DOE/OR/21826--T1

A Multi-Model Deployment Planning Problem

Final Report

Siriphong Lawphongpanich
Richard E. Rosenthal

Department of Operations Research
Naval Postgraduate School
Monterey, California 93943

September 1989

DISCLAIMER

Abstract

This report considers a multi-modal deployment planning problem in which movement requirements are allowed to originate from (supply) centers, ground transported to (sea or air) ports of embarkation, and, upon arrival at (sea or air) ports of debarkation, ground transported again to (demand) centers or destinations. This sequence of movements involves all three modes of transportation: air, land, and sea. We formulate this deployment problem as an integer program which has a columnar structure and allows for many different objectives. The complexity of this program along with optimality properties for its solutions are discussed. A heuristic solution procedure is also proposed.

Table of Contents

Executive Summary

This report describes the progress of the research on the time-sensitive deployment planning problem which is ongoing at the Naval Postgraduate School. As suggested at the meeting at Oak Ridge National Laboratory in November 1988, our originally proposed problem has been modified to include the functions of all three commands: Military Airlift Command (MAC), Military Sealift Command (MSC), and Military Traffic Management Command (MTMC). Also, the movement requirements are no longer assumed to be aggregated into full shiploads. Moreover, to include the function of MTMC, movement requirements are allowed to originate and destine for (supply/demand) centers other than ports of embarkation and debarkation. If desired, users are allowed to assign ports of embarkation and debarkation to any movement requirements. However, if users assign ports to all movement requirements, then the resulting problem becomes either a pure airlift or sealift deployment planning problem.

Under the above conditions, the problem of scheduling lift assets and ground transportation to deliver movement requirements from origins to destinations is formulated as as integer program. This formulation is similar in structure to our originally proposed formulation, in that both have the columnar structure. In our original formulation, a column represents a feasible pick-up and delivery schedule for a sealift asset and, because of our original assumptions, each element in a column is either zero or one to indicate whether a movement requirement is on the asset's schedule. In the current formulation, the column elements are no longer binary; they can be any nonnegative integers which indicate the quantities of cargoes to be transported by an asset at different time and locations. With this generalized definition of a column, the resulting integer program is quite flexible, for it allows the incorporation of rules regarding, e.g., asset schedules and port restrictions, and permits the consideration of different objective functions.

Although the integer programming formulation seems to capture most of the realistic aspect of the deployment planning problem, the resulting problem is difficult to solve optimally. One difficulty lies in the fact that the generation of columns is an NP-complete problem and can take exponentially long to solve. However, we are able to establish properties concerning an optimal solution. Under some appropriate conditions, one can infer from these two properties the following rule: to minimize the lateness or closure date, one must schedule assets to visit a minimum number of ports. Then, a heuristic procedure based on this rule is proposed for the sealift part of the deployment problem. To address the full problem, the procedure can be combined with the Lift Optimizer program of Rosenthal [1988].

The current plan for our research is to consider alternate models to the deployment planning problem. Our objective is to model the problem in a manner that does not require the explicit representation of the schedules for lift assets. Thus far, we have been following the standard methodology of trying to construct feasible schedules to answer the question of whether there exists a feasible deployment plan. It seems logical that the detail of schedules should be left to the three transportation commands and USTRANSCOM should only concern itself with the feasibility question. The advantage of this approach is the reduction in the computation effort, thereby making it more suitable for crisis deployment planning.

1. Introduction

The United States Transportation Command (USTRANSCOM) is responsible for coordinating the transportation planning effort among the three service-specific transportation commands or Transportation Operating Agencies (TOAs). The three TOAs are the Army's Military Traffic Management Command (MTMC), the Navy's Military Sealift Command (MSC), and the Air force's Military Airlift Command (MAC). MTMC is responsible for the surface transportation of material inside the continental United States and the operation of certain common user port facilities worldwide, MSC is responsible for the ocean shipping, and MAC is responsible for the overseas air transportation. Although the primary purpose for USTRANSCOM is to integrate global air, land, and sea transportation effort for the deployment of personnel and materiel worldwide prior to and subsequent to a war, USTRANSCOM also monitors the peacetime operation of the transportation assets controlled by the three TOAs. Because of these two roles, USTRANSCOM planning can be classified into two categories: deliberate and crisis planning.

In the deliberate planning process, the development of a deployment plan takes place over a period of weeks or months. The plan itself normally goes through several iterations of refinement to insure that it is both effective and efficient. The end result is a set of feasible schedules for assets in detail. In a crisis situation, the above approach to planning is too lengthy. Major tactical decisions must be made in a period of a few hours. These tactical decisions invariably rest upon knowing whether a particular plan can be supported logistically. Thus, the real concern during a crisis planning process is the existence of a feasible deployment plan, and the detail of the plan can be constructed later, preferably by the respective commands.

2. Problem Formulation

Lawphongpanich and Rosenthal [1988] described a column generation approach to a time-sensitive deployment planning problem which considers only the sealift assets and assumes that the MRs have been aggregated into full shiploads. The model below generalizes this approach to include all three modes of transportation (land, sea, and air) and relaxes the assumption about the aggregation. As presented, the resulting problem is an integer programming (IP) problem rather than the mixed set partition and covering problem obtained by Lawphongpanich and Rosenthal. However, the IP problem still maintains the columnar structure. The main difference is in the information which goes into each column. In Lawphongpanich and Rosenthal, each column represents a schedule for an asset, each has exactly m elements where m is the number of MRs to be deployed, and each element is either zero or one indicating whether a given MR is picked up (and delivered) by the asset. In the present formulation, a column contains information about the locations, time, and quantity of each MR to be picked by an asset. Therefore, the column elements can now be any nonnegative integer rather than a binary number. As before, a column describes an asset schedule for the entire length of the planning period and it is now referred to as a 'travel pattern.' Given a set of feasible travel patterns for each asset, the IP problem selects at most one pattern for each asset so as to optimize a given objective function.

To describe the deployment planning problem, we categorize the data into five major groups:

1) Movement Requirements (MR).

2) Lift Assets

3) Ports of embarkation/debarkation

4) Origins/destinations.

5) Ground Transportation

Within the above groups of data, the following information is assumed to be available.

<u>Movement Requirements</u>:

a) Origin of the MR.

b) Destination of the MR

c) Required port of embarkation (if any)

d) Required port of debarkation (if any)

e) Required mode of transportation (air or sea). It is assumed that the travel between origins/destinations and ports of embarkation/debarkation is always over land and the method of transportation is either by rail or truck.

f) Available date at the origin

g) Required delivery date at destination.

h) Quantity, e.g., in short tons.

i) Type of cargo

j) Required handling equipments

Lift Assets:

a) Initial Location

b) Travel Speed

c) Type (plane type or ship type)

d) Capacity

e) Available date

f) Cargo compatibility (For some assets, this information may be redundant with (c), in that the asset may only be compatible with only one type of cargo. Thus, the asset type implicitly indicates the type of cargo which it can accommodate, e.g., an oil tanker.)

g) Port compatibility.

Ports:

a) Type (sea or air)

b) Location

c) Processing Capacity, e.g., short ton per day

d) Available handling equipments

e) Ship compatibility

Origins/Destination:

a) Location

b) Processing Capacity

Ground Transportation:

a) A network describe possible ground transportation link between origins & POEs, POEs & POEs, PODs & PODs, and PODs & destinations.

b) The speeds of various type of ground transportation. For simplicity, it is assumed herein that there are only two types of ground transportation, truck and rail. From these speeds, the travel time for each transportation link can be calculated.

Figure 1 summarizes the underlying transportation network of a deployment planning problem. Note that there are two types of arcs (arrows) connecting node O1 to node A1 which represent an origin and an airport, respectively. These two arcs indicates the possibility of sending flow from origin O1 to airport A1 by truck or by rail. Also, there are two bi-directional arcs connecting airport A1 to airport A2. One represents the ground link between the two airports and the other represents the air link. There are no arc connecting airports to seaports and vice versa because only two combinations, ground/air and ground/sea, are permitted in the problem. All other arcs have similar meaning to the ones just described.

Note that the capacities for arcs are not depicted in Figure 1. The capacities of arcs representing air or sea transportation are implicitly determined by the number of assets available for the deployment. However, it is assumed that the processing capacities at origins and destinations sufficiently limit the flow of cargoes onto the arcs representing ground transportation so that their capacities becomes inessential to the problem.

To formulate the deployment problem as an IP problem, we define the following:

Definition: A travel pattern for a given lift asset is a travel plan which is feasible to the asset and also specifies the dates and ports at which the MRs to be picked and delivered. By feasible, we mean that

(i) the specified combination of ports, MRs, and the given asset are compatible,

(ii) the asset has enough speed to travel to the designated ports by the specified dates,

(iii) the specified MRs depart from their origins after their available date and arrive at the designated POE on the specified date (here, we assume that the required delivery date (RDD) can be violated at a penalty), and

(iv) the asset can complete the travel pattern within the length of the planning period, denoted henceforth as T_{max}.

Integer Programming Formulation:

Below, we present several formulations of the deployment problem. In these formulations, the following indices are utilized.

i = lift asset

j = travel pattern

m = movement requirement

p = port of embarkation

q = port of debarkation

o = origin

d = destination

t = time (in days). The index t ranges from 1 to T_{max}(the maximum allowable closure date).

Given a set of travel patterns for the lift assets, the following factors can be calculated for each travel pattern j of asset i:

A_m^{ij} = amount of the m^{th} MR to be delivered by the i^{th} asset using the j^{th} travel pattern.

B_{pt}^{ij} = total amount of cargoes to be loaded at the p^{th} POE onto the i^{th} asset using the j^{th} travel pattern on day t.

C_{qt}^{ij} = total amount of cargoes to be unloaded at the q^{th} POD from the i^{th} asset using the j^{th} travel pattern on day t.

D_{ot}^{ij} = total amount of cargoes requested from the o^{th} origin by the i^{th} asset using the j^{th} travel pattern on day t.

E_{dt}^{ij} = total amount of cargoes delivered to the d^{th} destination by the i^{th} asset using the j^{th} travel pattern on day t

G^{ij} = the day on which the last MR is delivered to its destination using the i^{th} asset and the j^{th} pattern.

L^{ij} = amount of late cargoes measured in, e.g., ton-day, due to the i^{th} asset using the j^{th} pattern.

N^{ij} = number of late MRs due to the i^{th} asset using the j^{th} pattern.

To illustrate how the above set of factors are calculated, consider the following situation in which there are 4 MRs, each weighs 5,000 tons and numbered from 1 to 4. MR 1 and 2 originate at origin O1 and destine for destination D1, and MR 3 and 4 originate at origin O2 and destine for destination D2. POE S1 and POD S3 are assigned to MR 1 and 2, and POE S2 and POD S4 are assigned to MR 3 and 4. Assume that a travel pattern of a (sea) lift asset A is being considered. Figure 2 provides the travel time for the essential arcs in the underlying network. These times are calculated from the speed of asset A, the speed of the ground transport (truck), and the geographical distances between various nodes. Assume that the available date and the required delivery date for all MRs are day 1 and day 50, respectively. Then, the following is a feasible travel pattern (schedule) for asset A:

1) Pick up MR 1 at POE S1 on day 3 (which implies that MR 1 departs from origin O1 on day 1).

2) Pick up MR 3 at POE S2 on day 6 (which implies that MR 3 departs from origin O2 on day 2).

3) Unload MR 3 at POD S4 on day 20 (which implies that MR 3 arrives at destination D2 on day 24).

4) Unload MR 1 at POD S3 on day 23 (which implies that MR 1 arrives at destination D1 on day 24).

5) Pick up MR 2 at POE S1 on day 38 (which implies that MR 2 departs from origin O1 on day 36).

6) Pick up MR 4 at POE S2 on day 41 (which implies that MR 4 departs from origin O2 on day 37).

7) Unload MR 4 at POD S4 on day 55 (which implies that MR 4 arrives at destination D2 on day 59).

8) Unload MR 2 at POD S3 on day 58 (which implies that MR 2 arrives at destination D1 on day 59).

We then obtained the following factors from the above travel pattern:

$A_1^{11} = 5{,}000$ $\qquad$ $A_2^{11} = 5{,}000$

$A_3^{11} = 5{,}000$ $\qquad$ $A_4^{11} = 5{,}000$

$A_m^{11} = 0$, for $m > 4$ (there are more that 4 MRs in the problem)

$B_{S1,3}^{11} = 5000$ $\qquad$ $B_{S1,38}^{11} = 5000$

$B_{S2,6}^{11} = 5000$ $\qquad$ $B_{S2,41}^{11} = 5000$

$B_{p,t}^{11} = 0$, for other POE p and day t.

$C_{S3,23}^{11} = 5000$ $\qquad$ $C_{S3,58}^{11} = 5000$

$C_{S4,20}^{11} = 5000$ $\qquad$ $C_{S4,55}^{11} = 5000$

$C_{q,t}^{11} = 0$, for other POD q and day t

$D_{O1,1}^{11} = 5000$ $\qquad$ $D_{O1,36}^{11} = 5000$

$D_{O2,2}^{11} = 5000$ $\qquad$ $D_{O2,37}^{11} = 5000$

$D^{11}_{o,t} = 0,$ for other origin o and day t

$E^{11}_{O3,24} = 5000$ $\qquad$ $E^{11}_{O3,59} = 5000$

$E^{11}_{O4,24} = 5000$ $\qquad$ $E^{11}_{O4,59} = 5000$

$E^{11}_{d,t} = 0,$ for other destination d and day t

$G^{11} = 59$

$L^{11} =$ 180,000 ton-day

(5000 tons of MR 2 late for 9 days + 5000 tons of MR 4 late for 9 days)

$N^{11} = 2$

Other given data are listed below.

α_m = quantity of the m^{th} MR.

β_p = capacity of the p^{th} POE.

φ_q = capacity of the q^{th} POD.

δ_o = capacity of the o^{th} origin.

ξ_d = capacity of the d^{th} destination.

Let x_{ij} denote the (binary) decision variable where the value 1 indicates that the j^{th} travel pattern is assigned to the i^{th} asset and 0 indicates otherwise. Below, several formulations of the deployment problem are presented. It should be noted that in each formulation only a subset of the factors introduced above are utilized.

Model 1: Minimize Lateness

$$\min \sum_i \sum_j L^{ij} x_{ij}$$

s.t

$\sum_i \sum_j A_m^{ij} x_{ij} \geq \alpha_m$	$\forall\ m$	(1)
$\sum_i \sum_j B_{pt}^{ij} x_{ij} \leq \beta_p$	$\forall\ p,t$	(2)
$\sum_i \sum_j C_{qt}^{ij} x_{ij} \leq \varphi_q$	$\forall\ q,t$	(3)
$\sum_i \sum_j D_{ot}^{ij} x_{ij} \leq \delta_o$	$\forall\ o,t$	(4)
$\sum_i \sum_j E_{dt}^{ij} x_{ij} \leq \xi_d$	$\forall\ d,t$	(5)
$\sum_j x_{ij} \leq 1$	$\forall\ i$	(6)
$x_{ij} = 0$ or 1	$\forall\ i,j$	(7)

Constraint 1 ensures that all MRs are delivered, constraints 2-5 guarantee that the capacities at each origin, destination, POE, and POD are not violated, and constraint 6 and 7 allow at most one travel pattern to be selected for each asset.

Model 2: Minimize closure time

$$\min\ z$$

s.t.

$\sum_i \sum_j G^{ij} x_{ij} \leq z$	$\forall\ i,j$	(8)

and constraints 1-7

Constraint 8 simply assigns the longest completion time of the selected travel patterns to z, thereby making z denotes the length of the deployment plan, and the objective in Model 2 is to reduce z as much as possible.

Model 3: Minimize amount of short fall

For this model, we define a new decision variable, u_m, to represent the amount of shortfall for the m^{th} MR, and a new set W(i) to represent the set of travel patterns for the i^{th} asset without any late MR, i.e.,

$$W(i) = \{ j: N^{ij} = 0\}$$

Then, the problem becomes

$$\min \Sigma_m u_m$$

s.t

$$\Sigma_i \Sigma_{j\varepsilon W(i)} A_m^{ij} x_{ij} + u_m \geq \alpha_m \qquad \forall\ m \qquad (9)$$

$$\Sigma_i \Sigma_{j\varepsilon W(i)} B_{pt}^{ij} x_{ij} \leq \beta_p \qquad \forall\ p,t \qquad (10)$$

$$\Sigma_i \Sigma_{j\varepsilon W(i)} C_{qt}^{ij} x_{ij} \leq \varphi_q \qquad \forall\ q,t \qquad (11)$$

$$\Sigma_i \Sigma_{j\varepsilon W(i)} D_{ot}^{ij} x_{ij} \leq \delta_o \qquad \forall\ o,t \qquad (12)$$

$$\Sigma_i \Sigma_{j\varepsilon W(i)} E_{dt}^{ij} x_{ij} \leq \xi_d \qquad \forall\ d,t \qquad (13)$$

and constraints 6 & 7

Model 4: Minimize the number of assets to be used for the deployment with the restriction that no late MR is allowed.

$$\min \Sigma_i \Sigma_j x_{ij}$$

s.t.

$$\Sigma_i \Sigma_{j\varepsilon W(i)} A^{ij}_m x_{ij} \geq \alpha_m \qquad \forall\ m \qquad (14)$$

and constraints 6, 7, and 10 to 13.

The above four models are only a sample of possible formulations of the deployment problem. In fact, if the cost for using each travel pattern can be calculated, one can also formulate an IP problem to minimize cost. However, it is clear from this sample that travel patterns allow for a variety of formulations. Another advantage of the travel pattern is the fact that in none of the model is there any specification of the way in which the travel pattern is to be generated. Thus, users have the flexibility to incorporate any operating restrictions imposed by rules and relationship specific to individual assets, ports, cargoes, or interaction of combinations of these (see, e.g, Brown, Grave, and Ronen [1987]). However, it goes without saying that the more flexibility one allows the more difficult it is to generate a travel pattern. In the next section, we discuss the complexity of this type of formulation.

3 Complexity of the Formulations with Travel Patterns

Consider the deployment problem in which all assets are of one type, e.g., breakbulk, and they all have the same capacity. Moreover, assume that the MRs have been aggregated so that each MR takes up the entire capacity of the asset, and that each MR has been assigned to specific POE and POD. This last assumption eliminates the need to consider the ground transportation in the optimization, if the processing capacities at origins and destinations are sufficiently large. Under the assumptions stated thus far, Buvik [1988] and Newton [1988] showed in their Masters theses that Model 2 (Minimize Closure Time) and Model 3 (Minimize Shortfall) reduce to the mixed set covering and partitioning problems. Both these problems are NP-complete. To obtain a 'good' solution, Buvik and Newton solved the LP relaxation problem instead. (Due to the degeneracy, the LP relaxation also presents difficulties. For further discussion, see Brown et al. [1987].) Besides the LP relaxation, there are a number of heuristics algorithms for solving the set covering and partitioning problem and the reader is referred to the Ph.D. thesis by Hey [1981] for a complete discussion.

Another aspect of the formulations with travel patterns is the travel patterns themselves. In all four models, it is implicit that the travel patterns are readily available. This may be true when the number of MRs is small. In practice, the generation of travel patterns is burdensome, if not impossible. There are two approaches to generating the patterns: one is to generate a subset of patterns prior to the solution process and the other is to generate them during the solution process using the column generation framework (i.e., the Dantzig-Wolfe Decomposition). The first approach requires an enumeration of a subset of possible combinations of MRs and ports. (Due to the extreme large number of possible combinations, it is usually impossible to enumerate all possible combinations.) In the column generation framework, the most beneficial pattern is generated when necessary. The benefit of a pattern to the deployment plan is measured by the value of the reduced cost associated with the pattern. The reduced cost is calculated from the dual variables of the most current linear programming relaxation. So, generating the most beneficial pattern is equivalent to selecting the most negative reduced cost to enter the basis in the standard simplex method. However, generating the most beneficial pattern requires solving an optimization problem. For Model 2 with the assumptions stated at the beginning of this section, Lawphongpanich and Rosenthal [1988] showed that this optimization problem is a shortest path problem with time windows which can be solved effectively by a modified Dijkstra algorithm developed by Desrochers et al. [1988]. Without the assumptions concerning the aggregation MRs and the capacities of the ports, the problem of generating the most beneficial pattern becomes a short path problem with several side constraints which is again NP-complete. Several researchers (Aneja et al. [1987], Beasley and Christofides [1986], Handler and Zang [1980], Joksch [1966], Minoux [1975], and Ribiero [1983]) have used dynamic programming and Lagrangian Relaxation technique to solve small to medium size problems.

4. Properties of an Optimal Solution:

In this section, we examine the necessary properties of optimal travel patterns. Assume for the discussion that

1) All POEs are all on one side of the ocean and all PODs are on the other side.

2) The distance measure satisfies the triangle inequality.

3) The loading time for an MR is same at all POEs.

Assumption 1 implies that a typical travel pattern requires that the asset makes several transoceanic trips. Prior to each transoceanic trip, an asset must pick up a collection of MRs from a number of POEs, the supply side of the ocean, and then crosses the ocean to unload the MRs at the PODs, the demand side of the ocean (see Figure 3).

Property 1: Assume that for a given optimal travel pattern, the MRs arrives to their designated POEs prior to the arrival of the asset, then, in order to minimize the lateness or closure time, the sequence in which the asset visits the POEs (to pick up the MRs) must yield the minimum traveling time.

Proof: Assume that MR numbered 1 to k are to be picked up by the asset. Let AR_i , for i = 1,..., k, denote the arrival time of MR i to their designated POE, and AR* denote the arrival time of the asset to its nearest POE. By assumption, $AR^* > AR_i$. Note that the time the asset has to spend at each POE includes the time to load the MRs and the time it has to wait for the MRs to arrive from the origins. By the assumption, the waiting time is zero. Thus, the total time that an asset has to spend on the supply side of the ocean is the loading time of k MRs plus the time to travel to the different POEs. By Assumption 3, the loading time is constant. So, by minimizing the traveling time, the asset can begin its transoceanic trip to the PODs earlier, thereby arriving at the PODs earlier and reducing the closure time and lateness, if any.[]

The problem of routing the asset through a set of POEs so as to minimize the completion time is equivalent to the Traveling Salesman Problem, an NP-complete problem. However, when the distance between POEs have special structure, e.g., straightline and shoreline, then the routing problem is simplified. Kim [1985] defines the straightline and shoreline structures as follows.

Definition: Let t(i,j) denotes the distance between point i and point j. Given a set of points 1, 2, ..., n, then this set of points is said to satisfy the straight line structure if, for all $1 \le i \le k \le j \le n$,

i) $t(i,i) = 0$,

ii) $t(i,j) = t(j,i)$,

iii) $t(i,j) \ge t(i,k)$,

iv) $t(i,j) \ge t(k,j)$,

v) $t(i,j) = t(i,k) + t(k,j)$.

Definition: Let t(i,j) denotes the distance between point i and point j. Given a set of points 1, 2, ..., n, then this set of points is said to satisfy the shoreline structure if, for all $1 \le i \le k \le j \le n$, the distance satisfies conditions (i) to (iv) above and

v') $t(i,j) \le t(i,k) + t(k,j)$.

Figure 4 illustrates both the straightline and shoreline structures. Note that both the straightline and shoreline structures are special case of the Euclidean distance.

With respect to Property 1, if the distances between the POEs satisfy either the shoreline or straightline structure, the routing problem is trivial, i.e., the asset should go along the straightline or the shoreline. However, if the MRs do not all arrive prior to the arrival of the asset, the problem becomes more difficult. In the straightline case, Kim [1985] showed that the problem can be solved optimally by a dynamic programming approach. For the shoreline case, the problem is NP-complete and Kim proposed a heuristic algorithm.

The above discussion assumes that the POEs to be visited has been determined for a given travel pattern. When the routing and the determination of POEs to be visited are be performed simultaneously, it would be logical to minimize the number of POEs an asset has to visit. In an ideal situation, this number is one.

Now, consider the problem on the demand side of the ocean, that is, how to unload the MRs on board an asset. In particular, we assume that (1) the asset in question is a sea transport, (2) there exists a ground link between any pair of POD and destination, and (3) ground speed is faster than sea speed. Then, we have the following property concerning how best to unload the MRs on board a sealift asset.

<u>Property 2</u>: Given that assumptions 1, 2, 3, and the preceding three assumptions hold. Then, it is optimal with respect to minimizing lateness and closure time to unload all MRs at <u>one</u> POD, if it has sufficient capacity.

<u>Proof</u>: Assume that the MRs on board are numbered from 1 to k. Moreover, assume that in an optimal solution the MRs are unloaded at two PODs: A and B. Define

1) I_A and I_B as the set of MRs unloaded at POD A and B,

2) $\tau_{A,B}$ as the travel time by sea from POD A to B,

3) $t_{A,B}$ as the travel time by truck from POD A to B, and

4) $t_{A,d(i)}$ and $t_{B,d(i)}$ as the travel time by truck from POD A and B, respectively, to destination d(i) of i^{th} MR.

Then, for all $i \in I_B$, the time that MR i arrives is its destination, d(i), is given by

$$\begin{aligned}&\text{Departure time from A + transit time from A to B + delivery time}\\&= \text{Departure time from A} + \tau_{A,B} + t_{B,d(i)}\\&> \text{Departure time from A} + t_{A,B} + t_{B,d(i)}\\&\geq \text{Departure time from A} + t_{A,d(i)}\\&> t_{A,d(i)}\end{aligned}$$

where the strict inequality follows from the assumption that ground speed is faster than sea speed, i.e., $\tau_{A,B} > t_{A,B}$, the inequality follows from the triangle inequality, and the last strict inequality follows from that fact that the departure time must be positive. Note that $t_{A,d(i)}$ is the time at which MR i, for $i \in I_B$, arrives at its destination if it was unloaded at POE A. Thus, by unloading all MRs at POD A, each MR that was originally unloaded at POD B arrives at their destination earlier. So, we can only improve the solution by unloading only at POD A, and the property is proved.[]

To summarize, we conclude from Property 1 that when possible it is logical to load an asset at one POE prior to an ocean crossing and from Property 2 that when the PODs have sufficient capacity sealift asset should be unloaded at only one POD. In the next section, we propose a heuristic procedure based on these two observations.

5. A Heuristic Procedure

Below, we present a heuristic algorithm for the deployment problem with the objective of minimizing the closure date or lateness. It is assumed that all MRs are to be sealifted from POEs to PODs. If there are MRs requiring airlift, they can be considered separately using the GAMS based program called the Lift Optimizer by Rosenthal [1988]. For MRs which can be transported by sea or air, the procedure below can be used to determine whether they can be delivered in a reasonable amount of time by sealift assets. If not, they must then be transported by air.

The motivation for this heuristic procedure is the observation made in the previous section that, with respect to the objective of minimizing closure time and lateness, a 'good' travel pattern requires a minimum number of port visits for the sealift assets. In trying to achieve the minimum number of port visits, the procedure sequentially constructs a portion of a travel pattern for one ship at a time as they become available. An asset becomes available for the first time when they completed their last mission prior to the deployment. Afterward, an asset becomes available again and again as soon as it finishes unloading at PODs. For the ship under consideration, the procedure constructs the portion of the schedule which includes first the visit to the POEs, the ocean crossing, and the visit to <u>one</u> POD. To minimize the number of visits to different POEs, the procedure always selects the POEs which provides the maximum amount of cargoes for the asset.

To formally state the procedure, we define AV(i) as the time that asset i will become available, N as the number of assets available for the deployment, and T_{max}, as before, the maximum allowable closure date.

<u>Step 0</u>: (Initialization)

Set AV(i) to the time when asset i will be available for the deployment.

<u>Step 1</u>:

If there is no more MRs to be delivered, stop. Otherwise, let $i^* = \text{arg. min.}\{AV(i) : i = 1,\ldots,N\}$, i.e., asset i* is the first asset to become available. Go to Step 2.

<u>Step 2</u>:

For asset i*, find a compatible POE at which a maximum amount of MRs can be loaded onto asset i*. Schedule asset i* to visit this POE, mark the corresponding as 'assigned' to asset i*, and update the remaining capacity of the POE appropriately. If asset i* is still not full, repeat this process with the remaining POEs and MRs.

Step 3:
Find a POD which is nearest to last POE and has sufficient capacity to unload cargoes on board asset i*. If none exists, go to the PODs in order of decreasing remaining capacity until all cargoes are unloaded from asset i*.

Step 4:
Compute

i) T*, the total time for asset i* to complete the loading of MRs, crossing the ocean, and unloading at the PODs, and

ii) T_{last}, the time the last MR assigned to asset i* arrives at its destination.

If T_{last} is greater than T_{max}, stop and it is not possible to close the deployment by T_{max}. Otherwise, set AV(i*) = AV(i*) + T* and go to Step 1.

There are different approaches in determining the maximum amount of cargoes which can be loaded on an asset at different POEs. We formally state one approach to illustrate the idea and the necessary calculation. First, define

1) W_m as the weight of MR m,

2) R_m as the ready date for MR m, and

3) $t_{o(m),p}$ as the travel time (by truck or rail) from origin o(m) of m^{th} MR to the p^{th} POE.

Then, for asset i* determined in Step 1,

1) For each pair, (m,p), of MR and POE, let

$$AR(m,p,i^*) = R_m + t_{o(m),p}, \text{ if the combination of MR m, POE p, and asset } i^* \text{ is compatible}$$
$$= 0, \quad \text{otherwise.}$$

2) For each POE p, let

$$M(p,\alpha,\beta) = \{ m : \alpha \leq AR(m,p,i^*) \leq \beta \text{ and MR } m \text{ has not been assigned or delivered} \}$$

where α and β are usually taken to be AV(i*) and the time that asset i* can arrive at POE p, respectively. So, $M(p,\alpha,\beta)$ is the collection of MRs which can arrive at port p between day α and day β.

3) For each POE p, let

$$\text{Load}(p,i^*) = \Sigma_m w_m, \quad \text{where the index } m \text{ ranges over the set } M(p,\alpha,\beta).$$

Thus, Load(p,i*) is the total amount of cargoes which can be loaded on to asset i* at POE p.

4) Let $CAP(p,\beta)$ be the remaining capacity of POE p on day β. Then, the maximum amount of cargoes that can be loaded on to asset i* at POE P is

$$L(p,i^*) = \max\{ CAP(p,\beta), \text{Load}(p,i^*) \}.$$

In Step 2, we would then choose the POE with maximum value of L(p,i*) as the one to visit.

6. Summary and Future Plan

We show that the deployment planning problem which includes all three TOAs can be formulated as an integer programming problem and that this problem is difficult to solve optimally. By examining the properties of an optimal solution to the integer programming problem, we are able to establish a heuristic rule for scheduling sea assets. Based on this rule, we propose a heuristic procedure to address a deployment problem.

The proposed heuristic procedure follows the general approach existed in the literature. This approach answers the feasibility question by actually constructing schedules to transport the MRs to their destination. If a feasible set of schedules can be constructed, then the tactical plan in question can be supported logistically. Otherwise, it cannot be supported.

However, a different approach is to bypass the construction of the schedules and focus on determining whether it is possible to deliver all MRs to their destinations. We believe that this approach has merit and plan to pursue it further.

References

Y.P. Aneja, Y. Aggarwal, K.P.K. Nair [1983], "Shortest Chain Subjected to Side Constraints," Networks 13, 295-302.

J.E. Beasley and N. Christofides [1986], "An Algorithm for the Resource Constrained Shortest Path Problems," Research Report, Department of Management Science, Imperial College, London, England.

L. Bodin, B. Golden, A. Assad, and M. Ball [1983], "Routine and Scheduling of Vehicles and Crews," Computer and Operations Research 10, No. 2, 1-211.

G.G. Brown, C.E. Goodman, and R.K. Wood [1987], "Annual Scheduling of Atlantic Fleet Naval Combatants," Technical Report, Department of Operations Research, Naval Postgraduate School, Monterey, CA, 93943.

G.G. Brown, G.W. Graves, and D. Ronen [1987], "Scheduling Ocean Transportation of Crude Oil," Management Science 33, No. 3, 335-346.

S. Buvik [1988], "An Algorithm for Generating Ship Schedules for a Crisis Deployment Problem," Masters Thesis, Department of Operations Research, Naval Postgraduate School, Monterey, CA, 93943.

K.S. Collier [1987], "Deployment Planning: A Linear Programming Model with Variable Reduction," Masters Thesis, Department of Operations Research, Naval Postgraduate School, Monterey, CA, 93943.

M. Desrochers and F. Soumis [1988], "A Generalized Permanent Labelling Algorithm for the Shortest Path Problem with Time Windows," Information Systems and Operations Research 26, No. 2, 191-212.

J. Desrosiers, F. Soumis, and M. Desrochers [1984], "Routing with Time Windows by Column Generation," Networks 14, 545-565.

B.L. Golden and A.A. Assad [1988], Vehicle Routing: Methods and Studies, North-Holland, New York.

G.Y. Handler and I. Zang [1980], "A Dual Algorithm for the Constrained Shortest Path Problems," Networks 10, 293-310.

A.M. Hey [1980], "Algorithms for the Set Covering Problem," Ph.D. Thesis, Department of Management Science, University of London, London, England.

J.M. Jaffe [1984], "Algorithms for Finding Paths with Multiple Constraints," Networks 14, 95-116.

J.J. Jarvis and H.D. Ratliff [1984], "System for Closure Optimization Planning and Evaluation (SCOPE)," PDRC Report 84-09, Department of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA, 30332.

H.C. Joksch [1966], "The Shortest Route Problem with Constraints," Journal of Mathematical Analysis and Applications 14, 191-197.

T. Kim [1985], "Solutions Algorithms for Sealift Routing and Scheduling Problems," Ph.D. Thesis, Department of Ocean Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.

M.J. Lally [1987], "Strategic Allocation of Sealift: A GAMS-based Integer Programming Approach," Masters Thesis, Department of Operations Research, Naval Postgraduate School, Monterey, CA, 93943.

S. Lawphongpanich and R.E. Rosenthal [1988], "A Column Generation Approach to a Time-Sensitive Deployment Planning Problem," a progress report presented at the Oak Ridge National Laboratory.

E.L. Lawler, J.K. Lenstra, A.H.G. Rinnooy Kan [1985], The Traveling Salesman Problem, John Wiley & Sons, New York.

N.R. Lima [1988], "A Column Generation Technique for A Crisis Deployment Planning Problem," Masters Thesis, Department of Operations Research, Naval Postgraduate School, Monterey, CA, 93943.

M. Minoux [1975], "Plus Court Chemin avec Contraintes: Algorithms et Applications,' Annales des Telecommunications 30, No, 12, 1-12.

H.N. Psaraftis, J.B. Orlin, D. Bienstock, P.M. Thompson [1985], "Analysis and Solution Algorithms of Sealift Routing and Scheduling Problems: Final Report," Sloan Working Paper 1700-85, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, 02139.

C.C.C. Ribiero [1983], "Algorithms de Recherche de Plus Courts Chemins avec Contraintes: Etude Theorique, Implementation et

Parallelisation," Thesis presented at Ecole Nationale Superieure des Telecommunications, Paris.

R.E. Rosenthal [1988], The Lift Optimizer, a GAMS program, Department of Operations Research, Naval Postgraduate School, Monterey, CA, 93943.

M.M. Solomon and J. Desrosiers [1988], "Time Window Constrained Routing and Scheduling Problems," Transportation Science 22, No. 1, 1-13.