Spring 4-2002

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Journal of Business & Economic Studies, Vol. 8, No. 1, 2002

A Risk/Cost Framework For Logistics Policy Evaluation: Hazardous Waste Management

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Abstract

The management of hazardous waste disposal operations is extremely complex involving a multitude of environmental, engineering, economic, social and political concerns. This article proposes a framework to assist policy makers in the evaluation of logistics policies. A spatial general equilibrium based policy evaluation model is developed to calculate risk, cost, and risk equity tradeoff curves. This framework provides policy makers a tool with which they can relate resulting logistics patterns and their associated risk, cost, and equity attributes to original policy goals.

INTRODUCTION

The management of hazardous waste disposal operations is extremely complex involving a multitude of environmental, engineering, economic, social, and political concerns. Public scrutiny over the siting and operation of hazardous waste facilities has always been a source of controversy and confrontation. As noted by Warmerdam and Jacobs (1994) it is unlikely that the hazardous waste stream will diminish significantly in the short term. In 1986 the total hazardous waste stream generated was on the order of 800 million tons (Behmanesh et al. 1992).

Even in the most simple, deterministic case, optimal logistics patterns based on minimum costs may unnecessarily expose people and the environment to risks associated with possible accidents. The movement of waste involves potential transfer of risks of damage to human health, environment, and ecology both along transportation routes and at the final disposal location; these risks result from accidents, improper handling, or disposal.

Typically, environmental policy decisions are driven by a combination of economics, political concerns, and risk calculations. As the Environmental Protection Agency has indicated that it considers the reduction of risk to be the most important goal of any environmental policy (Reilly 1991), it is reasonable to assume that environmental policy decisions should be greatly influenced by the level of risk posed by the environmental problems.

Generally, it is difficult to address and quantify the risks involved in the transportation, treatment, and disposal of hazardous waste. It would be ideal to use the actual risks; however, these are rarely known and policy makers must rely on

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the actual risks; however, these are rarely known and policy makers must rely on calculated risks or perceived risks. A risk/cost framework for the hazardous waste management system must include an assessment of the risks due to transportation, treatment, and disposal. In many cases the methodology for the assessment of risks from transport and disposal of hazardous waste are similar; although the factors differ, the overall objective is to quantify risk as an expected cost in the event of an undesired release.

Another factor which deserves significant emphasis in the development of hazardous waste logistics policy is the issue of equity. Equity is often measured by the largest impact per unit population (e.g., fatalities per thousand persons) or the difference between the largest and smallest of these.

In developing logistics policy regarding hazardous waste, we must consider the two main players in the system: the waste generators and the policy makers. Each of these stakeholders controls a different set of variables. Specifically, the government controls policy variables, i.e., the transportation restrictions, while the generators control the selection of final disposal methodologies and sites. Both the government and the generators behave according to their own objectives, i.e., social welfare and profit maximization, respectively. Policy makers face a two-part problem; they must predict the response of the generators to policy decisions and then choose among various alternatives to maximize their policy goals. Policy makers are essentially trying to answer the questions: What is the cost, risk, and risk equity associated with various policies? and, How do these levels correspond to our global environmental goals? In this vein, we need to consider potential siting of new disposal and transfer facilities in addition to determining the optimal route for wastes.

We contribute to the hazardous waste transportation literature in the development of a hazardous waste policy evaluation framework to determine the optimal transportation patterns for hazardous waste under multiple objectives. This framework will provide decision makers with a tool with which they can relate original policy goals with resultant logistics patterns.

HAZARDOUS WASTE TRANSPORTATION

The literature on the transportation of hazardous materials and the location of “obnoxious” facilities is relevant to the discussion of hazardous waste management. The hazardous waste management system can be broken down into three main components: the transportation of hazardous waste, the location of treatment and disposal facilities, and the assignment of waste to a specific disposal option. This research is focused on the assessment of the costs and risks associated with all three components. List et al. (1991) presented a comprehensive survey of the existing literature on modeling and analysis for hazardous materials transportation. The literature can be divided into three categories: routing, siting, and combined routing and siting models. In practice, it is difficult to separate siting from routing; therefore, this literature review will focus on the combined category.

Shobrys (1981) first presented a combined location-routing model for selecting routes and storage locations for spent nuclear fuel shipments. The routing part of the model is represented by a bi-objective shortest path formulation which minimizes ton-miles and population exposure. Decomposition is used to solve the problem with the siting decisions being controlled by the routing decisions. The solution yields the nondominated paths between each origin and each candidate destination.

Zografos (1987) presented a combined location-routing model for the selection of waste disposal sites and routes from origins to selected locations. A multi-criteria capacitated shortest path model was used for the routing decisions and the location problem is formulated as a maximin problem. Preemptive goal programming was used to solve a small scale test problem.

ReVelle et al. (1991) developed a multi-objective model which simultaneously chooses routes, places facilities, and clusters sources with facilities. Their model finds solutions which minimize the total ton miles and total tons past people. Paths chosen represent a compromise between shipping cost and population impact. They applied the problem to a case study of spent fuel storage and shipping. The model can be utilized for both short term (choosing among existing facilities) and long-term (to analyze national shipping policy) goals.

Zografos and Samara (1989) presented a model which considers multiple routing and siting objectives simultaneously. The objective of this model is to locate a specified number of disposal facilities so that they: (1) maximize the sum of the distances between population centers and disposal sites, (2) maximize the minimum distance between a population center and a disposal site, (3) minimize transportation risk, and (4) minimize waste travel time.

Warmerdam and Jacobs (1994) presented a linear programming model for the optimal simultaneous siting and routing of hazardous waste transport, storage, and disposal operations. Their multi-objective formulation allows tradeoffs between cost and risk.

They integrated perception of cost and risk through the introduction of fuzzy sets that represent the public's degree of acceptance toward unique policy options. Solutions to the model defined a tradeoff relationship between cost, risk, and the perception that the policy is acceptable. They used both linear and nonlinear fuzzy membership functions in the model. The model was illustrated with a case study which considered the effort by North Carolina to site a hazardous waste incinerator.

Giannikos (1998) developed a multi-objective model for locating disposal facilities and transporting hazardous waste from origins to destinations. Four objectives were considered: (1) minimize operating cost, (2) minimize total perceived disutility associated with treatment facilities. A goal programming approach was taken and the model was applied to a small test case.

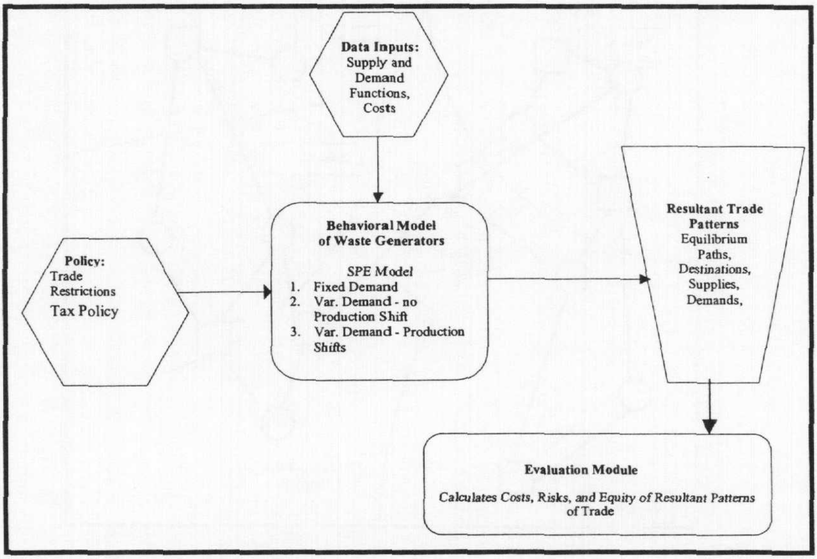
Several limitations on the scope of this research should be noted. We are interested in the assessment of risks and costs due to hazardous waste transportation, treatment and disposal; we do not consider risks and costs associated with waste generation. For the purposes of this research, risk focuses on risk to human populations. Although it is noted that ecological risks are important, these factors are considered outside the scope of this article.

POLICY EVALUATION FRAMEWORK

The impetus for our model is the need for the evaluation of policies for hazardous waste transportation. Solutions to the model allow policy makers to evaluate the effects of various transportation policies through resulting logistics patterns. This evaluation framework is broken down into two steps: (1) The behavioral model for waste generators is presented. (2) The evaluation module is presented which includes the derivation of expressions for risks and costs associated with the hazardous waste management systems.

Prior to outlining the details of each of the steps, it is helpful to provide a brief overview of the components and goals of the model. A schematic diagram of the Policy Evaluation Framework is presented in Figure 1. The policy evaluation model consists of two distinct modules or sub-models: (1) the behavioral model of the waste generators and (2) the evaluation module for the assessment of the risks and costs of each scenario. The behavioral model describes the resulting actions of the waste generators to regulatory constraints imposed by the policy-makers; solutions to the model provide routes and disposal sites for all generated hazardous waste. The evaluation module calculates the resultant costs and risks associated with the output from the behavioral model; solutions to the behavioral model are evaluated for their risks, costs and equity-tradeoff curves are derived.

Figure 1. Model 1 – Policy Evaluation Model

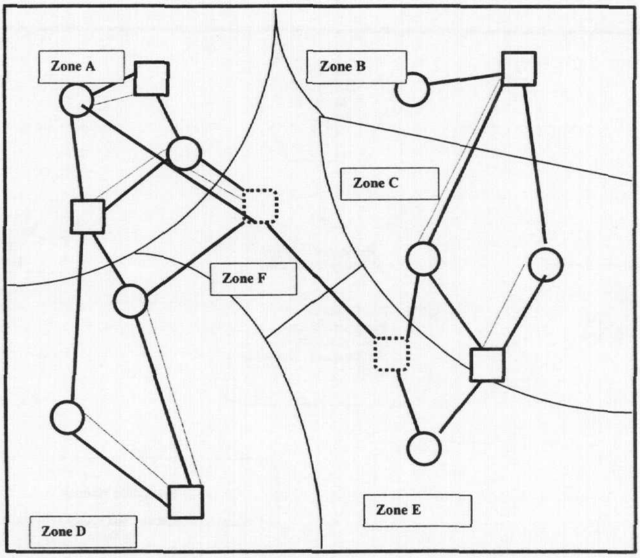


The policy evaluation model is a linear, network model of the hazardous waste management system; both network and planar measures are used to develop the objectives. Figure 2 presents a graphical representation of a hypothetical network. The multiple objectives in the model include risk minimization, cost minimization, and risk equity. Solutions to the model will produce routes and disposal sites for all generated hazardous waste; solutions will be evaluated for their risks and costs and tradeoff curves will be derived.

Model Formulation

As mentioned, the model developed in this phase consists of two parts: a behavioral model and an evaluation module. The combined model is utilized to evaluate policy scenarios and to develop cost-risk tradeoff curves for resulting logistics patterns. When used together, the two models provide a vehicle for the evaluation of policy scenarios and the development of risk-cost tradeoff curves.

Figure 2. Representative Network



For modeling purposes, costs and risks are estimated on a total as well as zonal basis. As shown in Figure 2, the study area is divided into zones; the total cost and risk exposure for each zone is a function of the routes, facilities, and transfer stations selected in each solution. One simplifying assumption in the model is that the estimate of the risk in each zone will be based upon the risk experienced at one central location in the zone. As the number of zones in the system increases, the error due to this assumption will decrease, as the computational complexity increases. Another approach which could be utilized is that the model can be run to identify potential "hot spots" for risk. These sensitive zones could then be broken down into smaller areas to fully calculate the risks to these zones. This type of approach to risk assessment allows us to evaluate the equity of risk distribution in each solution. This type of approach was used by List and Mirchandani (1991) in their combined routing and siting model for hazardous materials.

Behavioral Model

The behavioral model describes the reaction of the waste generators to transportation restrictions imposed by the policy makers. The output of this model is the resulting logistics patterns including final paths and destinations of all generated hazardous waste. In this system waste generators act independently from each other. Each generator chooses their paths and destinations based upon maximizing their utility; in this case the generators make decisions based upon minimizing their overall cost of disposal.

A network equilibrium approach is taken to model this system. The model simultaneously solves the problem of routing waste from the generator to the disposal site and assigns generators (or a portion of the waste generated) to a specific disposal facility.

As one of the issues we are attempting to model is the equity of trade patterns, or the distribution of waste throughout the system, the system of hazardous waste management has a very distinct spatial component. It is for this reason that a spatial price equilibrium model was chosen as the modeling tool for this research.

For modeling purposes, we need to view the hazardous waste management system in a unique manner. The waste generators "demand" treated waste and the waste processors "supply" treated waste. Therefore, the flows in the model are from waste processor to waste generator; flows in the "real" system will actually flow in reverse (i.e., material will flow from the generators to the treatment facilities with payments being made to the waste processors).

Treated waste is a commodity which is produced and consumed at each of several spatially separated markets. When a particular market experiences excess demand, demand greater than that which it can supply, it will seek to import quantities of treated waste from other markets. Similarly, a market with excess supply will seek to export quantities of treated waste to other markets. Importing and exporting adjustments go on until an equilibrium is reached for which the local market price is exactly equal to the price of any import, at the latter's market of origin, plus the unit cost of transportation between the two markets. To describe this situation mathematically it is first necessary to provide the following definitions:

i, j, k, l = nodes of the network
z = regions in the network (zones)
a = arcs of the network (all arcs are directed)
P_{kl} = set of available paths between node k and node l
p = a path between node k and node l $(p \in P_{kl})$
π_z = price of waste service in region z
c_p = price of transportation of treated waste on path p
D_z = demand for waste service in region z (i.e., amount of waste produced in region z)
S_z = supply of waste service in region z (i.e., quantity of waste treated in region z)

h_p = the flow of treated waste on path p
f_a = the flow of treated waste on arc a
δap = 1 if arc a is on path p (i.e., $a \in p$)
0 otherwise
fa $= \sum \delta$ ap hp
k: waste generator " demands treated waste"
l: waste processor " supplies treated waste"

With the above definitions, we may describe the equilibrium of interest in the following form:

(1) non-negativity of flows and prices
$h_p \geq 0$ ($\forall$i,j $p \in P_{ij}$)
$\pi_i \geq 0$ ($\forall$ i)

(2) equality of delivered process and local prices for nontrivial flows
$h_p > 0 \rightarrow \pi_k = \pi_l + c_p$ flow from l to k

(3) trivial flows for delivered prices which exceed local prices
$h_p = 0 \rightarrow \pi_k < \pi_l + c_p$

(4) conservation of flow at all markets
$\sum\sum h_p - \sum\sum h_p = S_l - D_l$
flow out of k flow into k

Any solution (π, h) which satisfies conditions (i)-(iv) is referred to as a spatial price equilibrium. These conditions are analyzed and discussed in greater detail in Jara-Diaz and Friesz (1982) and Tobin and Friesz (1983). As discussed in Tobin and Friesz (1983) this SPE problem can be solved using an equivalent optimization problem (EOP).

Evaluation Module

We assume that any region of interest can be divided into a set of Z non-overlapping zones on which a transportation network {N, A} can be superimposed. Each zone $z \in Z$ experiences cost and risk impacts due to (1) material and waste being shipped over nearby links and (2) wastes being processed at nearby treatment facilities.

The evaluation module calculates the risk, cost, and risk equity of trade patterns for the management of hazardous waste. The inputs to this model are the output, or resulting trade patterns, from the behavioral model described above. This module gives policy makers a tool with which they can compare the effects of resultant logistics patterns with original policy goals. Based upon the calculated risk, cost, and equity values, tradeoff curves are developed.

It is important to note the distinction between flows of hazardous waste in the system and flows of waste services. For the purposes of this research, all flows in the system are flows of waste treatment services from the treatment/disposal facility to the waste generator. The waste generator pays the treatment/disposal facility for services. In reality, this translates to an actual waste flow from the generator to the treatment/disposal facility.

The following are the outputs of the behavioral model:

x_{ij} = flow of waste services from node i to node j
D_z = demand for waste service in region z (i.e., amount of waste produced in region z)
S_z = supply of waste service in region z (i.e., quantity of waste treated in region z)
π_z = price of waste service in region z

Cost

CD_z = Cost for disposal and transportation in each region
$CD_z = D_z * \pi_z$
TCD_z = Total cost of disposal and transportation

$$TCD_z = \sum_z CD_z$$

Revenue

RV_z = Revenue from supply of waste disposal services in each region
$RV_z = S_z * \pi_z$
TRV_z = Total revenue from supply of waste disposal services

Risk

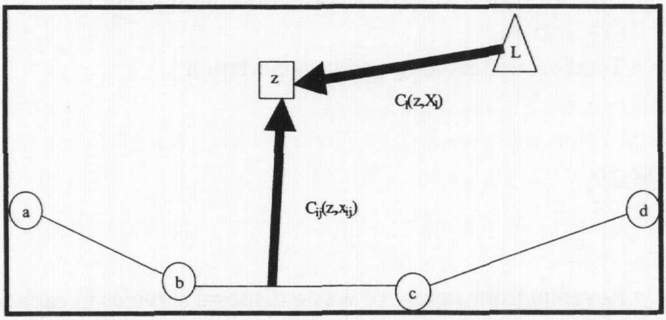
$$TRV_z = \sum_z RV_z$$

Risk assessment involves estimating the frequencies and consequences of undesirable events and then evaluating the associated risk in quantitative terms. As noted above, each zone z ∈ Z experiences cost and risk impacts due to: (1) material and waste being shipped over nearby links and (2) wastes being processed at nearby treatment facilities.

Each arc has associated with it a function $c_{ij}(z, x_{ij})$ which computes the per person impacts for each zone given shipment volume x_{ij} passing over arc ij. Abkowitz and Cheng (1988) presented an impact model for gas dispersion which illustrates this idea. Similarly, each treatment site is associated with a function $c_l(z, X_l)$ which computes the per-person impacts on zone z from volume X_l of waste processed at location l.

For each zone, combining the impact distributions for all arcs and treatment locations, generates a cumulative impact distribution (see Figure 3). This can then be translated into the risk perceived by the people living in zone z. We can define a function $RISK(c_{ij}(z, x_{ij}), c_l(z, X_l))$, which creates a scalar risk measure, such as a (dis)utility function, from the fatality, and injury projections provided by the individual impact components. As the derivation of such a function is extremely data intensive, we will use the per-person impacts (i.e., $c_{ij}(z, x_{ij})$ and $c_l(z, X_l)$) as surrogates for risk. The development of these risk functions is left for future research. The chain of relationships involved is shown further on in Figure 4.

Figure 3. Schematic to indicate effects (bold arrows) of an incident on link segment s due to transporting volume x_{ij} from node b to node c, and from treating volume X_l at site L.



Transportation Risk

TR_{ijz} = per person transportation impact in region z from material transported on arc ij

$$TR_{ijz} = x_{ij} * LEN_{ij} * (DIST_{ijz})^{-2} ARR_{ij}$$

Where:

LEN_{ij} = length of arc ij

$DIST_{ij}$ = distance from arc ij to region z

ARR_{ij} = accident release rate for arc ij

Note: The per-person impact is inversely proportional to the square of the distance between the arc and the region of consideration and proportional to the volume of material transported over the arc. The square of distance was chosen to reflect the fact that as the distance between bodies increases the relative impact they have on eachother decreases at an increasing rate (e.g.,gravitational pull).

TTR_z = total per person transportation risk in region z

$$TTR_z = \sum_i \sum_j TR_{ijz}$$

$TOTTR_z$= total transportation risk in region z

$TOTTR_z = TTR_z * POP_z$

Where:

POP_z = population in region z

Disposal Risk

DR_{kl} = per person disposal risk in region l from material treated in region k

$DR_{kl} = S_k * (RDIST_{kl})^{-2} * TRTYPE_k * DRR_k$

Where:

$TRTYPE_k$= treatment technology in region k

$RDIST_{kl}$ = distance from region k to region l

DRR_k = accident release rate for region k

TDR_l = total per person disposal risk in region l

$$TDR_l = \sum_k DR_{kl}$$

$TOTDR_l$ = total disposal risk in region l

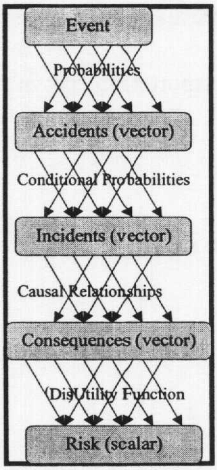
$TOTDR_l = TDR_l * POP_l$

Total Risk

$TOTRISK_z$ = Total risk in region z from resultant trade pattern - weighted sum of transportation and disposal risk

$TOTRISK_z = w_{tr} TOTTR_z + w_{dp} TOTDR_z$

Figure 4. Serial relationship among incidents, accidents, consequences and risk



Equity

In the past two decades, society has become increasingly conscious that the waste products of its advanced technology can pose danger to the health of citizens and to the viability of the ecosystem on which all depend. This concern has given rise to a number of salient policy issues centering on how to best minimize those dangers in efficient and equitable ways. An increased number of hazardous materials routing and siting models include risk equity as a factor (Goplan et al. 1990, Morell 1985, Jin et al. 1996). In addition to its place as a modeling objective, there is a large literature in risk and cost equity in many sociology, political, and geography journals (Carnes 1986, Chase 1993, Lazarus 1993, Anderton et al. 1994). There are numerous methods to characterize risk equity-minimizing the maximum per-person risk in a region-minimizing the difference between the minimum and maximum regional risks-minimizing the differences in relative risk among regions. We use relative risk to characterize the risk equity of resultant patterns of trade:

$$RELRISK_{kl} = |(TOTRISK_k - TOTRISK_l)|/TOTRISK_k$$

Conclusion

We have developed a framework through which policy makers can evaluate proposed hazardous waste management policies. Our framework models the resultant logistics patterns for a proposed policy; this is combined with an overall risk-cost tradeoff analysis to assist decision makers in the determination of appropriate policy decisions. This framework marks a significant improvement over the current practice of post hoc analysis. We take into account the varied interests of the multiple stakeholders involved in the development and implementation of a policy regarding the transboundary movement of hazardous waste as well as considering the multiple objectives of cost, risk, and equity.

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