 decision variables which makes the current model too big to handle. We have therefore taken an ad hoc approach by relying on the results of the system optimization problem that will be shown to work well for the given application and accompanying data.

The basic idea in this formulation is the fact that a fixed quantity of waste is assumed and more importantly the full capacity average pricing is incorporated in the leader's problem. Furthermore, for the fixed values of μ_w, ν_w and τ_w the follower's problem reverts to a conventional mixed integer programming problem that can readily be coded and solve by GAMS and its solvers. A notable distinction between this model and the general bilevel model is the fact that some of the coefficients of the lower objective function is determined by the leader (i.e., user charge, and taxes). This characteristic may lead to a class of solutions for the bilevel programming problem that can be an aid to the policy maker.

There is no conflict between the central authority and the firms in terms of the non-recyclable wastes since they will have to be incinerated due to absence of any alternative treatment methods. Consequently, these waste streams may be deleted in the initial model and used as a post optimality test.

4. Application to the San Francisco Bay area

Our models have been implemented, for a limited set of waste streams (see appendix), using San Francisco Bay area as a case study. The nine counties of this region, which form the Association of Bay Area Governments (ABAG), account for over 25% of the waste generated in California. Table 1 shows the total offsite disposal of hazardous wastes and current treatment capacity in each county.

The current implementation focuses on incinerable wastes, due to the acute shortage of treatment capacity for them and the limited number of treatment and disposal options. The model includes:

- 20 different waste types, based on California waste codes.
- Options for waste management are on- and off-site recycling and incineration, plus two disposal options for the residuals.
- Offsite facilities in three discrete sizes.
- Capital and operating costs are given for each type and size of facility, based on an EPA studies [9,10].
- Transportation costs are based on mileage, using the distance between the centers of the counties as average distances, and a cost of $0.23/ton-mile.
- Waste generation data for each waste type in each ABAG county, computed from the 'Tanner tapes' of DTSC's Hazardous Waste Information System.
- Waste generation in each county is divided among small, medium and large firms, with the assumption that they account for 20, 30 and 50%, respectively, of the total generation of each waste type.

Conceptually, the decision support model will consider the regional hazardous waste problem and depending on the desire of the policy makers and/or the availability of the information partition the problem into centralized or decentralized planning. Many solution techniques and commercial softwares are available for the linear or the convex optimization formulations of the centralized planning. One of the basic results of this model has been the dominance of the transportation costs. Further studies is war ranted and is underway. In case of nonconvex optimization problems (i.e., presence of economies-of-scale in the objective), there are less choices and specialized programs must be developed. For more detailed description of these technique see a monograph by Horst and Tuy [19].

If it is desired to develop optimal taxing or pricing scheme, we must formulate the problem as a hierarchical model. In the case of the linear upper (i.e., CA) objective and the linear lower (i.e., firms) objective, there are half a dozen algorithms with varying degrees of success (e.g., see [4,6,17]). To the best of our knowledge, they can handle about 100 leader variables and 100 follower variables and 50 constraints. When discrete variables are added, the manageable problem size shrinks by nearly an order of magnitude.

Table 2
Results (in ton) with no off-site recycling.

	Incinerator facility	On-site recycling facilities		
		Small firms	Medium firms	Large firms
Alameda		2 × 1,000	3,000	8,000
Contra Costa		1,000	3,000	8,000
Marin		1,000	1,000	1,000
Napa		1,000	1,000	1,000
San Francisco		1,000	3,000	8,000
San Mateo		3 × 1,000	2 × 3,000	8,000
Santa Clara	170,000	3 × 1,000	2 × 3,000	8,000
Solano		1,000	3,000	3,000
Sonoma		1,000	3,000	8,000
Tax & revenue		$47.09 million		
Operating cost (per year)		42.90 million		

In case of nonlinear objectives, only a few algorithms exist (e.g., see [31]) but they can only handle small size problems. Naturally, any final analysis depends on the political and physical considerations.

5. Computational results

An optimal solution to the revised model was obtained by generating the mixed integer programming formulation, and solving the newly generated problem with the use of penalty algorithm. In contrast to the system model an off-site recycling center with a capacity of 10,000 tons was designated in region 6 (San Mateo County) with a per unit charge of $v_w = \$245.80$ for all $w \in R(w)$. The incinerator charge and tax were set at $\mu_w = \$220.92$ and $\tau_w = \$105.00$ respectively. The uniformity of these prices over the waste streams is not at all surprising given that we had to content ourselves with artificial vendor pricing for the leader's problem. We should point out that in the revised formulation we did not levy a tax on the residual from the on-site recycling facilities that we can attribute to the implicit desire of the CA to encourage on-site recycling.

Large firms in regions 1, 6 and 7 (Alemeda, San Mateo, and Santa Clara, respectively) responded by installing a large recycling facility on their sites. Not surprisingly, a 170,000 tons incinerator facility was placed in Santa Clara county.

It should be noted that even in this artificial pricing environment, a proper taxing scheme discourages the use of the incinerator facility. In fact, the use of recycling facilities increased by 38.68%.

The revenues generated by the effluent tax is about 1.88 million dollars annually and the revenues from user charges is about 45.81 million dollars annually. The total operating expense to the Central Authority is about 48.16 million dollars per year which yields a net cost of about 470,000 dollars per year to the central authority. It is interesting to note that the optimal tax rate and the user fee did not induce a unique response from the firms. In fact, the lower problem responded with an alternative solution to the leader's signal.

A further investigation was made to determine the sensitivity of this problem to changes in the regional cost. In particular, we are interested to see the effect of change in off-site recycling prices. It is interesting to note that by decreasing this price from $270.00 per ton to $265.00 per ton the optimal solution resulted in an increase in off-site recycling facility and a decrease in the on-site facility. Region 1 (Alameda) was allocated 10,000 ton off-site facility. In response to the availability of a facility in region 1, the large firm in that region finds it optimal not to build an on-site facility. The use of off-site facilities will naturally increase the cost to the central authority. In fact, the net cost to the CA will increase to about $8 million per year.

It is possible for the CA to want to encourage on-site use rather than off-site use of the recycling facilities. In order to simulate this scenario we removed the on-site recycling costs from the CA's objective and solve the resulting problem. Naturally, all the resources will put on building on-site facilities with very high tax and user charge on regional facilities. The least amount the CA can charge in order to induce the proper response is to set $\mu_w = \$951.85$, and $\tau_w = \$761.481$. Clearly, this scheme is not practical since we can increase μ or τ to an infinity large number and get the proper response. The result of this scheme is presented in table 2 as an illustration only.

There are some small changes in the prices, location and sizes of the on-site facilities but overall push for the use of recovery facilities remains the same. The influence of the incinerator prices is rather dominant in the decision process given that we have assumed that recycling and incineration are coupled together. To further analyze the problem we have attempted to decouple these processes by ignoring the residual charges.

Many smaller generators use the off-site facility as a cheaper source of recycling and in order to see the behavior of such generators and the deviation on the taxing scheme we abandoned the use of off-site recycling facility.

6. Concluding remarks

We have developed a decision support system model in order to aid policy makers in developing a sound managerial decision regarding an important issue facing many industrialized nations. This paper gives a brief history of methods developed in the area of environmental economics including recent attempts in using optimization techniques. In this paper, we have recognized the interaction between the central player and the others by developing a hierarchical model that deals with setting optimal taxing schemes. Issues such as social welfare, and cooperation with firms are also addressed.

A single level model (i.e., where the CA controls all decision variables) is implemented in GAMS, a modeling and optimization package which enables a concise algebraic description of complex mathematical programming models. The current implementation contains more than 150,000 continuous variables and 300 binary variables. Due to the size of the problem, a smaller Hierarchical model is implemented using the algorithm developed by Amouzegar and Moshirvaziri [4]. This algorithm has been coded on Matlab using the subroutines developed in [26]. Unlike linear or even integer programming problems where we are able to solve very large scale problems, bilevel models need to be scaled down due to their inherent complexities. Hence the development of a decision support system where we are more concerned with a model that can interact with a decision maker.

Appendix

This appendix presents the 20 types of waste streams used in this paper. The numbers are the California Waste Category identification numbers.

Waste group	California waste category	
Recyclable:		
Halogenated solvents	211	Halogenated solvents
	741	Liquids with halogen (Org. comp. >1000 mg/l)
Non-halogenated solvents	212	Oxygenated solvents
	213	Hydrogen solvents
	214	Unspecified solvent mixtures
Oily sludges	222	Oil/water separation sludge
Waste oil	221	Waste oil and mixed oil
	223	Unspecified oil containing waste
Non-recyclable		
Organic liquid	133	Aqueous with total organics $>10\%$
	134	Aqueous with total organics $<10\%$
	341	Organic (non-solvents) liquids with halogens
	342	Organic liquids with metal
	343	Unspecified organic liquids mixture
Halogenated organic sludges and solids	251	Still bottoms with halogenated organics
	351	Organic solids with halogens
	451	Decreasing sludge
Non-halogenated organic sludges and solids	241	Tank bottom waste
	252	Other still bottom waste
Dye and paint sludges and resins	271	Organic monomer waste
Miscellaneous wastes	331	Off-spec, aged or surplus organics

References

[1] M.A. Amouzegar and K. Moshirvaziri, Determining optimal pollution control policies: An application of bilevel programming, European Journal of Operational Research 119 (1999) 100–120.

[2] Association of Bay Area Government, The San Francisco Bay area regional hazardous waste management plan (1989).

[3] M.A. Amouzegar and S.E. Jacobsen, A decision support system for regional hazardous waste management alternatives, Journal of Applied Mathematics and Decision Sciences 2 (1998) 23–50.

[4] M.A. Amouzegar and K. Moshirvaziri, A penalty method for linear bilevel programming problems, in *Multilevel Optimization: Algorithms, Complexity and Applications*, eds. A. Migdalas, M. Pardalos and P. Värbrand (Kluwer Academic Publishers, 1997) chapter 11.

[5] J.F. Bard, Convex two level programming, Mathematical Programming 40 (1988) 15–27.

[6] J. Bard and J. Moore, A branch and bound algorithm for the bilevel programming problem, SIAM Journal on Scientific and Statistical Computing 11 (1990) 281–292.

[7] A. Brooke, D. Kendrick and A. Meerhaus, *GAMS: A User's Guide* (Boyd & Frazer).

[8] G.B. Dantzig and P. Wolfe, Decomposition principle for linear programs, Operations Research 8 (1960) 101–111.

[9] DPRA Incorporated, St. Paul, MN, Baseline and alternative waste management cost estimation for first third land disposal restriction, prepared for US EPA (1989).

[10] DPRA Incorporated, St. Paul, MN, Baseline and alternative waste management cost estimation for third third land disposal restriction, prepared for US EPA (1989).

[11] Environmental report, County torn over hazardous waste facility as North Carolina searches state for location, in: *Environment Reporter*, Vol. 21 (19 February 1991) pp. 1839–1849.

[12] M. Hobbs, EPA threaten North Carolina, San Francisco Examiner 5 May 1991 (1991) p. A9.

[13] G.W. Graves, G.B. Hatfield and A. Whinston, Water pollution control using by-pass piping, Water Resource Research 5(1) (1969) 13–47.

[14] G.W. Graves, D.E. Pingry and A. Whinston, Application of a large scale nonlinear programming problem to pollution control, in: *AFIPS* (1971).

[15] J.Y. Haimes, M.A. Kaplan and M.A. Husar, Jr., A multilevel approach to determining optimal taxation for the abatement of water pollution, Water Resource Research 8(4) (1972) 851–860.

[16] J. Hall and S.E. Jacobsen, Development of an economic analytical frame work for solid waste policy analysis, Technical report, Office of Research and Monitoring, U.S. EPA, Washington, DC (1975).

[17] P. Hansen, B. Jaumard and G. Savard, New branch and bound rules for linear bilevel programming, SIAM Journal on Scientific and Statistical Computing 13(5) (1992) 1194–1217.

[18] J.E. Hass, Optimal taxing for the abatement of water pollution, Water Resource Research 6(2) (1970) 353–365.

[19] R. Horst and H. Tuy, *Global Optimization* (Springer-Verlag, 1993).

[20] S.E. Jacobsen, *Mathematical Programming and the Computation of Optimal Taxes for Environmental Pollution Control*, Lecture Notes in Computer Science, Vol. 41 (Springer-Verlag, 1975) pp. 337–352.

[21] C.D. Kolstad, Empirical properties of economic incentives and command-and-control regulation for air pollution control, Land Economics 62(3) (1986) 250–268.

[22] R.S. Larson, Staff report, Technical report, San Francisco Bay Area Hazardous Waste Management Facility Allocation Committee (1991).

[23] L.B. Lave, Air pollution damage, in: *Environmental Quality Analysis*, eds. A. Kneese and B. Bower (The John Hopkins Press, 1973) pp. 213–244.

[24] L.B. Lave, Methods of risk assessment, in: *Quantitative Risk Assessment in Regulation*, ed. L.B. Lave (The Brooking Institution, 1982) pp. 23–54.

[25] J.C. Liebman and W.R. Lynn, The optimal allocation of stream dissolved oxygen, Water Resource Research 2(3) (1966) 581–591.

[26] K. Moshirvaziri and M.A. Amouzegar, A MATLAB linear programming tool for use in global optimization algorithms, Technical Report ENG-95-146, Optimization and Communications Systems Laboratory, Department of Electrical Engineering, University of California, Los Angeles (1995).

[27] K. Moshirvaziri, M.A. Amouzegar and S.E. Jacobsen, Test problem construction for linear bilevel programming problems, Journal of Global Optimization 8(3) (1996) 235–243.

[28] Southern California Hazardous Waste Management Authority, The Southern California Hazardous Waste Management Plan (1989).

[29] H. von Stackelberg, *The Theory of the Market Economy* (William Hodge and Company Ltd., London, 1952).

[30] State of California, Assembly Bill AB2948 (1986). This bill formed Articles 3.5 and 8.7 of the Health and Safety Code.

[31] L.N. Vicente and P.H. Calamai, Bilevel and multilevel programming: A bibliography review, Journal of Global Optimization 5(3) (1994).