TRANSPORTATION SYSTEM MODELING AND SIMULATION IN SUPPORT OF LOGISTICS AND OPERATIONS

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SUMMARY

Effective management of DOE's transportation operations requires better data than are currently available, a more integrated management structure for making transportation decisions, and decision support tools to provide needed analysis capabilities. This paper describes a vision of an advanced logistics management system for DOE, and the rationale for developing improved modeling and simulation capability as an integral part of that system. We illustrate useful types of models through four examples, addressing issues of transportation package allocation, fleet sizing, routing/scheduling, and emergency responder location.

The overall vision for the advanced logistics management system, and the specific examples of potential capabilities, provide the basis for a conclusion that such a system would meet a critical DOE need in the area of radioactive material and waste transportation.

INTRODUCTION

Although the U.S. Department of Energy (DOE) is not primarily a transportation agency, it is nevertheless responsible for an extensive logistics system. The character of the materials being transported in this system adds considerable complexity. Effective management of the transportation activity requires accurate and timely data on material and waste movement requirements, available packages, the status or condition of those packages, and supporting documentation to ensure compliance with applicable regulations. Based on this data, the managers of this transportation activity need to be able to make effective decisions on a wide variety of issues. These issues include long-term decisions, such as investment in shipping containers, tactical decisions such as allocation of available equipment, and operational decisions such as routing and scheduling of individual shipments. To accomplish their objectives, they need high-quality decision support tools which are capable of operating in changing conditions and providing needed analyses of alternative decisions.

For example, a team representing both DOE's National Transportation Program and its Environmental Management Integration effort has recently identified several critical needs for radioactive waste transportation. These include:
- Establishing a more integrated complex-wide transportation management capability.
- Creating an inventory of special transportation (Type A and Type B) packages across the DOE complex,

- Establishing a Package Management Tracking System database, including location, physical condition, regulatory information, etc., for each package, and
- Increase the overall fleet capacity of Type B packages.

These are important steps toward a much more effective transportation and logistics system for DOE. An overall vision of such a system is shown in Figure 1. Data acquisition hardware and software receives real-time information on location, status and condition of the various elements of the operation (containers, trucks, shipments, etc.). This data is stored in a database, whose parts may be distributed across several locations in the complex, as well as at commercial waste generators, etc. All DOE sites should be linked to the network, including production facilities, repositories, national labs, DOE Headquarters, etc. The development of the Packaging Management Tracking System (PMTS) database has begun at Hanford (SAIC, 1995), and its completion is one important part of the overall vision described here.
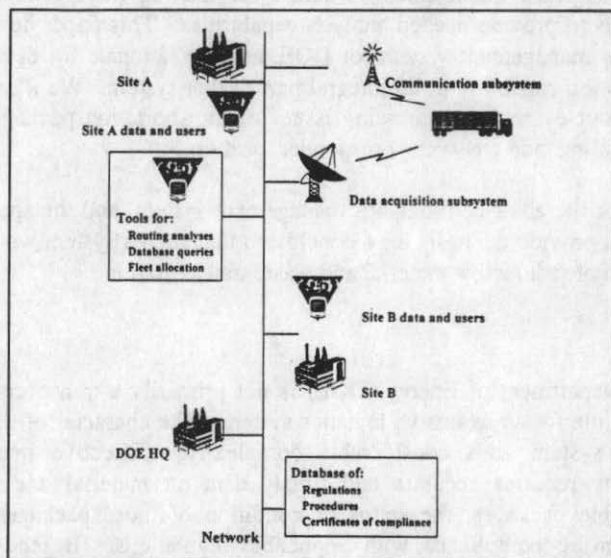

Figure 1. Graphical depiction of an advanced DOE logistics management system.

System modeling and simulation also need to be an integral part of this overall system. Modeling tools will directly support development and implementation of DOE's transportation strategies. A variety of tools need to be included in the system, to support the wide variety of decisions to be made and "what if" questions that will be asked.

The purpose of this paper is to discuss briefly some of the modeling and simulation tools which should be included in the overall decision support system, so that DOE has the capability it needs to manage its transportation processes effectively. Some of these tools can be created by modification of methods developed for use in private-sector manufacturing and transportation companies. Others are more specifically related to characteristics of radioactive materials and

wastes. In the following sections, we discuss first what can be learned from experience in other industries, and then discuss four specific ideas that illustrate general model functionality.

WHAT CAN WE LEARN FROM OTHER INDUSTRIES?

In recent years, industries with major logistics needs have invested heavily in fleet management tools and techniques. Examples include airlines, trucking firms, manufacturing companies, railroads, steamship lines, and wholesale and retail distributors. The introduction of just-in-time (JIT) philosophies has increased management focus on inventory and transportation operations. Knowing exactly what equipment is where, its condition, status, and expected next availability has become critical.

In many of these industries, there is a fleet of specialized containers of different types that must be managed. They must be tracked, inspected and recertified periodically by the "owning" organization. Demands for container use vary over time. In addition, some containers can be substituted for others, in a somewhat hierarchical fashion, to meet the needs of shipping various types of materials and products. The DOE transportation system exhibits all of these characteristics.

For example, in the railroad and trucking industries, the "containers" are vehicles (trucks or railcars) of various types. Some demands require a very specific type of vehicle, but substitution of one vehicle type for another is possible in many cases. The demand for trucks and railcars varies on a day-to-day basis, and there is a continuing need to direct empty vehicles to places of current demand. Because vehicles form a large fraction of the total asset base in these two industries, there is considerable attention paid to managing the fleets effectively. From an analytic perspective, this has resulted in the development and implementation of "dynamic vehicle allocation" models (e.g., Jordan and Turnquist 1983; Powell 1991). The growth of worldwide containerized cargo movement has created similar challenges for managing container fleets (Crainic, et al. 1993).

Manufacturers (especially in the automotive industry) invest heavily in reusable shipping containers. These containers typically cycle back and forth between parts manufacturing sites and vehicle assembly plants. Experience in fleet sizing for these containers (Turnquist and Jordan 1986; Beaujon and Turnquist 1991) can be transferred to considering fleets of DOE packages.

FOUR ILLUSTRATIVE EXAMPLES

In the following paragraphs, we describe four short examples of the types of modeling and simulation tools that can be implemented to help support DOE transportation and logistics operations. The first two of these are based on transferring experience from other industries. These two examples address issues of package allocation and fleet sizing. The second two examples reflect modeling tools more specifically created for analyzing issues associated with radioactive material transportation. These two examples deal with routing/scheduling issues and locating emergency responders.

Package Allocation

Radioactive material transportation packages are very specialized containers, for which there are varying demands at different times and in different places across the DOE complex. One fundamental problem in managing the set of resources represented by these packages is to determine which containers should be allocated to which shipments, in order to use the available fleet of packages most efficiently. To illustrate the problem, imagine that a series of shipments is to be made from site X to site Y, beginning on a certain planned date. This creates a demand for packages at site X, and if sufficient empty packages are not currently available at site X, they will have to be found somewhere else in the network and moved (probably empty) to site X.

Furthermore, as the series of shipments takes place and packages are unloaded at site Y, it may not necessarily be most efficient to return them empty to site X directly. Perhaps site Y is simultaneously moving some other material to site Z, and the same packages could be used for that movement (perhaps after cleaning or other preparation), and then returned to site X. An important point is that the package represents a resource available at a particular location at a specific time, and in a specific condition. To manage the whole set of such resources efficiently, we need to make decisions about allocating them to existing or anticipated demands based on considering the whole set of resources available and the whole set of demands to be met.

Conceptually, it is useful to think of this problem as moving resources of varying types through a network with both spatial and temporal dimension. A decision on allocating a package to a specific demand may imply an empty movement of that package followed by a loaded movement to a different location. This can be represented by a pair of arcs in a network that move the resource from where it is currently to some other location at some later time. When it reaches that location-time "node," it again becomes available for reallocation. Mathematically, this can be characterized as a stochastic optimization problem, in which we are trying to make the best decisions for currently available resources, with uncertainty about future demands and resource availability.

Fleet Sizing

Fleet sizing is a longer-term decision that is closely related to package allocation. The essential question is, "How many packages of a certain type do we need to have, to meet the transportation needs that are likely to arise?" More effective package allocation can reduce fleet size requirements, but the central investment question still needs to be answered.

Figure 2 illustrates some of the basic elements of the fleet sizing formulation. The backdrop is a time-space network, as used in the package allocation modeling. Locations (i, j, k) are listed down the left side, and time periods run along the top. If we focus on location i at time period t, we can define $w_i(t)$ as the inventory of packages (of a certain type) available. This inventory is augmented by arrivals of packages (loaded or empty) from other locations (e.g., j and k), and depleted by shipments to other locations. The net amount is carried forward to the next time period. The various movements in the network take different amounts of time, so $w_i(t)$ depends on dispatches made in several earlier time periods (from different locations), as well as $w_i(t-1)$.

Because the overall system contains many uncertainties, $w_i(t)$ is actually a random variable, with some probability distribution.
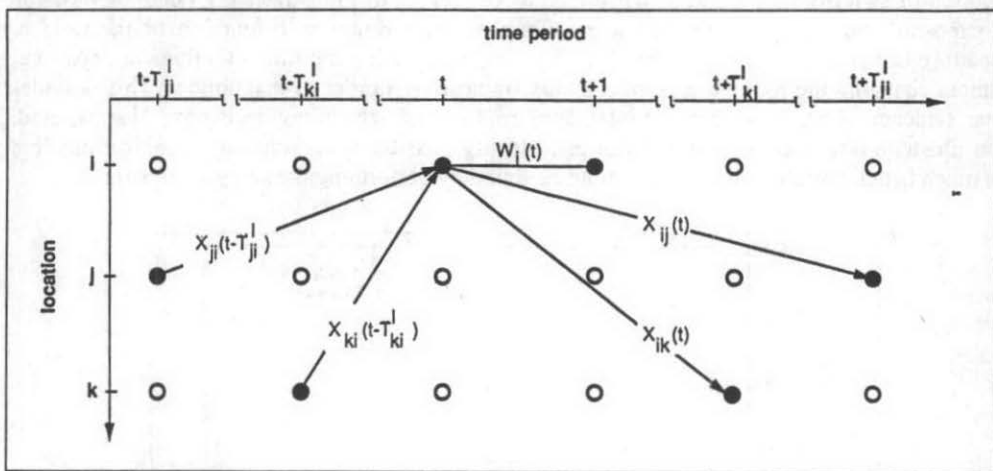

Figure 2. Time-space network representation for a fleet sizing model.

If the demand for packages at i exceeds the available supply, the inventory goes negative. That is, some of the demands are unmet (at least at the time desired). We can reduce the probability of a negative inventory (unmet demand) by adding more packages to the fleet (increasing $w_i(0)$, the initial inventory, for some locations, i). The fleet sizing question then becomes, "What are the values of $w_i(0)$ that minimize overall expected costs (including package ownership costs and penalties for unmet demand) over a defined time horizon?"

A combination of optimization and simulation modeling can be effective for addressing the fleet sizing issue. An optimization model for fleet sizing is forced to make several simplifying assumptions in order to remain mathematically tractable. Thus, we can use optimization to get the "best" answer to an approximation of the problem. We can then use simulation to refine this answer, by adding more detailed representation of the transportation system and testing different fleet sizes "in the neighborhood" of the approximate answer created in the optimization model. By using this combination of modeling tools, we can take advantage of their different strengths.

Routing/Scheduling Analyses

U.S. federal regulations require carriers of radioactive materials to select routes which "consider available information on accident rates, transit time, population density and activities, time of day and day of week ..." (49 C.F.R. part 173). The explicit inclusion of time of day and day of week information means that routing and scheduling decisions are closely interconnected (List, *et al.* 1991, Erkut and Verter 1995). Simultaneous routing and scheduling analysis requires more information than is required for simpler routing analyses based on average daily values of risk parameters. It also requires more sophisticated analysis methods – multiobjective routing algorithms that can accommodate time-varying network attributes.

To date, there has been little direct implementation of integrated routing/scheduling methods, but recent research illustrates that development of such models is feasible (Nozick, *et al.* 1997). Figure 3 (drawn from a case study performed by Nozick, *et al.*) illustrates the range of variation in exposure and accident rate parameters along a single route, as a function of the time of departure of the shipment during the day. By simply changing the time of shipment departure, without changing the route, exposure can vary by nearly an order of magnitude. This provides clear evidence of the importance of integrating routing and scheduling decisions. Nozick, et al. also illustrate how a combined analysis can identify possible route/schedule combinations that are much better overall than any that would be found by performing the analyses separately.
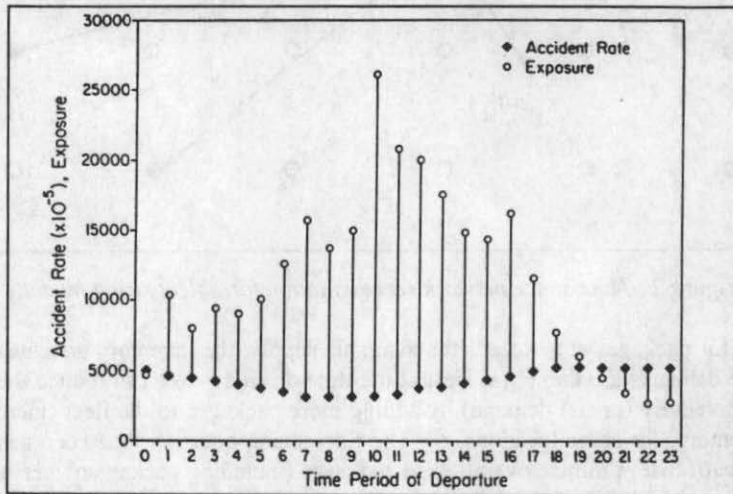

Figure 3. Variation in accident rate and exposure along a path, based on time of departure.

In the integrated logistics management system envisioned in Figure 1, integrated routing/scheduling tools would be readily available to shipment dispatchers as well as to shipment campaign planners. This would improve the effectiveness of real-time tracking of the shipments, because it would allow real-time data to be used in models for adjusting routes and schedules in light of changing information (e.g., weather, traffic incidents, etc.) (Beroggi and Wallace 1995).

Emergency Response Issues

There are many important uses of better data to facilitate improved emergency response capability, and modeling and simulation can also play an important role in this arena. One of the places where modeling can be extremely useful is in locating secondary response capability (specialized equipment and personnel specially trained in dealing with radioactive materials emergencies). These are not "first responders" to an emergency, but are teams who must be able to arrive at an incident scene quickly afterward, to take charge of activities. Because there are, on the whole, relatively few shipments of radioactive materials (as compared to more general

hazardous materials, for example), and the equipment and training is highly specialized, there are likely to be only a few such teams. In this situation, deciding where to locate the teams to best "cover" a wide range of shipments is an important issue, and modeling can contribute to finding good solutions.

Figure 4 shows a specific example of the output of a model developed for locating emergency response teams (List and Turnquist 1997). The case study from which Figure 4 is taken examined shipments of radioactive wastes from several DOE sites to the WIPP facility in southeast New Mexico. A key element in the analysis is simultaneous consideration of routing decisions and emergency responder location. A relatively small number (in the case shown, eight) emergency response teams can be located in a way that allows them to be within a relatively short distance from any potential incident location for a large set of shipments.
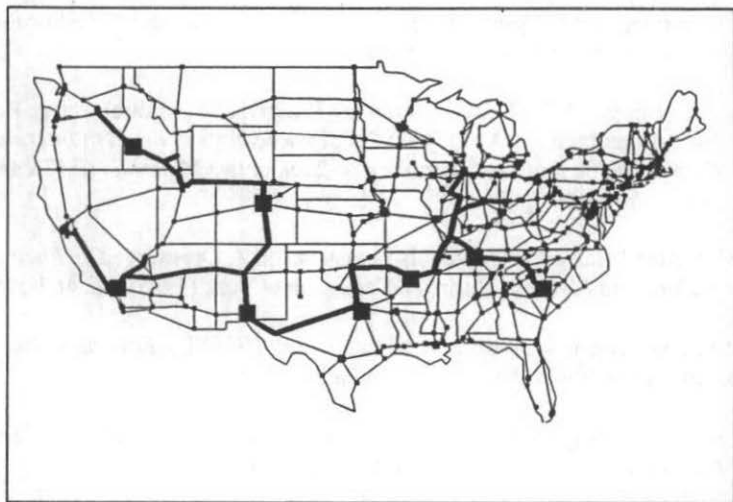

Figure 4. Location of emergency response teams for shipments to WIPP.

The four examples described here illustrate just some of the ways that an integrated logistics management system can be helpful for improving DOE's transportation operations. With further development, a wider variety of modeling and simulation tools can be put into place to address an even broader set of issues.

CONCLUSIONS AND NEXT STEPS

There is need for a multi-year initiative to develop and implement the vision for an integrated logistics management system for DOE. This development effort should include creation of a suite of modeling and simulation tools that expand on the set of examples provided here, as well as advanced data management, sensing, and communication elements. The effort needs to be defined in close collaboration with a variety of end users, so that there is a shared vision of how the system will be structured and what its functional capabilities should be.

There is already considerable evidence of the value of modeling and simulation tools in such an advanced management system, and of the potential benefits from their full-scale development. However, much effort remains to bring the vision to fruition.

REFERENCES

Beaujon, G.B. and M.A. Turnquist, "A Model for Fleet Sizing and Vehicle Allocation," *Transportation Science*, 25 (1991), pp. 19-45.

Beroggi, G.E. and W.A. Wallace, "Operational Control of the Transportation of Hazardous Materials: An Assessment of Alternative Decision Models," *Management Science*, 41 (1995), pp. 1962-1977.

Crainic, T., M. Gendreau and P. Dejax, "Dynamic Stochastic Models for the Allocation of Empty Containers," *Operations Research*, 41 (1993), pp. 102-126.

J.H. Ganter and J.D. Smith, "MPATHav: A Software Prototype for Multiobjective Routing in Transportation Risk Assessment," SAND 95-2842C, *Proceedings of the 11th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM '95)*, Las Vegas, NV, 3-8 December 1995, p. 992-999.

Erkut, E. and V. Verter, "Hazardous Materials Logistics," in Z. Dresner (ed.), *Facility Location: A Survey of Applications and Methods*, Springer-Verlag, New York (1995), pp. 467-506.

Idaho National Engineering and Environmental Laboratory (INEEL), *Environmental Management Integration Transportation Phase I Report*, Idaho Falls, ID, 1997.

Jordan, W.C. and M.A. Turnquist, "A Stochastic Dynamic Network Model for Railroad Car Distribution," *Transportation Science*, 17 (1983), pp. 123-145.

List, G.F., P.B. Mirchandani, M.A. Turnquist and K.G. Zografos, "Modeling and Analysis for Hazardous Materials Transportation: Risk Analysis, Routing/Scheduling and Facility Location," *Transportation Science*, 25 (1991), pp. 100-114.

List, G.F. and M.A. Turnquist, "Routing and Emergency Response Team Siting for High Level Radioactive Waste Shipments," *IEEE Transactions on Engineering Management*, (to appear, 1997).

Nozick, L.K., G.F. List and M.A. Turnquist, "Integrated Routing and Scheduling in Hazardous Materials Transportation," Transportation Science, 31 (1997), pp. 200-215.

Powell, W.B., "Optimization Models and Algorithms: An Emerging Technology for the Motor Carrier Industry," *IEEE Transactions on Vehicular Technology*, 40 (1991), pp. 68-80.

SAIC, Inc. *Packaging Management Tracking System (PMTS) Users Manual*, report WHC-SD-TP-UM-003, Hanford, WA, 1995.

Turnquist, M.A. and W.C. Jordan, "Fleet Sizing Under Production Cycles and Uncertain Travel Times," *Transportation Science*, 20 (1986), pp. 227-236.

SESSION 6.2

Waste and Back-End Packagings