

TABU SEARCH FOR SHIPPING DANGEROUS GOODS IN A RAIL-TRUCK NETWORK

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Abstract: The problem considered in this paper consists of planning and routing rail-truck intermodal shipments from a set of suppliers to a set of clients. The delivered quantities have to follow a truck-rail-truck intermodal path. There are three constraints to satisfy: the satisfaction of the demand is mandatory, each request should be delivered by its due date, and the capacity of a train cannot be exceeded. The objective function to minimize is a weighted summation of the cost and the risk. The former component concerns the fixed and variable transportation costs associated with trucks and trains, while the latter associated with dangerous goods is non-linear for trains. We propose a graph model to represent this problem and a tabu search metaheuristic to tackle it. Numerical experiments on realistic data are provided and discussed.

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1. INTRODUCTION

Rail-truck intermodal transportation, involving rail-haul operation by intermodal trains and drayage by truck, has experienced phenomenal growth since 1980 (AAR 2010). Rail-truck combination is attractive for two reasons: first, reduction in uncertainty and lead-times because a significant portion of the transport distance is covered by intermodal trains, which operate on fixed schedule and hence are quite punctual (Nozick & Morlok 1997); and, second, the ability to combine the best attributes of the two modes to yield a more efficient and cost-effective overall movement (AAR 2010). Although rail-truck intermodal transportation (IM) has been an active research area within the intermodal transportation domain (e.g., Bontekoning, Macharis & Trip (2004) and Macharis & Bontekoning (2004)), the focus has been on regular freight. Despite the increasing significance of IM in carrying hazmat, Erkut, Tjandra & Verter (2007) identified, through a comprehensive review of the literature on hazmat logistics, that intermodal transportation is an area that has not been well studied.

In this paper we pose the problem from the perspective of the intermodal railroad company, which offers a door-to-door service to the customers. For example, UMAX interline container program of CSX Intermodal and Union Pacific Railroad was conceived to ensure seamless freight movement across different transportation modes. Although such intermodal companies are interested in minimizing cost, they are also under governmental pressure to consider transport related risk. In an effort to address the interests of these two stakeholders, we propose an objective function that captures both transport risk and transport cost. The complexity of the problem structure, dictated by the characteristics of IM, necessitated the development of a metaheuristic, namely tabu search.

The remainder of this paper is organized as follows. In Section 2, we describe the problem and present a graph model for it. In Section 3, we propose a tabu search to tackle the problem. Results are given and discussed in Section 4, and the paper ends up with a conclusion.

2. PROBLEM DESCRIPTION

The considered problem is to determine the best shipment plan for both hazardous and regular freight in an IM network, and within customer specified delivery times. The objective is to minimize the total cost of transportation as well as the total public risk associated with hazmat. This task is complicated because the number and location of hazmat containers can vary considerably among intermodal trains of various types, which requires the use of a rather elaborate risk assessment technique and prohibits the development of a closed-form expression for

the risk objective. Furthermore, it is necessary to streamline the inbound drayage, intermodal rail haul and outbound drayage activities while making the trade-off between total transportation cost and total public risk.

To illustrate the complexity of the problem, we outline the characteristics of the intermodal service chain of a Class 1 railroad company in the U.S. Fig. 1 depicts the 20 intermodal terminals, and the 31 types of intermodal train services differentiated by route, and intermediate stops. These terminals are the access points for 37 shipper/receivers located in the mid-west, north-east, and south-east regions of the U.S., which were selected using the existing intermodal network in the region, and are represented via a geographical information system model using *ArcView* (<http://www.esri.com>). Furthermore, we assume that two types of intermodal train services (*regular* and *priority*) are operating between each terminal pair (i.e., a total of 62 types of intermodal train service), and that the latter train type is 25% faster than the former (this approximately captures the features of *Expedited* and *Expedited-Plus* services offered by *Norfolk Southern*).

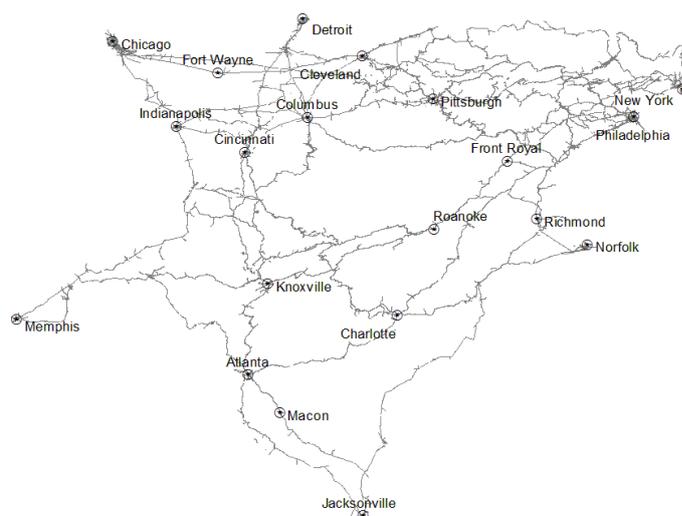


Fig. 1 Intermodal rail services

The considered problem can be represented with a graph model. Consider the following network $G = (V, A)$, with vertex set V and arc set A . The vertex set V is partitioned into four subsets I, J, K and L , where a vertex i in I represents a supplier location, a vertex j in J represents an origin train station, a vertex k in K represents a destination train station, and a vertex l in L represents a client location. There are only arcs from I to J , from J to K , and from K to L . Arcs (i, j) in $I \times J$ and (k, l) in $K \times L$ represent truck transportation options, while arcs (j, k) in $J \times K$ represent train

options. The problem consists of satisfying the requests of the clients located in L from a set of suppliers located in I . In order to ship a request r from a supplier i in I to a client l in L , the following *truck-train-truck* intermodal path has to be used: $i \rightarrow j \rightarrow k \rightarrow l$ (with j in J and k in K).

Since transportation from any i in I to any j in J are performed by trucks, there is only one associated arc (i, j) , even if several trucks travel from i to j , which represents the cheapest path from i to j . The same holds for arcs in $K \times L$.

In contrast, if there are several trains going from a vertex j in J to a vertex k in K , then each train is represented by a different arc. In order to avoid multiple arcs from j in J to k in K , we duplicate j as many times as the number of train options. A train u traveling from j to k can be denoted $u = (j, k, a, c, p)$, where a is the arrival time at destination, c is its capacity (120 containers), and p is its type, which can be regular or priority, the latter being faster and more expensive than the former.

A demand requested by a client l to a supplier i can be denoted $r = (i, l, t, d, q)$, where t is its type (regular or hazardous), d is the due date, and q is the number of containers in the command (up to 120 containers). The decision for each request r consists in determining a path of type $i \rightarrow j \rightarrow k \rightarrow l$, while satisfying the constraints and minimizing the objective function.

There are three constraints to satisfy: the satisfaction of the demand is mandatory, each request should be delivered by its due date, and the capacity of a train cannot be exceeded (assuming that each container needs one capacity unit on any train). We assume that at least one feasible intermodal route exists between each shipper-receiver pair. The objective function contains transport cost (C), transport risk (R), and a weight α in $[0, 1]$.

Thus, if s is a solution, then $f(s) = \alpha C(s) + (1 - \alpha) R(s)$. The following costs are considered. When a container of type t (regular or hazardous) moves by the use of a transportation mode (train or truck), a travel cost is encountered. When a transportation mode is used, a fixed cost has to be paid. In contrast, a risk only occurs for hazardous containers, and is non-linear only for train transportation: anytime m hazardous containers moves on a train, a risk is encountered, which is nonlinear in m .

In the U.S., trucks can travel at a maximum speed of 50 miles/hr, but due to lights and traffic an average speed of 40 miles/hr is assumed. Normally drayage is charged in terms of the amount of time the crew (driver-truck) is engaged, and an amount of 250\$/hr including the estimated hourly fuel cost is used. For example, if it takes four hours to complete inbound drayage (including travel and waiting time), the associated cost is 1000\$. Furthermore, it is estimated that approximately one hour is needed to load, unload, or transfer an intermodal container. Barton et al. (1999) estimated 140\$ to be the cost of a lift at the intermodal yard, but we assume 150\$ to reflect the current conditions.

There are two types of intermodal train services between each terminal pair (regular and priority), whose travel time includes two hours for loading and unloading at every terminal they visit. Average intermodal train speed was calculated using the *Railroad Performance Measure* (<http://www.railroadpm.org>), and was estimated to be 27.7 miles/hr for regular, and 36.8 miles/hr for priority service. Although Morlok & Spasovic (1995) estimated 0.70\$/mile as the intermodal rail-haul cost, a rate of 0.875\$/mile has been estimated for regular and 1.164\$/mile for priority service. The hourly fixed cost of running a regular intermodal train is 500\$ per hour, which takes into consideration the hourly rate for a driver, an engineer, a brakeman, and an engine, which are 100\$, 100\$, 100\$, and 200\$, respectively. The priority service is 50% more expensive at 750\$ per hour.

In estimating the transport risk associated with IM shipments, we use the classical population exposure model of Batta & Chiu (1988) only for assessing the transport risk associated with drayage operations, whereas the Verma & Verter (2007) model is used for assessing rail-haul risk.

3. SOLUTION METHODS

In order to ship a regular request $r = (i, l, t, d, q)$ (i.e. with $t = \text{regular}$), we have to search for shortest paths (it is assumed that shortest path is both the cheapest and quickest) from i to l in the network $G = (V, A, w)$, where the vertex set V and the arc set A are defined as above, and the weight $w(x, y)$ of arc (x, y) is the encountered unit cost if r uses arc (x, y) . Using the famous *Dijkstra's* algorithm, and ignoring the arcs associated with priority trains for the moment, each regular request r is assigned to the shortest feasible path. If a shipment is late, we replace the regular train with a priority train, thereby reducing travel time but augmenting the travel cost (and keeping optimality). Note that since drayage is already being performed using the quickest link, travel time cannot be reduced by moving to any other drayage link. The above described process is done once and for all in our general heuristic, and needs only a small amount of computing time (a few seconds).

The rail-haul risk objective does not have a generic closed-form expression and is nonlinear (Verma, Verter & Gendreau, 2010). This is because population exposure around each rail link is estimated by multiplying the length of the link, the threshold distance for the undesirable consequence of concern, and the population density in the vicinity. Given the complexity associated with rail-haul risk objective, routing hazmat containers using exact method would be both inefficient and cumbersome, especially for large scale problem instances. We choose to develop a tabu search. Before applying a tabu search to the considered problem, we perform the following pre-processing phase.

For each hazmat request $r = (i, l, t, d, q)$, it is easy to generate once and for all the set $F(r)$ which contains arcs (j, k) of $J \times K$ such that path $i \rightarrow j \rightarrow k \rightarrow l$ results in an on-time delivery. In other words, only the *feasible arcs* will be considered.

A basic version of tabu search can be described as follows. Let f be an objective function which has to be minimized. At each step, a neighbor solution s' is generated from the current solution s by performing a specific modification on s , called a *move*. All solutions obtained from s by performing a move are called *neighbor solutions* of s . The set of all the neighbor solutions of s is denoted $A(s)$. First, tabu search needs an initial solution s_0 in S as input. Then, the algorithm generates a sequence of solutions s_1, s_2, \dots such that s_{r+1} is in $A(s_r)$. When a move is performed from s_r to s_{r+1} , the inverse of that move is forbidden (with some exceptions) for *tab* (parameter) iterations, where *tab* is called the *tabu tenure*. The solution s_{r+1} is computed as $\arg \min_{s \in A'(s_r)} f(s)$, where $A'(s_r)$ is a subset of $A(s_r)$ containing all solu-

tions s' which can be obtained from s either by performing a move that is not forbidden (i.e. not tabu) or such that $f(s') < f(s^*)$, where s^* is the best solution encountered along the search so far. The process is stopped for example when a given amount of CPU time has elapsed. Extensions of this basic algorithm can be found for example in (Glover & Laguna, 1997).

In order to ship hazmat requests at minimum cost and risk, we mainly have to find their best assignments to the arcs in set $J \times K$. Let s be an assignment solution of all the hazmat requests to the arcs in set $J \times K$. If and only if s is completely known, we can compute the objective function $f(s)$. Given a solution s , we consider the network $G(s) = (V, A, w)$, where V and A are defined as above but, contrary to the regular case, the weight function w now depends on the considered solution s . Firstly, the weight $w(x, y)$ of arc $(x, y) \in (I \times J) \cup (K \times L)$ is the associated linear cost and risk. Thus, it is easy (using *Dijkstra's* algorithm) to once and for all compute (in a preprocessing phase) the shortest paths from any i in I to any j in J and from any k in K to any l in L . Secondly, the weight $w(j, k)$ of arc (j, k) in $J \times K$ is the linear cost and nonlinear risk (depending on s) associated with the requests using (j, k) . In other words, if $r = (i, l, t, d, q)$ will go via arc (j, k) , then one can construct the complete intermodal path from shipper i to receiver l as: the shortest path from i to j ; arc (j, k) with its cost and risk; and, the shortest path from k to l .

We propose the following neighborhood and tabu structures. Let s be the current solution (i.e. an assignment of the hazmat containers to the arcs in $J \times K$). In order to generate a neighbor solution s' from s , we propose to change the assignment of a hazmat request $r = (i, l, t, d, q)$, while maintaining the feasibility of the solution (i.e. we do not allow late shipments and capacity violations). More precisely, we move r from arc (j, k) to an arc (j', k') in $F(r)$. Such a move can be denoted by $[r; (j, k); (j', k')]$. If such a move is performed at iteration *iter*, it is forbidden to reassign r to (j, k) until iteration *iter* + *tab*, where *tab* is defined

as follows. Let $UNIF(a, b)$ be a function which randomly returns an integer number between a and b (inclusively). We use a dynamic way of managing the tabu tenures, which depends on the quality of the performed move, and, after preliminary experiments, we propose $tab = UNIF(1, 10) + 5 \cdot \max\{0; 100 [f(s) - f(s')] / f(s)\}$. Thus, if s' is better than s , the move is forbidden longer than if it is not the case. At each iteration, we always choose the best non tabu feasible neighbor solution s' (among a random sample of neighbor solutions, see below for details). A tabu move is allowed only if it leads to a solution better than the best one encountered so far. Because of the preprocessing phase, it will be easy and quick to build and evaluate s' from $s, f(s)$ and the considered move.

We had to tune two parameters N (percentage of neighboring solutions considered at each iteration of tabu search) and T (a time limit). Preliminary experiments showed that $N = 1\%$ and $T = 15$ minutes are good values. The overall solution method is summarized in Fig. 2. The returned solution is s^* (with value $f(s^*)$), which is the best solution encountered during the search.

Phase 1: find the optimal shipment of the regular containers

- Build $G = (V, A, w)$
- Assign each regular request $r = (i, l, t, d, q)$ to the shortest path from i to l

Phase 2: pre-processing and initializations

- For each hazmat request r , compute the set $F(r)$ of its feasible arcs of $J \times K$
- For each arc (j, k) , compute the shortest path from i to j and from k to l
- Generate a random initial solution s : assign each hazmat request r to a randomly chosen arc (j, k) of $F(r)$ and assign r to the shortest path from i to l via arc (j, k)
- Set $iter = 0, s^* = s$ and $f^* = f(s)$

Phase 3: find a good shipment of the hazmat containers with tabu search

- Update the iteration counter: set $iter = iter + 1$
 - Generate the best non tabu neighbor solution s' among a random sample of $N = 1\%$ of the whole neighborhood (break ties randomly and allow tabu moves leading to a best encountered solution); assume that the selected move consists in moving r from i to l through arc (j', k') instead of arc (j, k)
 - Update the best encountered solution: if $f(s') < f^*$, set $s^* = s'$ and $f^* = f(s')$
 - Update the current solution: set $s = s'$
 - Update the tabu status according to parameter tab : it is tabu to reassign r to (j, k) until iteration $iter + tab$
 - Go back at the beginning of phase 3 if $T = 15$ minutes have not elapsed
-

Fig. 2 General heuristic for the whole problem

4. COMPUTATIONAL EXPERIMENTS

We first outline the remaining details for the realistic problem instance introduced above, and then we analyze the solution and provide some managerial insights. The solution methodology was coded in *Python*, a dynamic object-oriented programming language, to solve a total of eleven problem instances. All numerical experiments were performed on an *Apple*, running *Mac OS X 10.5.6* and *Python 2.6.1* (<http://www.python.org>).

Fig. 1 represent the intermodal train services of different types available for solving the realistic size problem instances. In developing the problem instances, we use hypothetical demand data which were randomly generated utilizing the fuel oil consumption figures as compiled by the *Department of Energy* (<http://ton-to.eia.doe.gov>). It is important to note that no demand can be generated between a shipper and a receiver with access to the same terminal, since such movement will just use the highway network and not a complete IM chain. Such consideration results in 1110 supply-demand pairs, and not a 37×36 demand matrix. In our data set, a total of 22,190 intermodal containers, including 10,965 with hazardous cargo, have to be moved. Finally, without loss of generality, we also assume that the lead-time to satisfy demand at each shipper is two days (i.e., specified delivery-time of 48 hours).

We report below on a parametric analysis performed by attaching different weights to the two objectives (α will vary from 1 to 0 with 0.1 steps). The *Base Case* situation (i.e. with $\alpha = 0.5$), obtained after 15 minutes (13 682 iterations) of CPU time, has the following properties. The total costs is 72 670 111\$ (15 189 592\$ rail-haul and 57 480 519\$ drayage) and the total risk is 8 979 439 people (570 765 rail-haul and 8 408 674 drayage). Thus, the specified demand can be met by spending around 72.7\$ million, and exposing approximately 9 million individuals. Note that a significant proportion of both cost and risk is accruing from drayage operations, which should be of interest to decision-makers. In an effort to investigate the high risk numbers, we applied the proposed methodology to eleven separate problem instances generated using the intermodal infrastructure involving only a single pair of terminals. A total of seven different intermodal train routes were created to transport 3 881 intermodal containers between the 210 shipper-receiver pairs. Drayage risk accounted for 90% – 96% of intermodal transport risk in these problem instances.

In order to ascertain the performance of the proposed tabu-search based solution methodology, we also solved the realistic size problem instances by implementing a Greedy Algorithm (*GrA*). *GrA*, a constructive heuristic, builds a solution step-by-step. Initially the solution set is empty, and then at each step an item (i.e. a request) is added to the current partial solution, such that the augmentation of the objective function is minimized, and the algorithm stops when a complete solution is built. It was noticed that on average a complete solution was built in around 12 seconds,

but to facilitate fair comparison, *GrA* was also allowed to run for 15 minutes (with restarts, and providing the best generated solution as output) on eleven different instances of the realistic size problem.

In Table 1, for each instance (i.e. a specific value of α), we report f^{tabu} (the value of the best solution encountered by tabu search within 15 minutes), $\Delta f(GrA)$ (the additional value of f associated with the best solution encountered by *GrA* within 15 minutes), the cost and risk components of f^{tabu} , the number of regular trains used by tabu search (and, in brackets, the number of regular trains used by *GrA*), the number of priority trains used by tabu search (and, in brackets, the number of priority trains used by *GrA*). One can conclude that tabu search is consistently superior to *GrA* when one gives priority to the cost attribute (i.e. larger values of α), and relatively more effective when the risk coefficient carries more weight. The myopic behavior of *GrA* is evident by the consistent use of a larger number of priority trains in comparison to the proposed methodology. This has enabled more time for drayage, which would explain the lower risk numbers.

Table 1 Performance of tabu search

Instance	f^{tabu}	$\Delta f(GrA)$	Cost (\$)	Risk (people)	Regular	Priority
<i>Min Cost</i>	71277442	575870	71277442	14888317	173 (161)	41 (66)
$\alpha = 0.9$	65480698	373187	71455502	11707466	164 (162)	46 (65)
$\alpha = 0.8$	59330743	402269	71462375	10804216	172 (163)	40 (61)
$\alpha = 0.7$	53261093	259752	71671355	10303816	170 (165)	42 (63)
$\alpha = 0.6$	47147156	239574	72231191	9521104	165 (168)	50 (67)
<i>Base Case</i>	40824775	188182	72670111	8979439	170 (169)	49 (62)
$\alpha = 0.4$	34374236	184471	73714081	8147672	169 (164)	48 (70)
$\alpha = 0.3$	27734819	187716	74131896	7850358	176 (158)	41 (74)
$\alpha = 0.2$	21074355	106541	74860098	7627919	173 (161)	44 (71)
$\alpha = 0.1$	14302341	50809	75801586	7469092	171 (163)	57 (83)
<i>Min Risk</i>	7436203	3815	77290002	7436203	162 (149)	87 (99)

We now give some managerial insights of our approach (according to the results obtained by tabu search). In here, we report on the parametric analysis performed by varying the weights associated with the two objectives. Each row in Table 1 represents a non-dominated solution. The *Min Cost* solution (i.e. with $\alpha = 1$) is 2% less expensive than the *Base Case* solution, but 65% more risky. The increment in risk is primarily stemming from forcing drayage operations through shorter but more risky paths. On the other hand the *Min Risk* solution (i.e. with $\alpha = 0$) is 6.4% more expensive, thanks to a higher number of priority trains. It should be noted that the use of faster trains has enabled taking longer but less risky paths, which in turn translated into a 17.2% risk reduction.

From Table 1 one sees that the *Min Cost* solution entails a cost of around \$71.3 million and exposes 14.9 million people, whereas the *Min Risk* solution will cost \$77.3 million and expose 7.44 million people. By spending an extra \$6 million, it is possible to halve the population exposure risk. This may be a worthwhile trade-off for the regulators to pursue. Perhaps a more important observation is the significant increase in population exposure risk when the weight attached to the risk coefficient is decreased from 10% to 0% (i.e., from $\alpha = 0.9$ to $\alpha = 1$). This weight allocation results in a saving of around \$175 K but increases exposure risk by 3 million people, which implies that every saved dollar exposes 17.4 additional individuals to hazmat risk.

5. CONCLUSION

In this paper, we present a graph model and a tabu search for planning rail-truck intermodal shipments, when shippers and receivers have access to alternate terminals. It is important that route-selection, and hence the formation of feasible intermodal chain, be driven by customer specified delivery-times. Complexity of IM and the intent to exploit the problem structure motivated the development of a tabu-search based solution methodology, which was applied to realistic size problem instances.

This is the only work that proposes to solve the more general instance of the rail-truck intermodal transportation of dangerous goods problem first introduced in (Verma & Verter 2008). It is also the first application of a tabu-search based solution methodology to generate a number of non-dominated solutions, for the risk-cost frontier, that could be used for planning rail-truck intermodal tactical problems.

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BIOGRAPHICAL NOTES

Nicolas Zufferey is a professor of operations management at the Faculty of Economics and Social Science of the *University of Geneva* in Switzerland. His research interests mainly focus on the design of metaheuristics for combinatorial optimization problems in various fields, such as transportation, inventory management, production scheduling, frequency assignment, graph coloring, etc. He is the author and co-author of numerous papers and he has had research activities with about 15 Universities in Europe and North America.

Manish Verma is a professor of operations management and management sciences at the Faculty of Business Administration of *Memorial University of Newfoundland* in Canada. His research interests are in multimodal transportation of dangerous goods, risk assessment, network design and planning issues in transportation, global logistics, and green supply chain management. He is the author and co-author of over twenty peer-reviewed works, some of which have appeared in leading journals such as *Transportation Science*, *European Journal of Operational Research*, *Transportation Research E: Logistics and Transportation Review*.

