Combined Location-Routing Model for Hazardous Waste Transportation and Disposal

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Complementary to the hazardous waste routing problem is the problem of where to locate hazardous waste disposal and treatment facilities. However, the literature lacks combined location and routing models for hazardous waste transportation and disposal. An alternative way to study the hazardous waste transportation and disposal problem is presented herein by considering simultaneously the following location and routing criteria: (a) minimize disposal risk, (b) minimize routing risk, and (c) minimize travel time. A hypothetical example is used to illustrate the applicability of the model. The proposed model can be used by hazardous waste management agencies for planning and policy evaluation.

In recent years, the transportation of hazardous waste from generation sites to disposal or treatment sites has drawn considerable public attention. This heightened public concern stems from the catastrophic damages associated with the accidental release of hazardous waste.

Accidents involving hazardous waste may occur during the transportation, as well as disposal of these materials. Hazardous waste transportation accidents impact negatively on people and properties located along the routes used for transport, while accidents occurring during their disposal or treatment impact negatively on people and properties located in the vicinity of the disposal or treatment facilities.

An effective method of reducing the hazardous waste transportation risk is to select the safest possible routes connecting hazardous waste generation and disposal sites, or select routes that pass through sparsely populated areas. The risk of hazardous waste disposal can be reduced by locating hazardous waste disposal and treatment facilities in areas where the fewest number of people would be potentially exposed to hazardous waste release.

The location of hazardous waste disposal and treatment facilities affects the route selection for transporting the waste and, consequently, affects the hazardous waste transportation and disposal risk. Although there is an interaction between the hazardous waste route selection and the selection of hazardous waste disposal and treatment sites, most of the existing models focus on only one of the two aspects of the problem. Independent consideration of the routing and location aspects of the hazardous waste transportation and disposal problem may lead to inefficient solutions. However, models must be developed that are capable of simultaneously considering both location and routing criteria.

This paper is intended to develop a multicriteria location-routing model for improving the decision making framework of hazardous waste transportation and disposal. The remainder of this paper will present (a) previous related research, (b) the proposed multicriteria location-routing model for hazardous transportation and disposal, (c) an application of the proposed model to hypothetical transportation network, and (d) the conclusions of this research.

LITERATURE REVIEW

Routing hazardous materials has been considered by many researchers to be a potential risk-reduction mechanism (*1–7*). As a result, several hazardous materials routing models exist in the literature. These models can be classified into either single-criterion or multiple-criteria (or multicriteria) routing models. Single-criterion models use only one criterion at a time to select routes for transporting hazardous materials.

Examples of routing criteria used in single-criterion hazardous materials transportation studies include population at risk (*3*), community safety index (*5*), truck operating cost (*4*), accident likelihood (*4*), risk exposure (*4*), length of the shipment (*6*), and population exposure (*6*). The major drawback of the single-criterion models is their inability to identify trade-offs between conflicting criteria (*8, 9*). Thus, a route that minimizes the length of the shipment may not necessarily minimize the population exposed to the hazardous materials shipments, or a route that minimizes the accident likelihood may not coincide with a route that minimizes the truck operating cost.

Multicriteria models, which include more than one routing criterion at a time, have been recommended as a more realistic approach to modeling the route selection of hazardous materials shipments. The main advantage of the multicriteria hazardous materials routing models is their ability to examine trade-offs among conflicting routing criteria.

By definition, the solution of a multicriteria model does not generate a single, optimal route but, rather, generates several efficient routes. A route is efficient if its performance in terms of one criterion cannot be improved without degrading its performance in terms of another criterion.

Several multicriteria routing studies have appeared in the literature; these studies consider various routing criteria and solution techniques. Robbins (*6*) introduced a routing model that considers, simultaneously, the length of the shipment and the population brought into contact as routing criteria.

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Zografos and Davis (*10*) developed a multicriteria model that accounts for population risk, travel time, and property damage. Abkowitz and Cheng (*1*) presented a risk/cost formulation for routing truck movements. Finally, Turnquist (*9*) considered the problem of routing hazardous materials with multiple criteria and curfew restrictions.

Location of Disposal and Treatment Facilities

The main idea behind obnoxious facility location decisions is to minimize the number of people impacted by the operation of these facilities. The *maxi-sum* (*11*), *maxi-min* (*12, 13*), and *anticovering* (*14*) problems have been used to locate obnoxious facilities, including hazardous waste disposal and treatment facilities.

Maxi-sum locates a given number of undesirable facilities so as to maximize the sum of the weighted distances between population centers and their nearest obnoxious facility. Maxi-min locates a given number of undesirable facilities in such a way as to maximize the minimum distance between the obnoxious facilities and the nearest population center. Anticovering defines the maximum number of obnoxious facilities and their location so that no population center is located closer than a minimum safety distance from its nearest obnoxious facility.

These models are targeted to reduce the risk associated with the presence of obnoxious facilities in an area; however, they do not consider the effect of the location of the obnoxious facility on the hazardous waste transportation risk. Therefore, these models are not suitable for use in locating hazardous waste disposal facilities. An alternative approach would be to consider the interaction between the disposal and routing risks. The next section presents a combined location-routing model that considers this interaction.

COMBINED LOCATION-ROUTING MODEL

The proposed combined location-routing (CLR) model examines trade-offs between (a) hazardous waste transportation and disposal risks and (b) routing risk and travel time. Three objectives are used to formulate the proposed model: (a) minimization of transportation risk, (b) minimization of travel time, and (c) minimization of disposal risk.

The transportation risk is defined as follows: The product of the probability of a hazardous waste accident to occur, times the consequence of that accident (*3*). The risk associated with the links of the transportation network is the outcome of a risk estimation process and is an input of the proposed model. The travel time associated with the links of the transportation network is also an input of the proposed model and is given for every link of the transportation network.

The total distance between population centers and disposal sites is used as a surrogate measure of the risk imposed by the disposal of hazardous wastes. The greater the total distance, the lower the risk imposed to the neighboring population.

The maximization of the total distance between population centers and hazardous waste disposal sites (i.e., maxi-sum) was used to locate general obnoxious facilities (*12*). However, the maxi-sum criterion is not the only criterion governing the location of disposal facilities. Several additional criteria (geologic, physiographic, hydrologic, and climatologic) must be used in the initial screening of potential sites for locating disposal facilities (*15*). Thus, the maxi-sum criterion is used in the CLR model to select from a set of suitable hazardous waste disposal sites—the sites that maximize the total distance between them and the neighboring population centers.

The proposed model for hazardous waste transportation and disposal can be stated as follows: Given a set of candidate hazardous waste disposal sites, select a predetermined number of sites so as to (a) maximize the total distance between population centers and disposal facilities, (b) minimize the transportation risk, and (c) minimize the travel time.

The mathematical formulation of the CLR model is presented in the following sections.

Mathematical Expression of the CLR Model

The mathematical formulation of the CLR model is based on the following assumptions:

1. The transportation network, the origin of hazardous waste shipments, and the location of candidate disposal sites are given.
2. The supply of hazardous waste at each generation site must be disposed of entirely.
3. Assignment of supply to disposal sites could be partial (i.e., the hazardous waste of the *i*th generation site can be assigned to one or more open disposal facilities).
4. The risk associated with the links of the transportation network is given.
5. The travel time associated with the links of the transportation network is given.
6. The Euclidean distance between population centers and candidate disposal sites is considered as the separation measure for the part of the model concerning the location of disposal facilities.
7. An upper capacity limit exists for the links of the transportation network.

The CLR model requires the optimization of three, sometimes conflicting, objectives. Therefore, a multi-objective programming technique should be used for the mathematical formulation of the proposed model. Goal programming is a technique frequently used to solve multi-objective decision making problems. In goal programming, each objective is expressed as an inequality or equality constraint. The right-hand side of each constraint represents the desired attainment level of the objective. Each constraint is assigned a deviational variable that measures the underattainment of the objective. The objective of the goal programming method is to find the solution that minimizes the sum of the deviations over all the stated objectives (*16*).

The goal programming formulation of the CLR model can be written as follows:

$$\text{Min } F = P_1 d_1^- + P_2 d_2^+ + P_3 d_3^+ \qquad (1)$$

Subject to

$$\left(\sum_{i \in N} \sum_{j \in C^*} S_{ij} Y_{ij} \right) + d_1^- \geq S \qquad (2)$$

$$\left[\sum\sum_{(i,j)\varepsilon N}(X_{ij}\,R_{ij}) + \sum\sum_{(i,j)\varepsilon N}(X_{ij}\,W_j)\right] - d_2^+ \le R \tag{3}$$

$$\left(\sum\sum_{(i,j)\varepsilon N} X_{ij}\,t_{ij}\right) - d_3^+ \le T \qquad \forall\, i, j \tag{4}$$

$$\left[\sum_{K\varepsilon C^*} S_{ik}\,Y_{ik}\right] + (M - S_{ij})\,Y_{ij} \le M \qquad i\ \varepsilon\ N \qquad j\ \varepsilon\ C^* \tag{5}$$

$$\sum_{j\varepsilon C^*} Y_{ij} = 1 \qquad \forall\, i\ \varepsilon\ N \tag{6}$$

$$\sum_{j\varepsilon C^*} Y_{jj} = m \tag{7}$$

$$Y_{jj} \ge Y_{ij} \qquad \forall\, \mathrm{i}\ \varepsilon\ N \qquad \forall\, j\ \varepsilon\ C^* \tag{8}$$

$$\left[\sum_{i\varepsilon Sk} X_{ki} - \sum_{i\varepsilon Nk} X_{ik}\right] = d_k\ k\ K^* \tag{9}$$

$$\left[\sum_{i\varepsilon Sk} X_{ik} - \sum_{i\varepsilon Nk} X_{ki}\right] = O\ K\,\{N - C^* - K^*\} \tag{10}$$

$$\left[\sum_{i\varepsilon Nk} X_{ik} - \sum_{i\varepsilon Sk} X_{ki}\right] \le C_k\,Y_{kk}\ k\ C^* \tag{11}$$

$$X_{ij} \le U_{ij} \qquad \forall\, i\ \varepsilon\ N \qquad \forall\, j\ \varepsilon\ C^* \tag{12}$$

Where

C_k = allowable capacity at node k;
C^* = the set of candidate disposal sites;
d_1^- = deviational variable for the first objective;
d_2^+ = deviational variable for the second objective;
d_3^+ = deviational variable for the third objective;
K^* = the set of source nodes;
m = the number of disposal sites to be located;
M = a very large number (larger than the maximum distance between any two nodes on the given network);
N = the set of nodes in the network;
N_k = $\{i/\text{arc } (i, k) \text{ defined}\}$;
P_1 = priority factor for the first objective;
P_2 = priority factor for the second objective;
P_3 = priority factor for the third objective;
R = attainment level for the second objective (i.e., maximum permissible transportation risk);
R_{ij} = weight of link (i, j) representing the link risk factor;
S_{ij} = Euclidean distance between every note (i) and each candidate disposal site (j);
S_k = $\{i/\text{arc } (k, i) \text{ exists}\}$;
S = attainment level for the first objective (i.e., minimum allowable total distance between population centers and disposal sites);
T = attainment level for the fourth objective (i.e., maximum permissible travel time);
t_{ij} = travel time along link (i, j);
U_{ij} = maximum allowable flow on link (i, j);
W_j = node weight representing the amount of risk associated with node (j) (a high weight is attached to those nodes ranked first in importance);
X_{ij} = amount of flow along link (i, j); and
Y_{ij} = 1 if node (i) is assigned to node (j), 0 otherwise.

Equation 1 expresses the minimization of the deviation from the established attainment levels S, R, T. Inequalities 2 through 4 are the constraints that correspond to the three objectives of the CLR model. Inequality 5 requires each population center (i) to be assigned to its nearest open disposal facility. Equation 6 ensures that each population center (i) is fully assigned to only one disposal facility (i). Equation 7 requires that exactly m hazardous waste disposal facilities should be located. Inequality 8 restricts the assignment of population centers to open hazardous waste disposal facilities only. Constraints 9 through 11 express the flow conservation along the network, while Inequality 12 expresses the capacity limitation of the network links.

Sample Application of the CLR Model

A hypothetical problem involving the location of hazardous waste disposal facilities and the routing of hazardous waste from given generation sites to those facilities is used to illustrate the applicability of the CLR model. The transportation network of the study area is presented in Figure 1. Nodes 1, 9, and 10 of the network represent hazardous waste generation sites; while Nodes 3, 5, 6, and 15 represent candidate hazardous waste disposal sites.

The number of hazardous waste shipments available at each generation site, the capacity of the candidate disposal facilities, and the risk associated with the network nodes, are inputs of the CLR model and are given in Table 1.

The Euclidean distance (S_{ij}) between each population center (i) and each candidate disposal facility site (j) is given in Table 2. The risk, the travel time, and the capacity limits associated with the links of the hypothetical network are presented in Table 3.

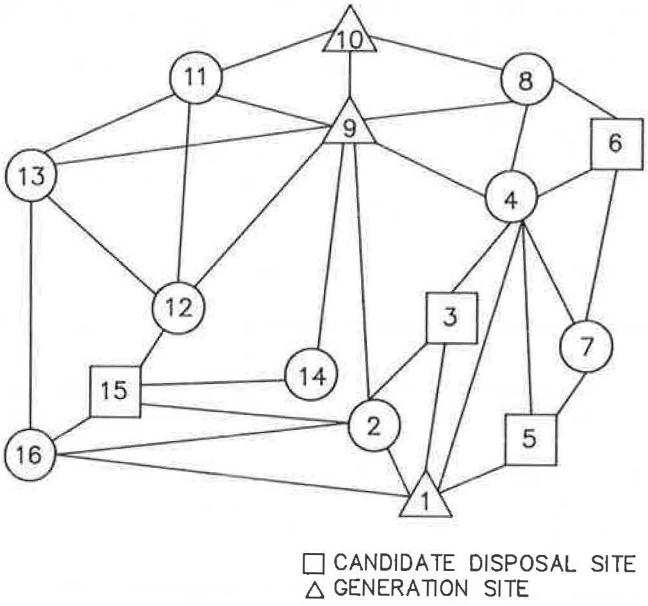

FIGURE 1 The hypothetical network.

TABLE 1 NODE CHARACTERISTICS OF THE HYPOTHETICAL NETWORK

NODE #	RISK $(X10^{-7})$	H.W. SUPPLY	CAPACITY	NODE #	RISK $(X10^{-7})$	H.W. SUPPLY	CAPACITY
1*	10.0	14.0	---	9*	20.0	12.0	---
2	8.0	---	---	10*	5.0	8.0	---
3**	10.0	---	50	11	5.0	---	---
4	19.2	---	---	12	8.0	---	---
5**	6.0	---	50	13	12.0	---	---
6**	5.0	---	50	14	2.0	---	---
7	3.0	---	---	15**	2.0	---	50
8	6.0	---	---	16	5.0	---	---

(*) Hazardous Waste Generation Sites
(**) Candidate Hazardous Waste Disposal Sites

TABLE 2 EUCLIDEAN DISTANCES BETWEEN EVERY NODE AND EACH CANDIDATE DISPOSAL SITE (CDS)

j i	CDS #3	CDS #5	CDS #6	CDS #15	j i	CDS #3	CDS #5	CDS #6	CDS #15
1	12.53	14.87	28.32	9.22	9	9.00	17.00	15.03	19.11
2	7.81*	13.00	24.41	8.06	10	14.00	21.54	16.16	23.02
3	0.00	10.00*	17.00	13.93	11	17.03	26.87	26.48	18.11
4	10.77	10.20	6.40	24.70	12	12.37	21.93	27.46	8.06
5	10.00	0.00	15.65	21.02	13	20.59	30.53	33.06	15.81
6	17.00	15.65	0.00	30.87	14	8.00	17.09	24.35	7.07*
7	18.44	10.20	12.37	31.02	15	13.93	21.02	30.87	0.00
8	17.70	19.42	5.83*	30.81	16	20.59	26.31	37.59	7.07*

The CLR model (Equations 1 through 12) was used for the mathematical formulation of the hypothetical problem under consideration. The Sperry UNIVAC/FMPS mixed-integer programming code was used to solve the problem.

An iterative procedure was used to solve the problem. At the first step of this procedure, the right-hand side values *S*, *R*, *T* of Equations 2 through 4 were calculated. These values indicate the desired goal attainment levels for the maxi-sum, minimum routing risk, and minimum travel time objectives, respectively. The values of *S*, *R*, *T*, were calculated by considering separately the three optimization problems corresponding to the three objectives of the problem.

At the second step of the solution procedure, several alternative scenarios were examined by changing the goal-attainment values and the priority for the attainment of the objectives. Table 4 describes the priority structure and the goal-attainment levels for the examined scenarios. In Scenarios 1 through 3 the goal-attainment values for *S*, *R*, *T* are the optimum values calculated in the first stage of the solution process. The priority structure for the attainment of the goals for Scenarios 1 through 3 is given in Table 4. In Scenarios 4 through 8 the priority structure indicates that the first objective has greater attainment priority than the second and that the second objective has greater attainment priority than the third.

Scenarios 4 through 8 were generated by reducing the attainment level of the first objective by an increment of 10 percent for each scenario. Thus, the value of *S* in Scenario 4

TABLE 3 LINK CHARACTERISTICS OF THE HYPOTHETICAL NETWORK

LINK	TRAVEL TIME (MIN)	LINK RISK $X(10^{-7})$	LINK CAPACITY
1-2	18.0	11.12	7
1-3	54.0	13.50	7
1-4	36.0	4.43	15
1-5	22.0	16.17	7
1-16	29.0	12.10	7
2-3	11.0	16.24	7
2-9	36.0	37.60	15
2-15	36.0	2.67	15
2-16	33.0	11.34	15
3-4	18.0	3.30	15
4-5	18.0	2.95	15
4-6	11.0	3.05	7
4-7	18.0	5.65	15
4-8	18.0	5.49	15
4-9	32.0	4.64	15
5-7	29.0	3.43	15
6-7	29.0	5.49	15
6-8	11.0	4.43	15
8-9	25.0	17.93	7
8-10	25.0	2.98	15
9-10	18.0	16.77	7
9-11	50.0	7.56	7
9-12	36.0	4.80	15
9-13	36.0	5.35	15
9-14	29.0	19.20	15
10-11	29.0	3.33	7
11-12	21.0	1.93	15
11-13	31.0	3.80	15
12-13	36.0	18.27	15
12-15	21.0	4.50	15
13-16	36.0	6.20	15
14-15	29.0	2.99	15
15-16	18.0	3.74	15

TABLE 4 PRIORITY STRUCTURE AND GOAL-ATTAINMENT LEVELS FOR ALTERNATIVE SCENARIOS

Objective	SCENARIO NUMBER							
	1	2	3	4	5	6	7	8
Maxi-Sum	P_1^1 (*) S=234.87	P_1^2 S=234.87	P_1^2 S=234.87	P_1^1 S=211.38	P_1^1 S=187.90	P_1^1 S=164.41	P_1^1 S=140.92	P_1^1 S=117.43
Minimum Routing Risk (10^{-7})	P_2^2 R=705.29	P_2^1 R=705.29	P_2^3 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29	P_2^2 R=705.29
Minimum Travel Time (VEH-MIN)	P_3^3 T=1273	P_3^3 T=1273	P_3^1 T=1273	P_3^3 T=1273	P_3^3 T=1273	P_3^3 T=1273	P_3^3 T=1273	P_3^3 T=1273

(*) P_1^1: Superscripts Indicate Goal Attainment Priorities.

is 10 percent less than the value of S in Scenario 3; while the value of S in Scenario 8 is 40 percent less than the value of S in Scenario 3.

The results of the solution of the hypothetical problem are presented in Tables 5 and 6. Table 5 presents the location and routing results for all the examined scenarios. For each scenario, Table 5 shows (a) the location of the disposal sites, (b) the population centers impacted by the selected disposal sites, and (c) the routes over which the waste should be transported. Table 6 gives the values of the deviational variables d_1^-, d_2^+, d_3^+ from the stated attainment levels for each of the eight examined scenarios. These deviations indicate the degree of underattainment for each of the problem objectives.

Table 6 shows the trade-offs existing among the maxi-sum, minimum routing risk, and minimum travel time objectives.

In Scenario 1, the first objective had the highest attainment priority. Thus, the value of the deviational variable d_1^- in this scenario is equal to zero. This means that the maxi-sum objective is fully attained, while the routing risk and the travel time objectives were underattained. In Scenario 2, the highest priority was assigned to the routing risk. Thus, the routing risk objective is achieved at the expense of the location risk and travel time objectives. In Scenario 3, the highest priority was assigned to the travel time objective. Therefore, the minimum travel time objective was achieved at the expense of routing risk. Note here, that the maxi-sum objective was achieved in this scenario, this means that the travel time and the maxi-sum objectives are not in conflict and that they can be achieved simultaneously.

The trade-offs among the three objectives can be studied by using the value path method (*16*) presented in Figure 2. In this figure, the vertical axis measures the percent deviation from the optimum value of each of the three problem objectives. Each scenario is represented by a line (value path) connecting the percent deviation of each objective. Thus, a value path shows the impact of a single routing alternative on each of the three model objectives. The measure of effectiveness of each alternative is the percentage deviation from the optimum goal level. The lower the percentage deviation for an objective, the higher the effectiveness of the routing scenario is with respect to this objective. A decision maker can use the value path method to (a) make quick comparisons among the examined scenarios and (b) reject the solutions that degrade one of the objectives without improving at least one of the other two objectives. The application of the value path method in the hypothetical example indicates that Scenarios 7 and 8 are inferior to Scenario 2 because both Scenarios 7 and 8 provide a higher deviation of the maxi-min objective than does Scenario 2, while they do not yield a lower deviation for the other two objectives (i.e., routing risk and travel time).

CONCLUSIONS

A CLR model for hazardous waste transportation and disposal was developed. The model determines the location of hazardous waste disposal facilities and the routes from given

TABLE 5 SUMMARY OF RESULTS FOR ALL THE EXAMINED SCENARIOS

SCENARIO NUMBER	1		2		3		4		5		6		7		8	
DISPOSAL SITES SELECTED	5	6	6	15	5	6	5	6	5	6	3	15	6	15	6	15
NODES LYING IN THE CATCHMENT AREA OF THE SELECTED DISPOSAL SITES	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	4 5 6 7 8 9 10	1 2 3 11 12 13 14 15 16	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	1 2 3 5 7 12 13 14 15 16	4 6 8 9 10 11	2 3 4 5 6 7 8 9 10 11	1 12 13 14 15 16	4 5 6 7 8 9 10	1 2 3 11 12 13 14 15 16	4 5 6 7 8 9 10	1 2 3 11 12 13 14 15 16
ROUTES SELECTED | FLOW UNITS	1-4/7 1-5/7 4-5/12 4-6/7 8-6/8 9-4/12 10-8/8		1-2/7 1-16/7 2-15/7 8-6/8 9-12/12 10-8/8 12-15/12 16-15/7		1-4/7 1-5/7 4-5/5 4-6/7 8-6/15 9-4/5 9-8/7 10-8/8		1-4/7 1-5/7 4-5/12 4-6/7 8-6/8 9-4/12 10-8/8		1-4/7 1-5/7 4-5/12 4-6/7 8-6/8 9-4/12 10-8/8		1-3/7 1-16/7 4-3/1 8-4/1 9-12/8 9-14/4 10-8/1 10-11/7 11-12/7 12-15/15 14-15/4 16-15/7		1-2/7 1-16/7 2-15/7 8-6/8 9-12/12 10-8/8 12-15/12 16-15/7		1-2/7 1-16/7 2-15/7 8-6/8 9-12/12 10-8/8 12-15/12 16-15/7	

TABLE 6 VALUES OF THE DEVIATIONAL VARIABLES FOR ALL EXAMINED SCENARIOS

Deviation	SCENARIO NUMBER							
	1	2	3	4	5	6	7	8
d_1^-	0.00	76.06	0.00	0.00	0.00	0.00	0.00	0.00
$d_2^+ \times 10^{-7}$	212.42	0.00	216.41	212.42	212.42	28.54	0.00	0.00
d_3^+	98.00	406.00	0.00	98.00	98.00	406.00	406.00	406.00

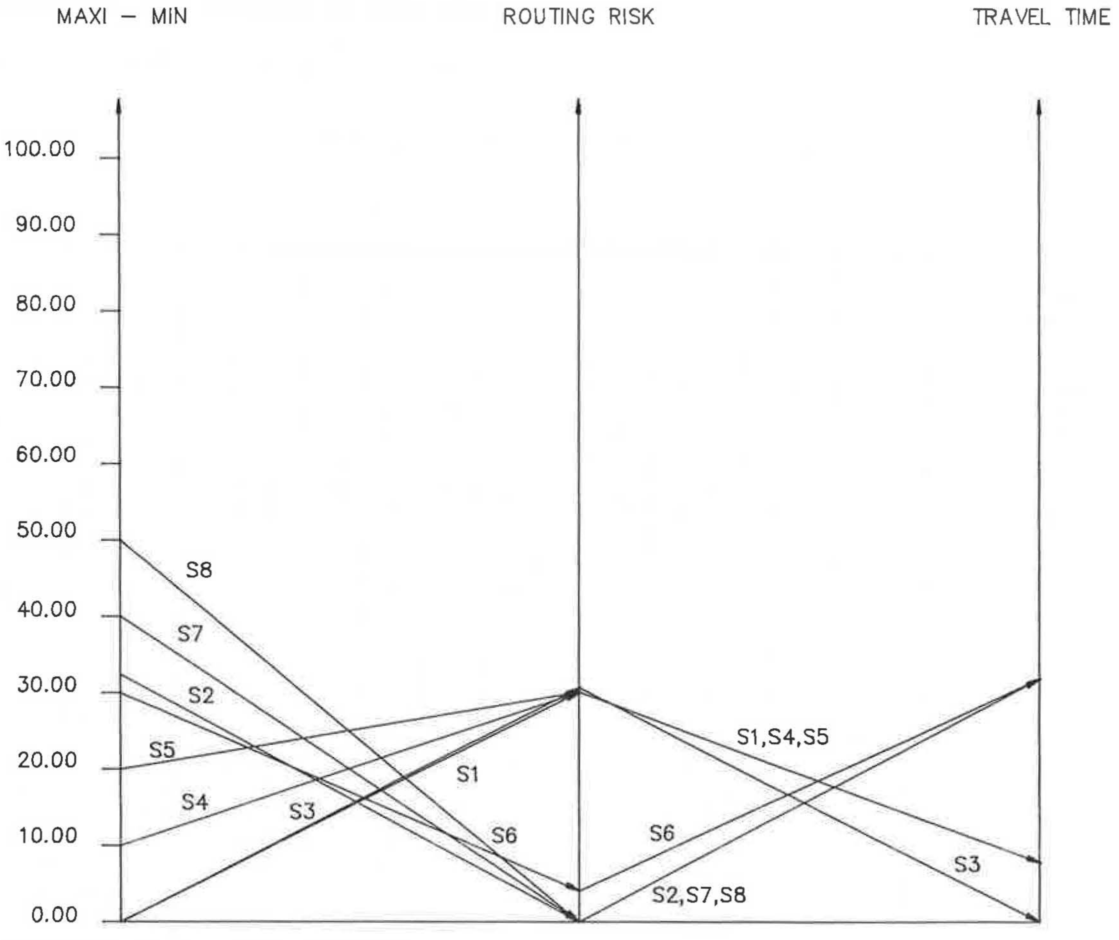

FIGURE 2 Value paths for all the examined scenarios.

hazardous waste generation sites to the selected disposal facilities. Alternative scenarios for locating disposal facilities and routing waste shipments to them can be examined by changing the priority structure and the goal-attainment levels of the problem. Trade-offs among location-risk, routing cost, and travel time also can be examined. The proposed model can be used by hazardous waste management agencies for planning and policy evaluation.

Although the proposed model establishes a good theoretical basis for the study of the CLR problem, more work is needed in addressing some of the practical considerations related to the application of the model to real world large-scale hazardous waste transportation and disposal problems. Suggestions for further research include issues related to (a) collecting the data needed to calculate the routing risk, and (b) examining the uncertainty associated with the parameters of the transportation network used to transport hazardous wastes.

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REFERENCES

1. M. Abkowitz and P. Cheng. Developing a Risk/Cost Framework for Routing Truck Movements of Hazardous Materials. *Accident Analysis and Prevention*, Vol. 20, No. 1, 1988, pp. 39–51.
2. E. J. Barber and L. K. Hildebrand. *Guidelines for Applying Criteria to Designate Routes for Transporting Hazardous Materials*. Report FHWA-IP-80-15. FHWA, U.S. Department of Transportation, 1980.
3. D. Pijawka, S. Foote, and A. Soeslo. Risk Assessment of Transporting Hazardous Material: Route Analysis and Hazardous Management. In *Transportation Research Record 1020*, TRB, National Research Council, Washington, D.C., 1985, pp. 1–6.
4. F. F. Saccomano and A. Y. W. Chan. An Economic Evaluation of Routing Strategies for Hazardous Road Shipments. In *Transportation Research Record 1020*, TRB, National Research Council, Washington, D.C., 1985, pp. 12–18.
5. R. Scanlon and E. J. Cantilli. Assessing the Risk and Safety in the Transportation of Hazardous Materials. In *Transportation Research Record 1020*, TRB, National Research Council, Washington, D.C., 1985, pp. 6–11.
6. J. Robbins. *Routing Hazardous Materials Shipments*. Ph.D. Dissertation. Indiana University, Bloomington, 1981.
7. T. Glickman. Rerouting Railroad Shipments of Hazardous Materials to Avoid Populated Areas. *Accident Analysis and Prevention*, Vol. 14, 1983, pp. 329–335.
8. K. G. Zografos. Modeling the Process of Hazardous Waste Transportation. *ORSA/TIMS Bulletin*, Vol. 22, 1986, p. 222.
9. M. A. Turnquist. Routing and Scheduling Hazardous Materials Shipments with Multiple Objectives and Curfew Restrictions. *ORSA/TIMS Bulletin*, Vol. 24, 1987, p. 130.
10. K. G. Zografos and C. F. Davis. A Multiobjective Programming Approach for Routing Hazardous Materials. *Journal of Transportation Engineering, ASCE*, Vol. 115, No. 6, Nov. 1989, pp. 661–673.
11. R. M. Church and R. S. Garfinkel. Locating an Obnoxious Facility on a Network. *Transportation Science*, Vol. 12, 1978, pp. 107–118.
12. Z. Drezner and G. Wesolowski. Location of Multiple Obnoxious Facilities. *Transportation Science*, Vol. 19, 1985, pp. 193–202.
13. E. Melachrinoudis and T. P. Cullinane. Locating an Undesirable Facility within a Geographical Region Using the Maximin Criterion. *J. of Reg. Sci.*, Vol. 25, 1985, pp. 115–127.
14. D. Moon and S. C. Choudhry. An Analysis of Network Location Problems with Distance Constraints. *Management Science*, Vol. 30, 1984, pp. 290–307.
15. G. Dawson and B. Mercer. *Hazardous Waste Management*. John Wiley & Sons, New York, 1985.
16. J. L. Cohon. *Multiobjective Programming and Planning*. Academic Press, New York, 1978.