Interactive Modeling for Multiobjective Scheduling and Routing of Radioactive Waste Shipments

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INTRODUCTION

Routing and scheduling decisions for radioactive waste shipments are important because these decisions alter the probability of accidents involving the shipments as well as the size of the population potentially exposed to the consequences of any accidental release. The costs of transportation are also closely related to the routes and schedules chosen, and thus decisions must be made in recognition of multiple objectives (e.g. minimizing risk and minimizing cost) which may be competing.

When multiple criteria are applied, there is usually no single "best" route or schedule for a given shipment. One alternative may minimize population exposed to risk, for example, while a second minimizes the probability of an accident, and a third minimizes cost. In this situation, our attention should be focused on identifying a set of "non-dominated" route/schedule alternatives. The actual alternative chosen should be from this set, but within this set a choice must be made by explicitly trading off one objective for another.

The measures chosen to reflect many of the potential objectives in routing and scheduling of shipments are both dynamic (varying by time of day) and stochastic (requiring estimation of uncertain values). An example of this is population within 0.5 mile of the route, a common measure of exposure, which clearly varies by time of day in many areas, and for which estimates are highly uncertain. Dynamic variation in the measures of interest means that scheduling and routing decisions are closely interrelated -- a route that may be attractive for some scheduled times of travel may be very unattractive (or even unavailable) at other times. Thus, we must develop methods for identifying route/schedule combinations simultaneously, and which can accommodate multiple objectives and uncertainty in the measures of interest as well.

This paper develops a basic methodology for multiobjective routing and scheduling of radioactive waste shipments, and describes its implementation in an interactive microcomputer-based model. The core of the method is the application of efficient multiobjective pathfinding algorithms to networks representing either routing alternatives (spatial networks) or scheduling alternatives (temporal networks). This network analysis is done within a context of statistical sampling of arc measures from distributions which characterize the level of uncertainty in the various measures. The result of the analysis is construction of a set of likely non-dominated route/schedule combinations for a specified origin and destination, along with an estimate of the confidence level of each alternative (the probability that it is non-dominated).

RELATED PREVIOUS RESEARCH

Several routing models have been developed for evaluating radioactive waste shipments, and movements of other types of hazardous materials. Joy and Johnson (1983) developed a highway routing model, and Glickman (1983) and Peterson (1985) developed railroad routing models. Brogan and Cashwell (1985) discuss enhancements of the Joy-Johnson model to make it more applicable to state and local questions rather than nationwide routing analyses. Cashwell et al. (1986) performed a comprehensive analysis of transportation options for moving radioactive wastes from generation points to potential repository sites, incorporating results from these routing models. All of these modeling efforts use a single criterion for routing, and thus identify a single "optimal" route between any pair of points.

Saccomanno and Chan (1985) describe a multiple-criteria analysis of hazardous material routing strategies on a highway network, but use a model which handles only one criterion at a time. Another rudimentary effort in dealing with multiple criteria in hazardous materials transportation is the work by Robbins (1981).

In the operations research literature, several approaches have been taken to the problem of finding multiobjective non-dominated paths through networks. One approach uses a multidimensional generalization of the optimality principle which is the basis for dynamic programming. This produces algorithms which are very similar in structure to single-objective dynamic programming methods for finding shortest paths. Examples of this approach are the works by Daellenbach and deKluyver (1980), Loui (1983) and Warburton (1983).

Cox (1984) developed a technique which uses the idea of a multidimensional principal of optimality, and also draws some useful algorithmic ideas from Dijkstra's (1959) work on single-objective shortest-path algorithms. This method is the basis for the model described here.

Finding shortest paths in restricted networks is another aspect of previous research upon which the work described here is based. Halpern and Priess (1974) provided a useful approach to the problem of finding the shortest path through a network in which some links are not available for travel at certain times, and some nodes may allow "parking" (i.e. waiting for links to become available) while others do not. The essential elements of this approach have been incorporated into the model described here.

MULTIOBJECTIVE PATHFINDING

The multiobjective pathfinding problem may be described as finding the set of all efficient or non-dominated paths from a given origin to a given destination. It is assumed that there are r measures or criteria that are to be minimized, and that these measures are non-negative and additive along the arcs of a path. One path dominates another if it is preferable on at least one of the r criteria, and no worse on any of the others. A set of all efficient paths includes those that are not dominated by any other path, but at least one path in the efficient set dominates any path not in the set.

Turnquist (1987) provides a description of an algorithm, based on the earlier work of Cox (1984), which solves the problem of finding the set of all efficient paths. In the interest of keeping this paper brief, the description will not be repeated here. However, it is important to note that this algorithm can be applied to both spatial networks, to address routing issues, and temporal networks, to address scheduling issues. These two types of analyses are illustrated in the following two sections.

AN EXAMPLE ROUTING ANALYSIS

As an example application of the multiobjective pathfinding algorithm, we will consider the problem of routing a shipment of radioactive waste over a highway network. Fig. 1 shows the network, which consists of 41 nodes and 146 directional arcs. Each of the arcs shown in Fig. 1 represents a bidirectional roadway, and is expanded to two directional arcs for analysis. Each arc has five measures associated with it: length, travel time, cost, population within one-half mile, and probability of accident. Because this is a hypothetical network, all of the data for each link are artificial, but serve to give an example of how the routing analysis is done.

For purposes of this example, the last three measures will be considered -- i.e. cost, population exposure, and accident probability. Table 1 shows the set of efficient paths found for a shipment originating at E and destined for HH. The table shows that 7 paths form the efficient set between E and HH, and the values of the measures along each path illustrate the tradeoffs available in determining a route. None of these seven routes is better on all measures than any of the others. For example, the first route shown in Table 1 is the cheapest, but has the highest population exposure and the largest accident probability. In order to reduce the risk measures, we must incur additional costs. By choosing the fifth route shown, we could minimize the accident probability, and also reduce (though not minimize) the population exposure, but costs increase by about 3.5%.

SCHEDULING ANALYSIS

Scheduling analysis is important because some links of the network may be subject to curfews (e.g. no travel during morning or afternoon rush hours), and also because some of the measures of interest (e.g. population exposure) may vary by time-of-day. Thus, along any specified route, there is a scheduling problem which may also have multiple objectives (minimize both en route delay and population exposure, for example). The scheduling problem also has constraints due to driver hours-of-service limits, required stops for refueling or pre-notification, etc.

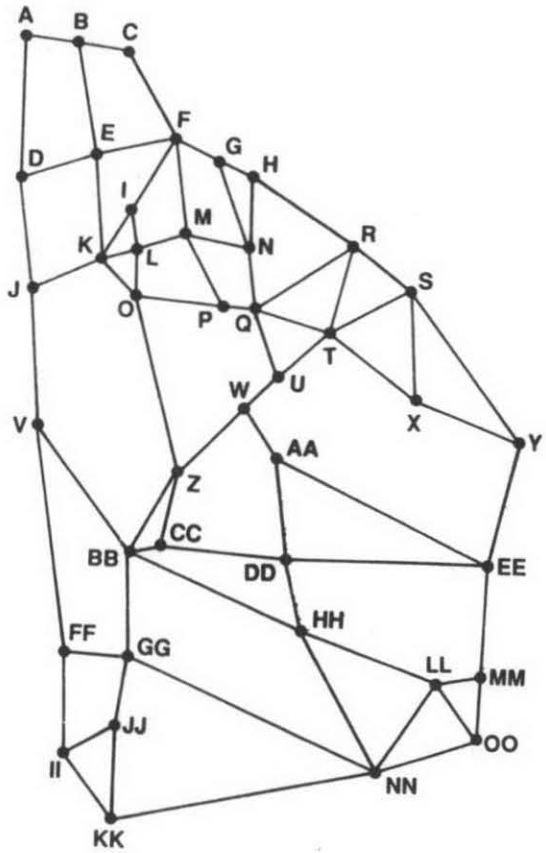

Figure 1. Network for example application of model.

Table 1. Example of efficient paths from one simulation trial.

Path	Cost ($)	Population (x 10^5)	Prob (Accident) (x 10^{-4})
E-K-O-Z-BB-HH	785	1.84	9.93
E-K-O-Z-CC-BB-HH	791	1.84	9.48
E-K-O-P-Q-U-W-Z-BB-HH	807	1.37	9.06
E-K-O-P-Q-U-W-AA-DD-HH	801	1.02	9.28
E-K-O-P-Q-U-W-Z-CC-BB-HH	813	1.37	8.61
E-K-L-O-P-Q-U-W-AA-DD-HH	841	1.01	9.61
E-K-L-O-P-Q-U-W-Z-CC-BB-HH	853	1.36	8.94

We can use the same multiobjective pathfinding method, on a temporal network, to analyze scheduling alternatives and identify efficient options. Each node of this network represents a specific time at a specific location along a route. Arcs connect this node to other nodes representing either the same location, or the next location along the route, at later times. Because the nodes, and the arcs connecting them, represent time-of-day as well as location, variations in characteristics such as travel time or population exposure, which are time-related, can be represented explicitly. A path through this temporal network represents a schedule for a trip along the specified route, with the sequence of nodes and arcs indicating arrival and departure times at the various locations along that route.

As an example of using this modeling approach, consider one of the routes identified in the previous section, E-K-O-P-Q-U-W-AA-DD-HH (the fourth route in Table 1). We will consider two objectives -- minimizing delay and minimizing population exposure -- assuming that curfews are imposed at locations O through AA between 7:00 AM and 11:00 AM, and between 3:00 PM and 7:00 PM. We will also assume a hypothetical time-varying population function, with a peak in the early morning as might represent a residential area.

Fifteen-minute intervals are used as possible departure times from E throughout a twenty-four hour period. The entire network for this analysis consists of twelve stages, 809 nodes and 2144 arcs.

A set of nine efficient paths are found, with delay values ranging from 0-120 minutes, and population exposure ranging from approximately 75,000-83,000. Note that these population exposure levels are about 17-25% below the value listed in Table 1, in which it was assumed that the population level was at a constant, average value throughout the day. The tradeoffs among the nine schedule solutions are illustrated in Fig. 2.

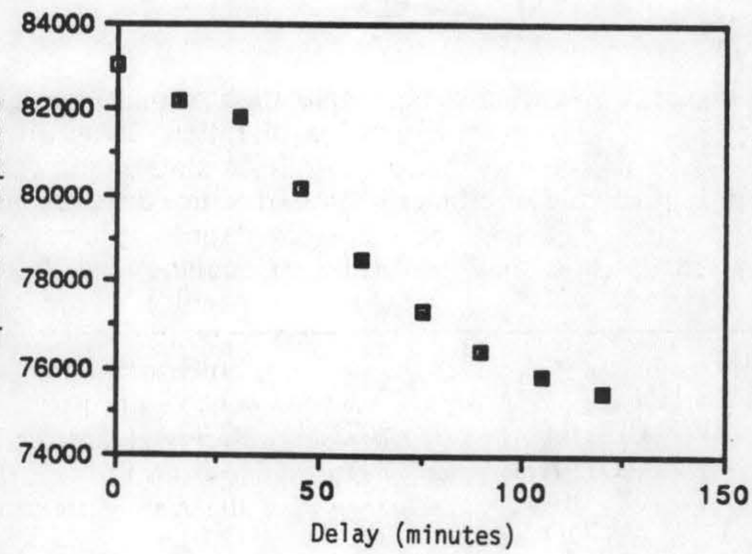

Figure 2. Population exposure vs. delay for example route.

The differences among these nine solutions are variations in departure time at E and delay at O, the first location en route with a curfew. In this example, there are many departure times from E which allow traversal of the route with no curfew delay. The "zero-delay" solution identified is the one which minimizes total population exposure. In order to reduce population exposure further, it is possible to leave E a little earlier, in order to travel across the first two links of the route during a lower population period, and then wait at O before traversing the remainder of the route. All nine solutions leave O at the same time, and arrive at HH at the same time.

INCLUDING UNCERTAINTY IN THE ANALYSIS

The analyses described in the previous two sections made the assumption that all arc measures of interest have known values. We must recognize, however, that measures such as accident probabilities, population exposed, etc. have values about which we are uncertain. Thus, the arc measures should be considered as probability distributions, and our determination of sets of efficient paths is based on statistical comparisons, not deterministic ones. Turnquist (1987) describes the statistical basis for establishing confidence levels on whether a particular path is efficient.

Table 2 shows the results of 30 simulation trials for the example routing problem discussed earlier, and lists all the paths which appeared in the efficient set in any trial. The column headed "Frequency" gives the number of trials in which each path appeared in the efficient set. The column headed "Confidence Level" indicates the degree of confidence, as a percentage for each path p, that we could place in the statement, "The probability that path p is in the efficient set is at least 0.75." It is quite clear that there are four paths which are very likely to be efficient, one more that is possible, and the remainder can probably be neglected without risking serious oversight in the analysis.

CONCLUSION

The analysis methods described in this paper have been implemented in an IBM PC environment, allowing interactive exploration of route/schedule alternatives. The model has characteristics of both simulation and optimization. Network optimization methods are used to find route/schedule combinations within the context of a statistical sampling (simulation) scheme for handling uncertainty in values of the measures to be optimized.

The value of this research is that it develops a computationally feasible way of illustrating the tradeoffs present between various measures of risk and cost in routing and scheduling radioactive waste shipments. By providing a means of generating potentially "efficient" solutions and offering clearer insight into the implications of choosing any particular alternative from this set, this work contributes to better decision-making regarding the management of radioactive materials transportation.

Table 2. Potential efficient paths based on 30 trials.

Path	Frequency of Occurrence	Confidence Level (P ≥ .75)
E-K-O-P-Q-U-W-AA-DD-HH	30	> 99.99%
E-K-O-Z-CC-BB-HH	28	> 99%
E-K-O-P-Q-U-W-Z-CC-BB-HH	27	98%
E-K-O-Z-BB-HH	25	90%
E-K-L-O-P-Q-U-W-AA-DD-HH	23	67%
E-K-O-P-Q-U-W-Z-BB-HH	19	10%
E-F-I-L-O-P-Q-U-W-Z-CC-BB-HH	19	10%
E-F-I-L-O-Z-CC-BB-HH	19	10%
E-K-L-O-P-Q-U-W-Z-CC-BB-HH	15	< 0.1%
E-K-L-O-Z-CC-BB-HH	14	"
E-F-I-L-O-Z-BB-HH	11	"
E-F-I-L-O-P-Q-U-W-AA-DD-HH	10	"
E-F-I-L-O-P-Q-U-W-Z-BB-HH	8	"
E-K-L-O-P-Q-U-W-Z-BB-HH	7	"
E-K-O-Z-CC-DD-HH	6	"
E-K-L-O-Z-BB-HH	6	"
E-K-O-P-Q-T-U-W-AA-DD-HH	3	"
E-F-M-P-Q-U-W-Z-BB-HH	2	"
E-F-M-P-Q-U-W-Z-CC-BB-HH	2	"
E-F-M-P-Q-U-W-AA-DD-HH	2	"
E-F-G-N-Q-U-W-Z-BB-HH	2	"
E-F-G-N-Q-U-W-Z-CC-BB-HH	2	"
E-K-L-O-P-Q-T-U-W-AA-DD-HH	1	"
E-K-L-O-Z-CC-DD-HH	1	"
E-F-I-L-O-Z-CC-DD-HH	1	"
E-K-O-P-Q-U-W-Z-CC-DD-HH	1	"

REFERENCES

Brogan, J.D., and Cashwell, J.W. "Rerouting Models for the Transportation of Hazardous Materials - State Level Enhancements and Modifications," Transportation Research Record 1020, 19-22 (1985).

Cashwell, J.W., Neuhauser, K.S., Reardon, P.C., and McNair, G.W., Transportation Impacts of the Commercial Radioactive Waste Management Program, Sandia National Laboratories, Report SAND85-2715, Albuquerque, NM (1986).

Cox, R.G. Routing and Scheduling of Hazardous Materials Shipments: Algorithmic Approaches to Managing Spent Nuclear Fuel Transport, Ph.D. Dissertation, Cornell University, Ithaca, NY (1984).

Daellenbach, H.G., and deKluyver, C.A. "Note on Multiple Objective Dynamic Programming," Journal of the Operational Research Society 31, 591-594 (1980).

Dijkstra, E. "A Note on Two Problems in Connexion With Graphs," Numerische Mathematik 1, 269-271 (1959).

Glickman, T. "Rerouting Railroad Shipments of Hazardous Materials to Avoid Populated Areas," Accident Analysis and Prevention 15, 329-335 (1983).

Halpern, J., and Priess, I. "Shortest Path With Time Constraints on Movement and Parking," Networks 4, 241-253 (1974).

Joy, D.S., and Johnson, P.E. HIGHWAY, A Transportation Routing Model: Program Description and Revised Users' Manual, Report ORNL/TM-8759, Oak Ridge National Laboratory, Oak Ridge, TN (1983).

Loui, R.P. "Optimal Paths in Graphs With Stochastic or Multidimentional Weights, Comm. of the ACM 26, 670-676 (1983).

Peterson, B.E. INTERLINE, A Railroad Routing Model: Program Description and Users' Manual, Report ORNL/TM-8944, Oak Ridge National Laboratory, Oak Ridge, TN (1985).

Robbins, J. Routing Hazardous Materials Shipments, Ph.D. Dissertation, Indiana University, Bloomington, IN (1981).

Saccomanno, F.F., and Chan, A.Y-W. "Economic Evaluation of Routing Strategies for Hazardous Road Shipments," Transportation Research Record 1020, 12-18 (1985).

Turnquist, M.A., "Routes, Schedules and Risks in Transporting Hazardous Materials," in Strategic Planning in Energy and Natural Resources (B. Lev et al., eds.), Elsevier Science Publishers, North-Holland (1987).

Warburton, A. "Exact and Approximate Solution of Multiple Objective Shortest Path Problems," Working Paper 83-74, Faculty of Administration, University of Ottawa, Canada (1983).