

# NAVAL POSTGRADUATE SCHOOL MONTEREY, CALIFORNIA



## THESIS

### OPTIMIZING STRATEGIC SEALIFT

Gust W. Pagonis

September, 1995

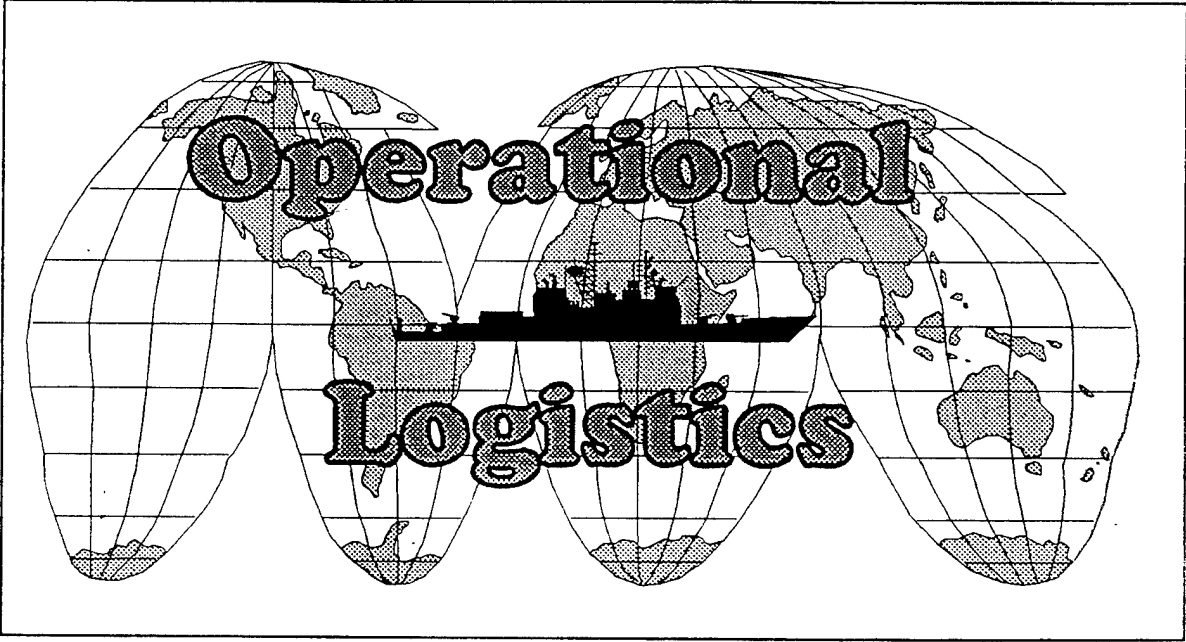
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**OPTIMIZING STRATEGIC SEALIFT**

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Submitted in partial fulfillment  
of the requirements for the degree of

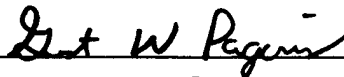
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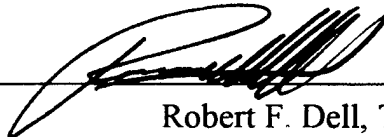
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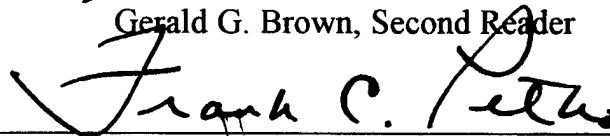
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## ABSTRACT

Strategic sealift is critical for the United States to be able to project military power worldwide. During the 1990 Persian Gulf War, over 95% of all military equipment arrived in theater via sealift. The importance and difficulty of sealift planning has motivated the development of a number of decision aids. These aids, relying heretofore on a combination of heuristics and simulation, help determine for a given sealift mission the overall gross transportation feasibility. The key to this transportation feasibility is satisfying desired force closure --- the time units arrive in the theater of operations. This thesis introduces optimization models to help plan ship schedules that deliver units as close as possible to their required arrival times. The prototypic models are demonstrated on a dual major regional conflict, obtaining near optimal solutions in less than two hours.



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## EXECUTIVE SUMMARY

Strategic sealift is critical for the United States to be able to project military power worldwide. During the 1990 Persian Gulf War, over 95% of all military equipment arrived in theater via sealift. The importance and difficulty of sealift planning has motivated the development of a number of decision aids. These aids, relying heretofore on a combination of heuristics and simulation, help determine for a given sealift mission the overall gross transportation feasibility. The key to this transportation feasibility is satisfying desired force closure --- the time units arrive in the theater of operations. The imprecise, heuristic nature of the current decision aides may lead them to incorrectly declare a desired force closure to be infeasible.

This thesis develops optimization models to help plan ship schedules that deliver units as close as possible to the desired force closure dates. A ship schedule is a list of what units the ship picks up, what day it picks them up, where it picks them up, when it discharges them, and where it discharges them. The number of possible candidate ship schedules may be very large, for a given scenario, and could cause the subsequent optimization to be difficult. This thesis develops a schedule generator that produces only good candidate schedules. From this candidate set of ship schedules the optimization model selects the subset that delivers units as close as possible to their desired force closure date, while enforcing port capacities, and ensuring the movement of all units.

By not considering every possible day a ship could pick up a unit, the number of candidate ship schedules is reduced. This restriction can cause a problem during optimization. There might be a set of good schedules that delivers every unit by its desired force closure, but on one day, in one port, there may be one too many ships. Here, it would be reasonable to delay one ship by one day. We deal with this by allowing a violation of the port capacities at a penalty. If there is a violation of a port capacity, manual post processing determines which ship, at what port, and at what time the delay should occur.

This thesis demonstrates sealift planning for both a single and a dual major regional conflict. The generation of ship schedules takes less than 25 minutes on a personal computer. Implementable ship schedules can be selected in less than two hours, and only minimal manual post processing and expert interpretation has been required.

This thesis demonstrates that the critical assessment of transportation feasibility can be sharpened with optimization. Furthermore, reliable answers are obtainable in a relatively short amount of time (compared with most simulation models), and are face valid and usable as a basis for the execution of an Operations Plan.

## **I. INTRODUCTION**

This thesis optimizes the scheduling of strategic sealift with respect to force closure and priority of units. Known data about unit transportation requirements and available sealift assets are used to produce optimal ship schedules. Prior to this thesis, there were only simulation models to help plan and execute strategic sealift.

### **A. STRATEGIC SEALIFT**

#### **1. Definition of Strategic Sealift**

Strategic sealift is the collection of ships designed and used for inter-theater shipment of military equipment [Military Sealift Command, 1992, p2]. The term strategic sealift can also denote the planning and execution of operations involving these ships.

#### **2. Importance of Strategic Sealift**

A critical component of the United States' (US) foreign policy is the ability to project military power throughout the world. The projection of military power is impossible without sealift. Historically, sealift moves the bulk of military cargo into a theater of operations. During the 1990 Persian Gulf War, over 95% of all military equipment arrived in theater via sealift [Pagonis, 1992, p10].

Currently, US military forces are being reduced to implement the Bottom Up Review [Aspin, 1993]. As a result, there are now fewer forward deployed units. This forces a greater reliance on sealift to get the US military forces to a theater of operations.

### 3. Strategic Sealift Assets

#### *a. Fast Sealift Ships*

The Fast Sealift Ship (FSS) (Figure 1.1) is a large combination Roll-On/Roll-Off (RO/RO) and Lift-On/Lift-Off (LO/LO) ship. (The Appendix lists all acronyms contained in this thesis.) It can carry up to 180,000 square feet of RO/RO unit equipment and 182 twenty-foot equivalent containers. RO/RO and container space is interchangeable on a limited basis. The US currently has eight of these ships, and all are on active duty.

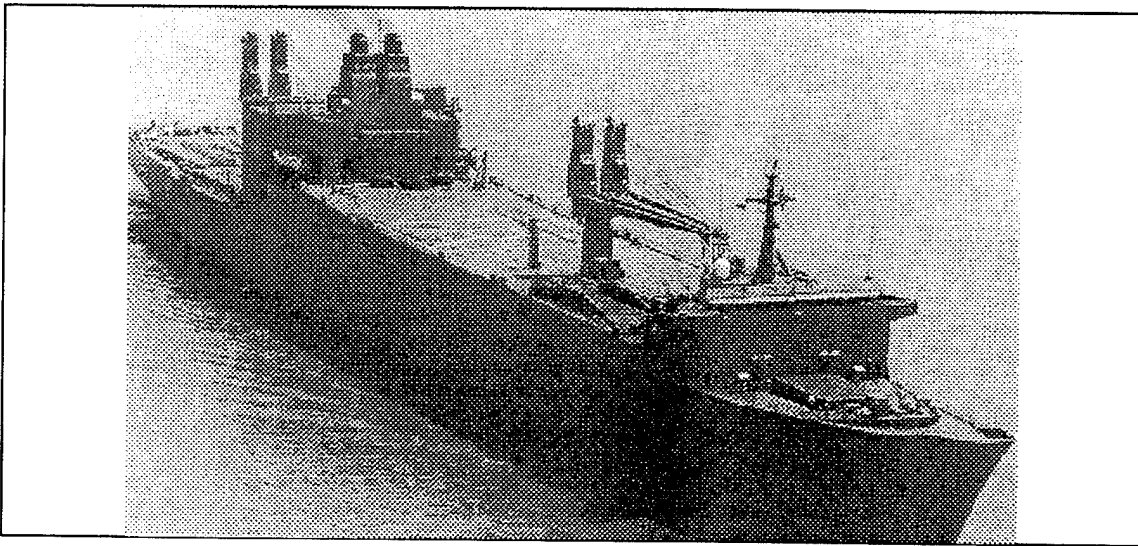


Figure 1.1. The Fast Sealift Ship USNS Capella is underway during the 1990 Persian Gulf War. The forward part of the ship has six decks and can hold up to 180,000 square feet of Roll-On/ Roll-Off equipment. The aft part of the ship has four holds and can hold up to 182 twenty-foot equivalent containers. Scheduling the eight Fast Sealift Ships is critical during a deployment because of their relatively large cargo capacity and fast speed. [Military Sealift Command, 1992, p16].

*b. Prepositioning Ships*

There are 11 ships with US Army equipment and 13 ships with US Marine Corps equipment pre-loaded. The bulk of these ships are in Diego Garcia and can respond very quickly to any contingency near that location. These ships (Figure 1.2) have different sizes, but are all designed to allow the military to establish a quick presence and to facilitate the follow-on surge to the theater of operation. These ships are available for general use after they unload their initial equipment in the theater of operation.

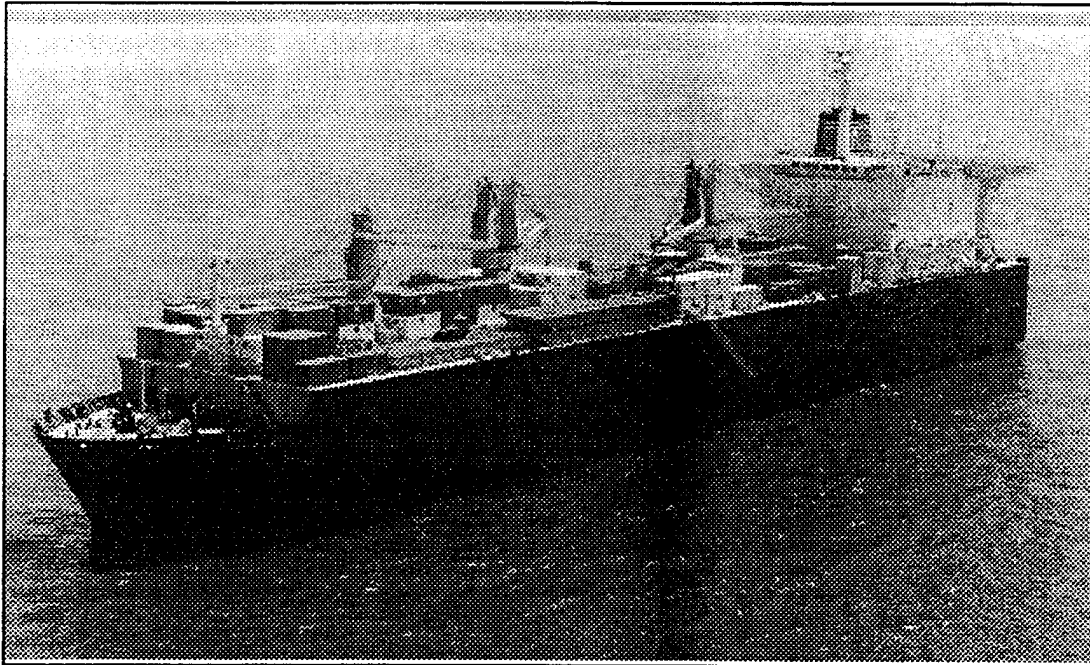


Figure 1.2. The Maritime Prepositioning Ship MV 1st LT Jack Lummus. United States Marine prepositioning ships, in combination with United States Army prepositioning ships, will likely be the first ships to enter a theater. United States Army versions carry key port opening packages that allow the use of the port by follow-on ships. After these ships unload their initial cargo, their subsequent scheduling and use is like any other ship type. [Military Sealift Command, 1992, p17].

*c. Roll-On/Roll-Off Ships*

There are 17 RO/RO ships (Figure 1.3) in the Ready Reserve Fleet (RRF) which vary in size. These ships carry unit equipment, and only a few twenty-foot equivalent containers.

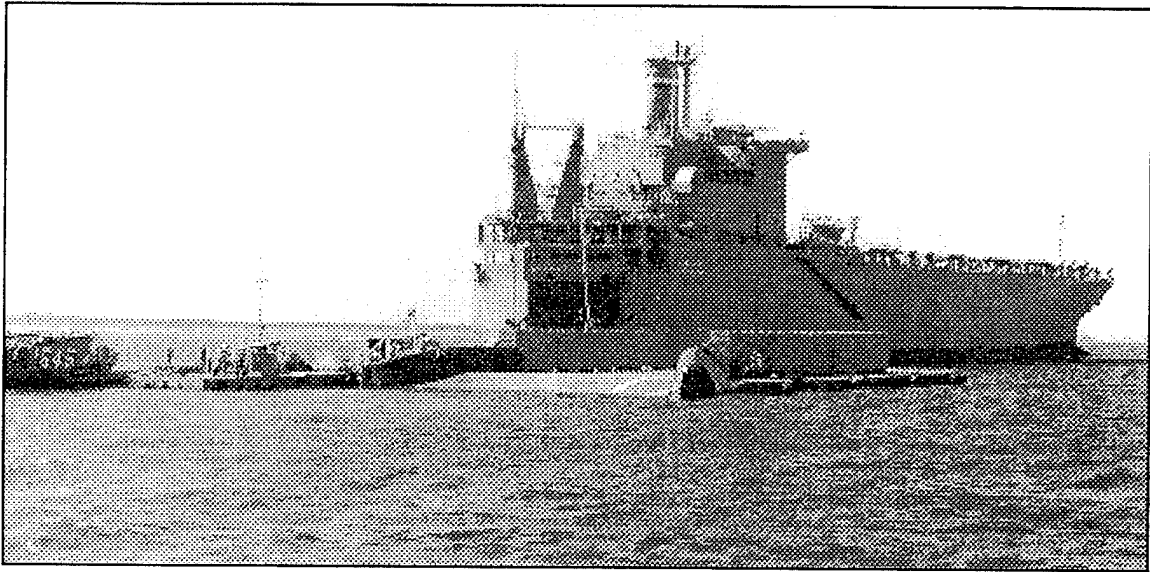


Figure 1.3. The MV Cape Ducato during a Joint Logistics Over the Shore exercise. The scheduling of Roll-On/ Roll-Off ships is important for deploying unit equipment (rolling stock). These are reserve ships and activation must occur before use. Once activated, these ships provide most of the United States capability to move unit equipment. [Military Sealift Command, 1992, p7].

*d. Container and Break Bulk Ships*

There are 48 Break Bulk (BB) and 9 container ships (Figure 1.4) in the RRF. These are LO/LO ships and take considerably longer to load than the RO/RO ships with unit equipment. However, the container ships are large and can carry up to 820 twenty-foot equivalent containers.

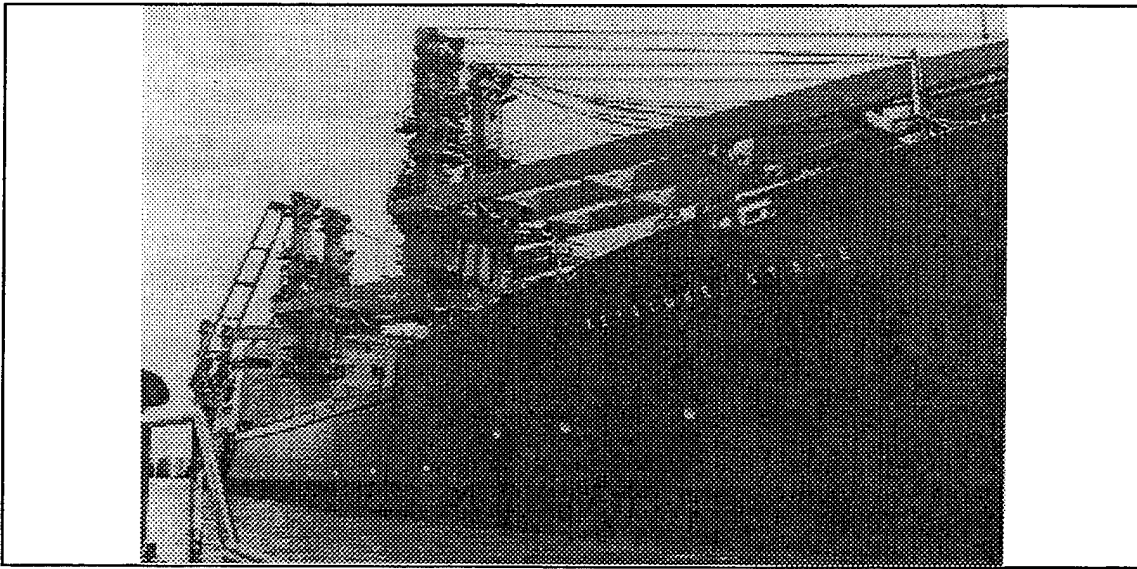


Figure 1.4. The container ship SS Keystone State. Scheduling of container ships is normally more important during the sustainment phase of an operation. Container ships carry up to 820 twenty-foot equivalent containers. Like the Roll-On/ Roll-Off, ships they are in the reserve, and activation must occur before use. Break Bulk ships are older, slower, and carry less cargo than any other class of ship. The scheduling of the reserve Break Bulk ships is a last resort. [Military Sealift Command, 1992, p19].

*e. Location of the Ready Reserve Fleet*

The RRF is split between many locations in the continental US to allow flexibility for future deployments. Figure 1.5 shows the locations of the RRF, and Table 1.1 shows the numbers by ship type in the RRF along with the total active duty fleet.

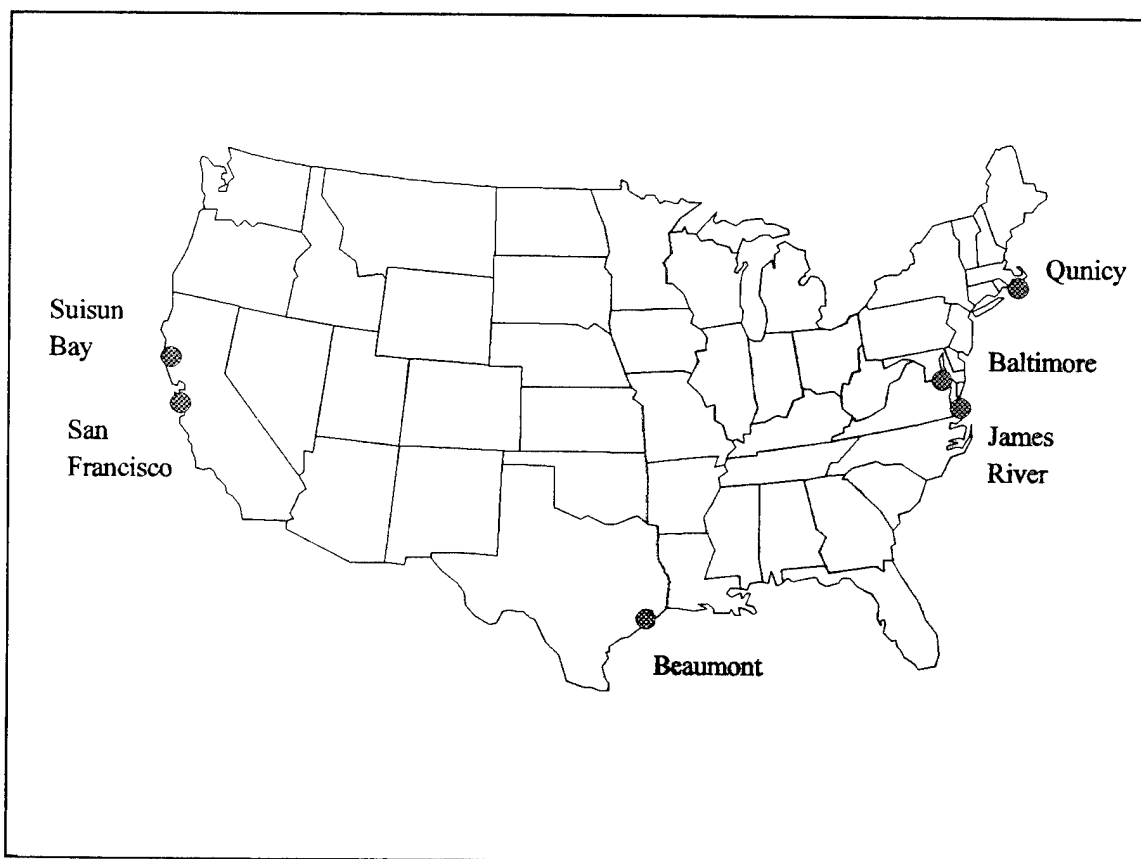


Figure 1.5. The Ready Reserve Fleet is located to allow flexibility during operations. The Ready Reserve Fleet requires activation by the Secretary of Defense before use. Scheduling these ships is critical during most deployments.

Location	FSS	PREPO	BB	Container	RO/RO
James River, VA			15	3	6
Beaumont, TX			10	3	5
Suisun Bay, CA			20	3	6
Quincy, MA			1		
Baltimore, MD			1		
San Francisco, CA			1		
Active Duty	8	24			
<b>TOTAL</b>	<b>8</b>	<b>24</b>	<b>48</b>	<b>9</b>	<b>17</b>

Table 1.1. Locations and numbers of ships in the Ready Reserve Fleet and on active duty as of 1 JAN 95 [Kaskin, 1995, p23]. These ships represent the total military strategic sealift assets of the US. The scheduling of these limited assets is critical during any deployment.

## **B. STRATEGIC SEALIFT PLANNING**

### **1. Operations Plan Development**

The US military divides the world into regions. Each region is the responsibility of one Unified Command with its own Commander-In-Chief (CINC). Each CINC has

many Operations Plans (OPLANs) (war contingency plans defining US military actions) detailing various responses to potential conflicts in his region. An important part of these plans is the Time Phased Force Deployment Data (TPFDD). This data includes information such as the time each military unit is ready to load on ships, the earliest and latest time the unit can be off-loaded, and the size of the deploying unit.

The Joint Operational Planning System (JOPES) [Department of Defense, 1993] builds and maintains a TPFDD for each OPLAN. This system uses the requirements identified by the CINCs, and documents the entire deployment.

## **2. United States Transportation Command**

United States Transportation Command (USTRANSCOM) is a unified command with elements from all the military services. One major mission of USTRANSCOM, in support of the different CINCs, is to determine transportation feasibility for each OPLAN. The most important consideration is force closure. In this context, force closure is the date a unit is completely in the theater of operations. Each unit has an earliest arrival date in a theater (EAD) and a latest arrival date in a theater (LAD). Other factors limiting transportation feasibility include the various ship lengths, speeds, configurations (usable container space and RO/RO space), and usable pier space at each various port (total feet of pier space). Using different simulation models, USTRANSCOM seeks a feasible way to deliver all the units on time. If no feasible plan is discovered, and the OPLAN is not allowed more strategic sealift or airlift assets, the supported CINC decides which units can

arrive later than originally scheduled. This data is then conveyed to JOPES, and maintained by USTRANSCOM for later execution.

## **C. STRATEGIC SEALIFT EXECUTION**

### **1. Military Sealift Command**

The OPLAN's strategic sealift execution is the responsibility of the Military Sealift Command (MSC). MSC is a subordinate of USTRANSCOM and its major responsibility is the RRF. MSC issues orders to the ships to load units at specific ports at specific times [MSC, 1992, p6].

### **2. Operations Plan Execution**

Because more details become available during OPLAN execution, the OPLAN is modified on the fly. This can cause drastic changes to the TPFDD. It is common for the TPFDD to continue to change throughout the deployment [Pagonis, 1992, p72].

Currently, MSC implements all changes manually, relying on the experience of MSC planners and the ship crews.

## **D. DIFFICULTIES IN STRATEGIC SEALIFT PLANNING AND EXECUTION**

### **1. Experiences During the 1990 Persian Gulf War**

During the 1990 Persian Gulf War the force size grew dramatically, highlighting an acute shortage of sealift. The use of foreign ships, in combination with those that the US owned, met the requirements of the war [Pagonis, 1992, p10]. Without this external help it would have been difficult to complete the same mission [Pagonis, 1992, p215].

A critical problem was the activation of the RRF. The RRF operates according to the Readiness Operating Status (ROS). Each ship's ROS is the number of days it takes to ready itself to sail. Unfortunately, the RRF's record during the 1990 Persian Gulf War was poor. Often the times needed to activate ships were much longer than expected. Even when a reserve ship was finally ready, qualified merchant mariners were often unavailable to sail it [Pagonis, 1992, p216].

During the war the VII Corps (consisting of four armor and mechanized infantry divisions) deployed from Germany. The distance between Germany and Saudi Arabia (via the Suez Canal) is only about half the distance between the US and Saudi Arabia. It required over 60 ships (almost half the total requirement of the entire war) to transport the VII Corp's unit equipment [Pagonis, 1992, p135]. Currently the US Army has less than one corps remaining in Europe compared to more than two army corps in 1990. Therefore, another sealift of this size would take even longer or require more ships.

## **2. Improvements to Strategic Sealift Since the 1990 Persian Gulf War**

Resolution of some glaring problems in strategic sealift occurred after the 1990 Persian Gulf War. In 1992 Congress approved funding to procure an additional 17 Large Medium Speed RO/RO (LMSR) ships [MSC, 1992, p21]. Six of these ships are to preposition US Army forces afloat, and the rest are for the RRF. This may not completely solve the problem because of two factors: all the ships will not be ready until the year 2003, and many reserve ships are becoming very old and may not last until then.

MSC has changed the ROS system to make it more realistic and responsive. Small crews have been assigned to the quick response ready reserve ships to maintain them. The crews must pass annual tests and get their ship ready to sail during the specified ROS time. The reduction in response time is encouraging, but on average the crews are still not meeting the deadlines imposed by the new ROS system [MSC, 1992, p20].

Considering the current state of the RRF, sealift is still a critical commodity to project a US military force. Improvements to the RRF are encouraging. However, the US military does not have (nor will it have in the near future) a surplus of sealift. The management of these ships is critical.

## **E. OBJECTIVE**

### **1. Thesis Objective**

Sealift is critical in any military deployment. Without sealift the US cannot project the bulk of its military forces overseas. Limited ships demand efficient use of strategic sealift planning and execution. This thesis suggests a tool to optimally determine force closure for any OPLAN.

### **2. Thesis Outline**

This thesis has five chapters. Chapter I has defined strategic sealift while Chapter II covers related research. Chapter III covers the methodology used in this thesis. There are two main parts: generation of good candidate schedules, and the optimal selection of a workable set of schedules from the acceptable candidates. Chapter IV covers the results obtained using these models with data for both a single Major Regional Conflict (MRC) and a dual MRC. Chapter V contains conclusions, and the Appendix contains a list of acronyms.

## II RELATED RESEARCH

There are three different types of existing models related to this thesis. The first answers questions about strategic sealift ship scheduling using simulation and heuristics. The second uses optimization modeling similar to this thesis. The last type of model generates the data needed for this thesis.

### A. SIMULATION MODELS

#### 1. Analysis Mobility Platform - Model for Intertheater Deployment by Air and Sea

Analysis Mobility Platform - Model for Intertheater Deployment by Air and Sea (AMP-MIDAS) [GRC & Marcotte, 1992, p1] is a combination heuristic and simulation in wide use as a component of USTRANSCOM's Analysis Mobility Platform. It deals with both strategic airlift and strategic sealift during a deployment. AMP-MIDAS has the following multiple objectives: efficient use of strategic airlift and sealift assets, arrival of forces as soon as possible, sequential order of forces by unit required delivery date, supplies for sustainment, and unit integrity.

Resolution of conflicts between its multiple objectives occurs by ranking. The highest ranked objective is the efficient use of airlift and sealift, followed by arrival of forces as soon as possible. Its purpose is to determine if a deployment is feasible. The

major deficiency with this approach (along with all simulation models) is that it may answer this question incorrectly by overlooking alternatives.

## **2. Joint Flow and Analysis System for Transportation**

Joint Flow and Analysis System for Transportation (JFAST) [USTRANSCOM, 1991, p2] is a simulation model in use at both USTRANSCOM and United States Army Logistics Evaluation Agency (USALEA). In much the same way as AMP-MIDAS, JFAST simulates a scenario and produces an assessment of transportation feasibility.

## **3. FINDIT/FLOWIT**

FINDIT/FLOWIT [Caviller, 1994, p8] is a simulation model under development by Pennsylvania State University and USALEA. The major advantage of this model over the other simulation models is that it takes less than 15 minutes to run, compared to hours for the other models.

# **B. MOBILITY OPTIMIZATION MODELS**

## **1. Airlift Mobility Optimization Model**

An airlift mobility optimization model [Morton, Rosenthal, and Weng, 1995] optimally chooses the best schedules for aircraft. It minimizes the total weighted penalties for late deliveries and non-deliveries. The degree of lateness and the unit priority form the basis for these penalties. One major deficiency is that the model can produce fractional route sorties. These fractional values correspond to fractional schedules for aircraft and

are not implementable. This problem is currently under revision by the US Air Force and at the Naval Postgraduate School. Morton, Rosenthal, and Lim (1995) survey several other models for airlift.

## **2. Scheduling the United States Atlantic Fleet**

Brown, Goodman, and Wood (1990) optimize US Atlantic Fleet annual employment scheduling. The problem is to match a diverse set of events to the set of ships eligible for participation in these events over an entire year. Candidate ship schedules are admissible for the subsequent optimization **only** if they meet a set of strict rules that greatly reduces their number. The most desirable **subset** of these candidate schedules is optimally chosen, while ensuring all the requirements for the events are met. This approach is similar to the one in this thesis.

## **3. Flight Crew Scheduling**

There are numerous studies for commercial airline **flight** crew scheduling. Graves et. al. (1993) is a good example drawn from their work for United Airlines. A schedule is the assignment of air crews to scheduled flights. United Airlines uses a restricted forward enumeration to produce only a small subset of all possible **alternate** schedules by using heuristic rules to eliminate less desirable schedules. They **then** optimally choose the best subset of schedules. This subset is large, but nonetheless a **restricted** set of **alternatives**. Each possible schedule has a corresponding binary selection **variable**. If the optimizer chooses a schedule its corresponding binary variable is **one**, **and** zero if it is **not** chosen.

### **C. DATA GENERATION MODEL**

This thesis needs input data describing unit movements that includes the Port of Embarkation (POE), the Port of Debarkation (POD), the available to load date (ALD), and required delivery time. PAMM [Aviles, 1995] is a model that produces some essential elements of a TPFDD and answers these questions in an optimal manner. The basis for the PAMM optimization is force closure. Aviles does not deal with port size, ship speed, ship length, ship configuration (how much container space and RO/RO space is usable), or unit configuration explicitly, dealing with these factors implicitly instead. The results of Aviles's model are usable as input for the work reported here.

### **III AN OPTIMIZATION MODEL FOR STRATEGIC SEALIFT**

The two primary parts of this thesis are a ship schedule generator, and an optimization model. A ship schedule is a list of voyages including what units the ship picks up, what day it picks them up, where it picks them up, when it discharges them, where it discharges them, and how much penalty is accrued by these deliveries. The optimization model optimally chooses from all supplied candidate ship schedules the subset that yields the lowest total penalty. For operations that are larger than a few ships and units, the number of potential candidate schedules could easily become impractical. The use of an "intelligent" schedule generator can reduce the number of candidate schedules.

#### **A. SHIP SCHEDULES**

Each unit has a port where it must be loaded (POE), a time it is ready to be loaded (Available to Load Date (ALD)), a port where it must be discharged (POD), an earliest arrival and latest arrival date (EAD, LAD), and a priority. The unit priority corresponds to the importance of transporting the unit on time (a higher unit priority implies greater importance). Each ship schedule has an associated penalty which is composed of the earliness or lateness of a unit delivery modified by the unit's priority. The following is an example ship schedule that the optimization model uses: Ship 1 picks up unit 1, with

priority 1, at POE 1, on day 7, and discharges it at POD 1, on day 27, with a voyage or leg penalty of 0 (the unit arrives within the interval EAD and LAD). Ship 1 then returns to pick up unit 11, with priority 3, at POE 3, on day 46, and discharges it at POD 2, on day 67. This voyage or leg penalty is greater than zero because the unit is discharged after the unit's LAD. The ship schedule then receives a total penalty (a summation of the voyage or leg penalties).

## **B. ASSUMPTIONS**

There are a number of assumptions that apply to both the optimization model and the schedule generator:

- \* Time increments are days.
- \* A ship carries only one unit or a portion of one unit at a time (unit integrity).

This suggests aggregation of the units so that units are bigger than the largest ship. After this aggregation, typical units require multiple ships for full transportation;

- \* There is no chance of interdiction of any ship by the enemy, or that the ship will experience a mechanical failure;

- \* All material handling equipment and the personnel required to load and discharge the ships are present. This allows the use of a mean load and off-load time by ship type;

\* The Military Traffic Management Command (MTMC) reports the broken stow factor for the ships and the ports is 25% (unusable percentage of the ship or port) [MTMC, 1992]. In other words, only 75% of the cargo space (RO/RO) is usable for the ships, and only 75% of the total feet of pier space is usable for the ports; and

\* All unit requirements for transportation are divided into two separate categories: twenty-foot equivalent containers (hereafter referred to as containers), and RO/RO combined with Break Bulk.

### C. OPTIMIZATION MODEL

#### 1. Indices

- \* **i**            Ships, ( $i = 1, 2, \dots, I$ );
- \* **c**            Count of the number of ships ( $c = 1, 2, 3, 4$ );
- \* **e**            POE, ( $e = 1, 2, \dots, E$ );
- \* **d**            POD, ( $d = 1, 2, \dots, D$ );
- \* **s**            Schedules, ( $s = 1, 2, \dots, S$ ); and
- \* **t**            Time (in days), ( $t = 1, 2, \dots, T$ ).

#### 2. Data

- \* **POE**<sub>e,s,t</sub>        Feet of pier space used at POE e, by schedule s, during time t;
- \* **POD**<sub>d,s,t</sub>        Feet of pier space used at POD d, by schedule s, during time t;

- \* **PEN**<sub>i,s</sub> Total penalty for ship i using schedule s;
- \* **MoveSQFT**<sub>i,s,u</sub> Total unit square feet (RO/RO & Break Bulk) moved by ship i, using schedule s, for unit u. This comes from the schedule generator and the ship characteristics;
- \* **MoveCont**<sub>i,s,u</sub> Total number of unit containers moved by ship i, using schedule s, for unit u. Determined as in MoveSQFT<sub>i,s,u</sub>;
- \* **DMax**<sub>d,t</sub> Maximum usable feet of pier space at POD d, at time t;
- \* **EMax**<sub>e,t</sub> Maximum usable feet of pier space at POE e, at time t;
- \* **UVolSq**<sub>u</sub> Total square feet (RO/RO, Break Bulk) in unit u;
- \* **UCont**<sub>u</sub> Total containers in unit u;
- \* **PORTEXCEED**<sub>c</sub> Penalty for exceeding the port constraints by 1 ship more than c - 1;
- \* **CONTPEN** Penalty per container not transported for all units;
- \* **SQFTPEN** Penalty per square foot not transported for all units ; and
- \* **MAXSHIP** The maximum length of all ships in feet.

### 3. Binary Variables

- \* **X**<sub>i,s</sub> 1 if ship i uses schedule s, or 0 otherwise;
- \* **PENPOD**<sub>c,d,t</sub> 1 if the maximum number of usable feet of pier space at POD d at time t is exceeded by c or more ships, or 0 otherwise; and

\*  $PENPOE_{c,e,t}$  1 if the maximum number of usable feet of pier space at POE e at time t is exceeded by c or more ships, or 0 otherwise.

#### 4. Continuous Variables

\*  $DEVS_u$  Amount of square feet of unit u not moved (an elastic constraint violation indicator); and

\*  $DEVC_u$  Amount of containers of unit u not moved (an elastic constraint violation indicator).

#### 5. Model Formulation

Minimize: (1)

$$\sum_{i,s} PEN_{i,s} * X_{i,s} + SQFTPEN \sum_u DEVS_u + CONTPEN \sum_u DEVC_u + \sum_{c,e,t} PORTEXCEED_c * PENPOE_{c,e,t} + \sum_{c,d,t} PORTEXCEED_c * PENPOD_{c,d,t}$$

Subject to the following constraints:

$$\sum_s X_{i,s} \leq 1 \quad \forall i \quad (2)$$

$$\sum_{i,s} (MoveSQFT_{i,s,u} * X_{i,s}) \geq UVolSq_u + DEVS_u \quad \forall u \quad (3)$$

$$\sum_{i,s} (MoveCont_{i,s,u} * X_{i,s}) \geq UCont_u + DEVC_u \quad \forall u \quad (4)$$

$$\sum_{i,s} (POE_{c,s,t} * X_{i,s}) \leq EMax_{c,t} + MAXSHIP \sum_c PENPOE_{c,e,t} \quad \forall e,t \quad (5)$$

$$\sum_{i,s} (POD_{d,s,t} * X_{i,s}) \leq DMax_{d,t} + MAXSHIP \sum_c PENPOD_{c,d,t} \quad \forall d,t \quad (6)$$

$$X_{i,s} \in \{0,1\} \quad \forall i,s; \quad PENPOE_{c,e,t} \in \{0,1\} \quad \forall c,e,t; \\ PENPOD_{c,d,t} \in \{0,1\} \quad \forall c,d,t; \quad DEVS_u, DEVC_u \geq 0 \quad \forall u \quad (7)$$

The objective function (1) minimizes the total penalty for all ships plus penalties for not moving all the units or exceeding port capacities. Constraint set (2) ensures each ship gets assigned at most one schedule. Constraint set (3) forces the total square feet moved (RO/RO & Break Bulk) by all ships to be greater than or equal to the square feet requirements for each unit or it suffers a penalty in the objective function with the elastic variable,  $DEVS_u$ .

Constraint set (4) ensures that all unit containers are moved in the same way as the unit square feet. In implementation, the constants SQFTPEN and CONTPEN are 1,000 and 10,000 respectively. The difference in the constants is a scaling factor which equates containers to square feet (each container has approximately 100 square feet of usable space). These penalties equate a unmoved square foot to roughly discharging a ship's portion of a priority 3 unit 18 days after its LAD. This penalty scale shows the emphasis to move a unit even when the unit is discharged after its LAD.

Constraint sets (5) and (6) limit the maximum number of ships in a port at any time or incur an elastic penalty. The constant MAXSHIP is the length of the longest ship, a 1,100 foot FSS. In the objective function, a progressively larger penalty is added for each of these ship lengths exceeding the port limit ( $PORTEXCEED_c$ ).

## **D. SCHEDULE GENERATOR**

A lot of possible ship candidate schedules exist for a given scenario. A ship can load a unit on a number of days, discharge a unit on a number of days, and may make many trips to transport multiple units. The schedule generator follows a few simple rules to eliminate many candidate schedules and keep only those that discharge units close to the time window between its EAD and LAD. The basis for this determination is a schedule penalty. Every schedule is given a penalty cost of at least one, so that the optimization breaks ties by using the smallest number of candidate schedules (ships) possible.

### **1. Ship Schedule Penalty**

The ship schedule penalty derives from unit delivery dates achieved and unit priorities. It is desirable for ships to completely discharge units between their EAD and LAD. If a ship discharges a unit (or portion of a unit it is carrying) before its EAD, then the ship schedule accrues a small penalty (one). If a ship discharges a unit between the its EAD and LAD there is no incremental penalty. However, if a ship does not discharge a unit until after its LAD, the ship schedule accumulates a progressively larger penalty. Here, the added penalty is the square of the number of days the ship discharges the unit after LAD. For example, if the unit is three days late, the added penalty is nine.

A user defined unit priority modifies these penalties. The units for this thesis receive a priority between one and three with three being the highest. The unit priority multiplies its lateness penalty. These penalties are cumulative for all units the ship

transports, and if they ever exceed a user defined threshold the candidate ship schedule is discarded. Here, this threshold is 1,000 which is equivalent to a priority 3 unit being discharged approximately 18 days after its LAD. This restriction may possibly cause the problem to be infeasible if this threshold is set too low.

## **2. Limits on Ship Schedule Generation for Loading Units**

If a unit waits longer to load than a user defined maximum number of days, the schedule generator does not allow a ship to load the unit. This shortens the total ship schedule generation time by not generating less desirable candidate schedules. Here, this maximum unit waiting is 3 to 14 days past its ALD.

## **3. Limits on Ship Schedule Generation for Discharging Units**

The discharge time follows the time when a ship begins to load a unit, the ship's load time, the ship's travel time from the POE to the POD, and the time it takes to discharge the ship. If the discharge time exceeds the maximum late discharge time (14 days herein) the ship schedule is considered infeasible. Otherwise, the schedule generator computes the ship schedule penalty.

## **4. Delaying Ship Schedules**

The schedule generator loads and discharges each unit as soon as it is possible. However, delaying a ship from loading or discharging a unit for a day or number of days can also produce feasible candidate schedules. A delay in discharge times may change the voyage or leg penalty, and produces an entirely new schedule. These delays could occur at either the POE or POD (in any combination) until the discharging of the unit is more

than 14 days after the unit's LAD for each voyage or leg of the ship schedule. Delaying ships can be advantageous in relieving port congestion (number of ships in a port on a given day), but increases the total number of ship candidate schedules generated.

*a. Explicit Delay Generation*

This thesis limits loading or discharging delays to three days. Even with this limitation, there are approximately 27 times more ship candidate schedules than without delay.

*b. Implicit Delay Generation*

One way not to generate so many candidate schedules is to implicitly consider delaying a ship. The use of the variables  $PENPOE_{c,e,t}$  and  $PENPOD_{c,d,t}$  implicitly mimics ships waiting to load or discharge units. The penalties associated with these variables show the emphasis to not violate port capacities unless there is a substantial reward. This reward typically is either to ensure the movement of all units, or a large overall improvement on the unit delivery times.

When variables  $PENPOE_{c,e,t}$  or  $PENPOD_{c,d,t}$  are one, this implies that a ship must wait to load or discharge a unit. Each  $PENPOE_{c,e,t}$  and  $PENPOD_{c,d,t}$  explicitly states which port (d or e), at what time (t), and by how many ships (c) a port capacity is violated. A post analysis of the selected ship schedules allow a decision maker to decide which ship(s) to delay in order to satisfy the port capacities (if needed). This post analysis is relatively easy if only a few of the  $PENPOE_{c,e,t}$  and  $PENPOD_{c,d,t}$  variables have value one (a situation expected for an implementable TPFDD). Explicit generation would be

needed when many of these variables have value one to provide the optimization model  
greater flexibility

## IV COMPUTATIONAL EXPERIENCE

All data used for this thesis is unclassified. The ship schedule generator is written in Pascal [Cooper, 1992]. The schedule generator runs on a personal computer and writes the mixed integer problem to a file in MPS format [Schrage, 1986]. An IBM RS6000 model 590 workstation is used with the CPLEX optimizer [CPLEX Optimization, INC., 1994] to collect the MPS model data and render solutions.

### A. EXAMPLE SEALIFT PLANS

#### 1. Single Major Regional Conflict

The sealift ships for the single Major Regional Conflict (MRC) are all currently available for use by the US military. A summary of the ship characteristics is in Table 4.1. USALEA provided the unit data (TPFDD) for this scenario. Table 4.2 shows the unit data after aggregation. This aggregation occurs only with units in the TPFDD that have the same ALD, POE, POD, EAD, and LAD. The port data in Table 4.3 is fictitious, representing average size deep water (50 feet) ports.

SHIP #	CLASS	ENTRY DAY	LOAD DAYS	UNLOAD DAYS	SPEED (KNOTS)	DRAFT (FEET)	LENGTH (FEET)	USABLE SQ FT	CONT
1 - 8	FSS	3	2	2	27	29	946	163,200	182
9 - 19	RO / RO	10	1	1	23.3	30	705	152,250	30
20 - 25	RO / RO	15	1	1	23.3	30	705	152,250	30
26 - 73	BB	20	4	4	20.4	32	565	53,970	30
74 - 82	CONT	20	4	4	20	33	668	0	894

Table 4.1. Ship Characteristics for use in the single Major Regional Conflict scenario. The arrangement of these ships is by class. For example the Fast Sealift Ship USNS Capella is ready for use on day 3 (Entry Day), takes 2 days to load and discharge (Load and Unload Day), sustains 27 KNOTS (Speed), it draws 29 feet (Draft), is 946 feet long (Length), carrying 163,200 square feet of unit equipment (Usable SQ FT), and 182 containers (CONT). The data is from the Military Traffic Management Command and reflects average data from the 1990 Persian Gulf War. The usable square feet includes a 25% broken stow factor.

UNIT #	SQ FT	CONT	POE	POD	ALD	LAD	EAD
1	408,105	175	2	2	7	24	20
2	453,895	221	2	1	11	28	24
3	453,895	220	2	2	13	30	24
4	453,895	220	2	1	15	32	24
5	398,899	331	3	2	15	35	31
6	75,014	22	1	1	17	33	32
7	369,179	84	1	1	18	38	32
8	174,910	41	1	1	21	40	36
9	451,750	437	4	1	25	46	42
10	451,750	437	4	2	28	49	45

Table 4.2 Unit characteristics for the single Major Regional Conflict scenario. Units in the Time Phased Force Deployment Data which share the same Available to Load Date (ALD), Port of Embarkation (POE), Port of Debarkation (POD), Earliest Arrival Date (EAD), and Latest Arrival Date (LAD) have been aggregated reducing the original 32 units to 10. Maintaining unit integrity (not splitting units which have different POEs between ships unless necessary) is still possible. Unit names are omitted so the data remains unclassified.

PORT NUMBER	USABLE PIER SPACE (FEET)
POE - 1	5,250
2	7,875
3	5,250
4	5,250
5	5,250
6	5,250
POD - 1	5,250
2	7,875

**DISTANCE BETWEEN PORTS (In Nautical Miles)**

POE/ POD	1	2	3	4	5	6
1	4,200	9,807	8,276	10,825	8,825	8,424
2	4,200	9,807	8,276	10,825	8,825	8,424

Table 4.3 Port characteristics for the single Major Regional Conflict scenario. This table defines the ports that the units (Table 4.2) require. The depth and berth lengths of the ports are representative of average size deep water (50 feet) ports. The distances represent average distances from different United States military ports to a port in Asia.

**2. Dual Major Regional Conflict**

Table 4.4 lists the strategic sealift for the dual MRC scenario. This scenario uses the two new LMSR class ships. The Fort Leavenworth theater level exercise Prairie Warrior 95 [Command and General Staff College, 1995] provided unit data (TPFDD) for this scenario. Unit data is aggregated in the same way as the single MRC scenario (Table 4.5). This data clearly shows a division of the two MRCs at unit number 19. The port

data in Table 4.6 is fictitious, representing average size (9,750 feet of usable pier space)  
 deep water (50 feet) ports

SHIP #	CLASS	ENTRY DAY	LOAD DAY	UNLOAD DAY	SPEED (KNOTS)	DRAFT (FEET)	LENGTH (FEET)	USABLE SQ FT	CONT
1 - 8	FSS	3	2	2	27	29	946	163,200	182
9 - 19	RO RO	10	1	1	23.3	30	705	152,250	30
20 - 25	RO RO	15	1	1	23.3	30	705	152,250	30
26 - 73	BB	20	4	4	20.4	32	565	53,970	30
74 - 82	CONT	20	4	4	20	33	668	0	894
83 - 93	LMSR #1	3	2	2	22	34	1300	292,500	180
94 - 99	LMSR #2	3	2	2	22	34	1200	243,000	180

Table 4.4. Ship Characteristics for the dual Major Regional Conflict scenario. The difference between this table and Table 4.1 is the addition of the two Large Medium Speed RO/RO (LMSR) ships. These ships are to correct the shortages apparent during the 1990 Persian Gulf War. The activation of these ships should occur between 1997 and 2003. Without these ships it is impossible to complete the strategic sealift requirements for this scenario.

UNIT #	SQ FT	CONT	POE	POD	ALD	LAD	EAD
1	281,476	131	1	1	7	26	22
2	1,712,772	795	2	2	7	28	22
3	937,159	435	3	1	7	26	22
4	276,225	130	4	1	7	26	22
5	617,579	287	5	2	7	26	22
6	246,955	115	6	1	7	26	22
7	1,712,772	795	2	2	10	29	25
8	196,940	91	2	1	22	41	37
9	139,465	65	3	2	22	41	37
10	47,154	22	5	1	22	41	37
11	50,095	23	1	2	22	41	37
12	114,220	33	6	1	22	41	37
13	96,985	45	1	1	37	56	52
14	693,313	322	2	2	37	56	52
15	283,883	132	3	2	37	56	52
16	69,601	32	4	1	37	56	52
17	532,150	247	5	2	37	56	52
18	97,768	46	5	1	47	66	52

Table 4.5.A Unit characteristics for the dual Major Regional Conflict scenario for the first 18 units (the remaining units are in Table 4.5.B). Aggregation of the units from the TPFDD in Prairie Warrior 95 reduced the number of units from 62 to 31. There is a clear division of the two different MRCs between unit 18 and unit 19: units 1 - 18 discharge at Ports of Debarkation 1 or 2, while units 19 - 31 discharge at Port of Debarkation 3.

19	48,904	23	2	3	57	76	72
20	50,832	24	5	3	57	76	72
21	135,442	63	1	3	67	86	82
22	620,498	288	2	3	67	86	82
23	320,973	149	3	3	67	86	82
24	332,092	154	5	3	67	86	82
25	127,849	63	5	3	77	96	92
26	145,330	68	3	3	87	106	104
27	169,034	79	5	3	87	106	104
28	175,932	82	1	3	97	116	114
29	957,778	445	2	3	97	116	114
30	779,655	362	3	3	97	116	114
31	153,786	71	5	3	97	116	114

Table 4.5.B Unit characteristics for the dual Major Regional Conflict scenario for units 19 - 31. The other units are in Table 4.5.A.

**DISTANCE BETWEEN PORTS (In Nautical Miles)**

POE/ POD	1	2	3	4	5	6
1	4,200	9,807	8,276	10,825	8,825	8,424
2	4,200	9,807	8,276	10,825	8,825	8,424
3	9200	4,200	4,200	3,200	4,200	4,200

Table 4.6 Port characteristics for the dual Major Regional Conflict scenario. The lengths of the ports represent the size of average (9,750 feet of usable pier space) deep water (50 feet) ports in the world. The distances represent average distances between the United States military ports and ports in Asia and the Middle East.

## **B. COMPUTATIONAL EXPERIENCE**

The implementation of both the single MRC and dual MRC scenario includes the two forms of schedule generation (implicit and explicit delay) giving four different sets of results.

### **1. Single Major Regional Conflict**

#### *a. Implicit Delay Generation*

The maximum number of days late to pick up a unit is 14 for this scenario, resulting in 567 candidate ship schedules generated in 45 seconds. CPLEX optimized the associated mixed integer program (567 rows, 719 columns, and 4711 coefficients) in 137 seconds (with an integrality gap of 6.33%). The integrality gap is the difference between the objective function value of the best feasible solution identified and a lower bound on the objective function value (not necessarily a feasible solution), expressed as a percentage of the lower bound. The resulting unit ship assignments are in Table 4.7. There is no violation of any port constraint in the solution.

A positive square foot or containers excess in Table 4.7 signifies that there is more ship space available for the set of ships moving the unit. Two units have a negative square feet excess (units 1, and 8) and therefore are not fully transported. However, each unit has excess container space that can be used for square feet (on a limited basis) so the units can be transported.

Units 3, 4, and 5 have a negative container excess. There appears to be enough excess square feet to transport these containers.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
1	5	26	2		
	6	26	2	-81,705	189
2	2	30	2		
	10	31	3		
	19	31	3	13,805	21
3	12	33	3		
	16	33	3		
	17	33	3	2,855	-130
4	13	35	3		
	22	35	3		
	25	35	3	2,855	-130
5	4	32	0		
	14	32	0		
	24	32	0	68,801	-89
6	33	37	4		
	41	37	4	32,926	38

Table 4.7.A. Ship schedules chosen for first six units in the single Major Regional Conflict, using the implicit delay generation (the remaining units are in Table 4.7.B). Each unit has multiple ships that transport it. Each ship has a discharge date (Discharge Date) which determines the number of days a unit is late (Days Late) in comparison to the unit's LAD. The excess square feet and excess containers represent unused space in the collection of ships that transported a particular unit. A negative number in either column represents unit equipment that is not moved. To a small degree the container space and square feet space on a ship can be interchangeable, and therefore a tradeoff between the two can occur. A comparison between any unit that has negative excess space in one category and positive excess space in the other reveals that all units can be transported. These ship schedules are implementable.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
7	32	37	0		
	36	37	0		
	43	37	0		
	45	37	0		
	50	37	0		
	56	37	0		
	65	37	0	8,611	126
8	47	38	0		
	48	38	0		
	63	38	0	-13,000	49
9	1	46	0		
	3	46	0		
	9	46	0	26,900	0
10	7	48	0		
	10	48	0		
	21	49	0	26,900	0

Table 4.7.B. Ship schedules chosen for units 7 - 10 in the single Major Regional Conflict, using implicit delay generation.

***b. Explicit Delay Generation***

The explicit delay generation single MRC scenario allows units to be loaded up to 3 days after their ALD. For this scenario, 784 candidate ship schedules were generated in 525 seconds, and CPLEX optimized the mixed integer program (784 rows, 1,447 columns, and 14,119 coefficients) in 6,440 seconds (with an integrality gap of 9.21%). Unit ship assignments are in Table 4.8. In the original results, unit 6 required

two ships, but the second ship carried only five containers, and the first ship had excess square feet. Only one ship is needed and Table 4.8 reflects this change.

There are seven units that do not get all of their cargo moved (units 1, 2, 3, 4, 5, 8, and 9). Substituting container and square feet space, units 3, 4, 5, 8, and 9 can still be transported. There are not enough ship schedules to transport units 1 or 2 when only allowing schedules to load units 3 days after their ALD. From the implicit generation results (up to 14 day delay after ALD), we know that all units can be transported more than 3 days past ALD. However, explicit generation of all these candidate schedules is time consuming. The resulting optimization models have many more binary variables and therefore were both more difficult to read into CPLEX and to solve.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
1	7	26	2	-244,905	7
2	1	30	2	-290,695	-39
3	2	32	2		
	5	32	2	-127,495	144
4	8	34	2	-127,495	144
5	10	32	0		
	12	32	0		
	13	32	0		
	15	32	0		
	21	32	0		
	24	32	0		
	25	32	0	666,851	-67
6	26	38	5	77,146	0
7	27	37	0		
	29	37	0		
	39	38	0		
	45	38	0		
	51	38	0	94,940	0

Table 4.8.A. Ship schedules chosen for first seven units in the single Major Regional Conflict, using explicit delay generation (the remaining units are in Table 4.8.B). A comparison between any unit that has negative excess space in one category and positive excess space in the other reveals that all units except 1 and 2 can be transported. This makes these ship schedules non-implementable (unless units 1 and 2 need not fully deploy). Implicit delay generation provides better results since it implicitly considers many more possible schedules with far fewer binary variables and requires only minimal post processing.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
8	28	38	0		
	31	38	0		
	69	38	0	-13,000	49
9	3	46	0		
	14	46	0		
	16	46	0	15,950	-195
10	4	49	0		
	6	49	0		
	9	49	0	26,900	0

Table 4.8.B. Ship schedules chosen for units 8 - 10 in the single Major Regional Conflict, using the explicit delay generation.

## 2. Dual Major Regional Conflict

It is reasonable to assume that the second MRC does not begin until completing the loading of the last unit in the first MRC. This divides the problem into two parts. Any ship that delivers a unit in the first MRC incurs a 20 day delay from the discharge of its last unit to return to the US before it can begin to load any unit in the second MRC.

### *a. Implicit Delay Generation*

Units are allowed to be loaded up to 14 days after their ALD for this problem. For this scenario, 2,027 candidate ship schedules were generated in 1,185 seconds, and CPLEX optimized the mixed integer program (2,027 rows, 10,412 columns, and 151,974 coefficients) in 8,130 seconds for both Major Regional Conflicts combined (with an integrality gap of 22%). However, the best incumbent solution was discovered

after only 900 seconds. Unit ship assignments are in Table 4.9. There is a violation of only one port constraint (POD 2 on Day 27). The violation is repaired by delaying unit 2 by one day. Table 4.9 reflects this change.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
1	92	19	0	11,024	49
2	1	27	0		
	2	28	0		
	4	27	0		
	7	28	0		
	83	30	3		
	91	30	3		
	94	30	3		
	98	30	3	11,028	653
3	15	27	1		
	89	27	1		
	93	27	1		
	99	27	1	43,091	135
4	87	32	6	16,275	50
5	84	28	2		
	85	28	2	0	73
6	88	27	1	45,545	65

Table 4.9.A. Ship schedules chosen for the dual MRC using implicit generation for the first six units (the remaining units are in Tables 4.9.B and 4.9.C). A negative number in the days late column indicates that the unit arrives early (and the ship schedule receives a small penalty of one). Originally there was one port constraint violated (POD 2 on day 27). By delaying ships 2 and 7 (carrying unit 2) by one day, this port constraint is satisfied without disrupting any other ship schedule. These ship schedules are implementable.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
7	3	29	0		
	5	29	0		
	11	30	1		
	14	30	1		
	16	30	1		
	17	30	1		
	18	30	1		
	19	30	1		
	90	33	4		
	97	33	4	62.628	109
8	95	46	5	46.060	89
9	96	42	0	103.535	115
10	25	40	0	105.096	8
11	26	39	0	3.875	7
12	21	39	0	38.030	0
13	87	51	-1	195.515	135
14	6	56	0		
	7	60	4		
	9	57	1		
	13	57	1		
	23	57	1	898.370	132
15	2	57	1		
	4	57	1	42.517	232
16	20	58	2	82.649	0

Table 4.9.B. Ship schedules chosen for the dual MRC using implicit generation for units 7 - 16. The rest of the units are in Tables 4.9.A and 4.9.C.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
17	22	55	0		
	92	58	2		
	1	57	1	75,800	145
18	99	64	0	14,5232	134
19	3	68	-4	114,296	159
20	96	74	0	192,168	156
21	97	84	0	107,558	117
22	85	80	-3		
	87	83	0		
	90	79	-3	257,002	252
23	26	84	0		
	83	79	-3	25,497	61
24	86	79	-3		
	88	79	-3	252,908	206
25	99	96	0	115,151	117
26	3	98	-6	17,870	114
27	83	99	-5	123,466	103
28	99	116	0	67,068	98
29	87	109	-5		
	90	109	-5		
	96	109	-5		
	97	109	-5	113,222	275
30	85	109	-5		
	86	109	-5		
	88	109	-5	97,845	178
31	3	114	0	9,414	111

Table 4.9.C. Ship schedules chosen for units 17 - 31 in the dual Major Regional Conflict, using implicit delay generation.

*b. Explicit Delay Generation*

The maximum number of days late to pick up a unit is 7 days for this problem. For this scenario, 2,543 candidate ship schedules were generated in 1320 seconds, and CPLEX optimized the mixed integer program (2,543 rows, 22,245 columns, and 309,555 coefficients) in 4,271 seconds for both Major Regional Conflicts combined (with an integrality gap of 9.91%). Units 2, 3, 7, and 14 are not fully transported (Table 4.10). An excess in square feet or containers means that there is more ship space available for the set of ships moving that unit. Units 7 and 14 have a negative container excess. There is probably enough square feet excess to move both units. Units 2 and 3 each have a negative excess of square feet. There is probably enough positive container excess to compensate for the lack of square feet for unit 3, but not for unit 2.

The resulting ship schedules are not implementable. Comparing these schedules with the results using the implicit delay generation (Table 4.9) shows that implicit results are much better. Increasing the days late a unit can be loaded after its ALD from 7 to 14 might produce enough additional candidate schedules to render better results, but resulting MPS files were difficult to read into CPLEX.

Although units 19 and 20 have different POEs, combining them into one unit at two different locations would allow a more efficient use of the ships at a very small increase in lateness.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
1	84	19	0	11,024	49
2	2	26	0		
	4	26	0		
	5	26	0		
	6	26	0		
	7	26	0	-816,000	115
3	83	27	1		
	88	27	1		
	89	27	1		
	96	30	3	183,341	285
4	1	28	1	-113,025	52
5	85	28	1		
	86	28	1		
	87	28	1	259,921	253
6	92	30	3	45,545	65

Table 4.10.A. Ship schedules chosen for the dual MRC using explicit generation for the first six units (the remaining units are in Tables 4.10.B and 4.10.C). If units 19 and 20 are combined, their transportation requires only one ship. A comparison between any unit that has negative excess space in one category and positive excess space in the other reveals that all units except unit 2 can be completely transported. These schedules are not implementable. The implicit delay generation yields much better results since it implicitly considers many more possible schedules with far fewer binary variables and required only minimal post processing.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
7	3	29	0		
	8	29	0		
	9	30	1		
	10	30	1		
	11	30	1		
	12	30	1		
	13	30	1		
	14	30	1		
	15	30	1		
	16	30	1		
	18	30	1		
	19	30	1	136,128	-131
8	90	45	4	95,560	135
9	98	42	1	103,535	115
10	95	43	2	195,846	158
11	84	40	0	242,405	157
12	97	42	1	128,780	147
13	9	50	0	55,265	0
14	17	57	1		
	20	57	1		
	21	57	1		
	22	57	1		
	23	57	1	143,671	-172
15	93	57	1	8,617	48
16	99	62	6	173,399	148

Table 4.10.B. Ship schedules chosen for the dual MRC using implicit generation for units 7 - 16. The rest of the units are in Tables 4.10.A and 4.10.C.

UNIT	SHIP	DISCHARGE DATE	DAYS LATE	EXCESS SQ FT	EXCESS CONT.
17	91	58	2		
	94	58	2	3,350	113
18	26	63	0	54,482	0
19	5	67	0	114,296	159
20	97	74	0	192,168	156
*19 & 20	97	74	7	141,336	131
21	5	84	0	27,758	119
22	84	79	-3		
	86	80	-2	257,002	72
23	1	78	-4		
	95	79	-3	85,227	213
24	90	79	-3		
	98	80	-2	203,408	206
25	97	94	0	115,151	117
26	1	98	-6	17,870	114
27	94	100	-4	73,966	101
28	96	113	-1	67,068	98
29	83	110	-4		
	85	111	-3		
	87	112	-2		
	93	110	-4	212,222	275
30	89	110	-4		
	91	110	-4		
	92	110	-4	97,845	178
31	2	108	-6	9,414	111

Table 4.10.C. Ship schedules chosen for units 17 - 31 in the dual Major Regional Conflict, using the explicit delay generation.



## V CONCLUSIONS

### A. CONCLUSIONS

The best set of ship schedules for a strategic sealift operation can be selected in an optimal manner at least if the candidate schedules are limited to good, face valid schedules. This process has two parts: generating good candidate ship schedules, and optimally selecting a subset of these. When generating candidate ship schedules, the total number of possible schedules for a given deployment is very large, and could make the subsequent optimization difficult. Therefore, only candidate ship schedules with a realistic chance of implementation are generated. The schedule generator tries to load and discharge units as soon as possible. However, it can be advantageous to delay the ships to avoid port congestion. Two delaying tactics (implicit and explicit) have been suggested. Implicit delay generation has the advantage of producing less candidate ship schedules than explicit delay generation. Candidate ship schedules can be generated in under 25 minutes for either the single or dual MRC scenario.

The optimization model selects an implementable subset of the candidate ship schedules for both the single and dual MRC scenarios. The implicit delay produces less candidate schedules, but yields better results.

## **B. FUTURE RESEARCH**

A complete decision support system for Strategic Sealift optimization will require additional work. The research reported here focuses on the most innovative technology: optimization.

The schedule generator developed here captures just enough realism at a daily level of detail to support the optimization demonstration. After all, the schedule generator is principally an identity simulation of ports, ships, units, and their interactions --- simulation details already well studied and understood by others. We treat available square feet and container space as separate ship capabilities, when in fact there is some substitutability between these. This provides an opportunity to recognize such limitations in the optimization model or we may not need to express either of these limitations explicitly at all. It may suffice for the generator to simply inform the optimization that the schedule is admissible and conveys a set of units in some way not specified, except for the overall schedule penalty. It is also possible for an intelligent generator to render sets of related candidate ship schedules, or ship schedule packages, and convey these to the optimizer as a cohort. This mimics human schedulers who worry about a complete coordinated sealift rather than daily details for individual ships.

Best results will likely be achieved by mating the schedule generator and the optimizer. The generator would still produce an initial, seed subset of good alternate candidate schedules for each ship. But, given a look at an optimized incumbent sealift

selected from the restricted set of initial candidates, the generator would also generate additional candidate schedules to offer help with infeasibilities in the incumbent plan. Cyclic interaction of the generator (to offer more alternatives) and the optimizer (to advise the best global incumbent yet seen) would offer enormous iterative improvements (see Graves, et. al. 1993 for similar advice from United Airlines).

We have resorted to manual interpretation and post processing of optimized solutions. This is a surrogate for an automated, or at least semi-automated post processing procedure which requires much more real-world experience than we can bring to bear.

During an actual sealift, the guiding OPLAN and the underlying TPFDD change constantly. Responding to such changes will require a decision support system which has knowledge of the already-published schedules, honoring as many of these as possible while dealing with changes and alterations. The idea is to minimize turbulence caused by these changes. Persistence modeling (e.g., Brown, Dell, and Farmer [1995], and Brown, Dell, and Wood [1995]) provides a framework to produce optimally revised schedules that consider decisions that have already been made, but might need changing.

A suite of all these components would be most enhanced by a well-designed graphical user interface helping an expert scheduler employ his judgment and quickly making visible the global consequences of individual manual interventions.

It is these global assessments that are the weakness of simulation, but the distinguishing advantage of optimization.



## APPENDIX. [ACRONYMS]

ALD: Available to Load Date.

AMP-MIDAS: Analysis Mobility Platform - Model for Intertheater Deployment by Air and Sea.

BB: Break Bulk.

CINC: Commander-In-Chief.

EAD: Earliest Arrival Date.

FSS: Fast Sealift Ship.

JFAST: Joint Flow and Analysis System for Transportation.

JOPES: Joint Operational Planning System.

LAD: Latest Arrival Date.

LMSR: Large Medium Speed RO/RO.

LO/LO: Lift-On/ Lift-Off.

MRC: Major Regional Conflict.

MSC: Military Sealift Command.

MTMC: Military Traffic Management Command.

OPLAN: Operations Plan.

POD: Port of Debarkation.

POE: Port of Embarkation.

ROS: Readiness Operating Status.

RO/RO: Roll-On/ Roll-Off.

RRF: Ready Reserve Fleet.

TPFDD: Time Phased Force Deployment Data

USALEA: United States Army Logistics Evaluation Agency.

USTRANSCOM: United States Transportation Command.

## LIST OF REFERENCES

- Aspen, L., Secretary of Defense, *Bottom Up Review*, Office of the Secretary of Defense, 1993
- Aviles, S., *Scheduling Army Deployment to Two Nearly Simultaneous Major Regional Conflicts*, Masters Thesis, Department of Operations Research, Naval Postgraduate School, Monterey, CA, September 1995.
- Brown, G., Dell, R., Farmer, R., "Scheduling Coast Guard District Cutters", to appear in *Interfaces*, 1995.
- Brown, G., Dell, R., and Wood, R., "Modeling with Persistence (DRAFT)", Naval Postgraduate School, Monterey, CA, 1995
- Brown, G., Goodman, C., Wood, R., "Annual Scheduling of Atlantic Fleet Naval Combatants", *Operations Research*, vol 38, no. 2, pp 249 - 259, 1990.
- Caviller, J., *FINDIT/FLOWIT*, Information Briefing Slides, Pennsylvania State University, 1994
- Command and General Staff College, *Prairie Warrior - 518*, Command and Control Exercise, Fort Leavenworth, KS, 1995.
- Cooper, D., *Oh! Pascal 6.0*, 3rd edition, W.W. Norton & Company, New York, NY., 1992.
- CPLEX Optimization, INC, *CPLEX Linear Optimizer 3.0 with Mixed Integer Solver*, Incline Village, NV, 1994.
- Department of Defense, *The Joint Staff Officers Guide 1993*, AFC PUB 1, US Government Printing Office, Washington, D.C., 1993.
- Graves, G., McBride, R., Gershkoff, R., Anderson, D., and Mahidhara, S., "Flight Crew Scheduling", *Management Science*, vol 39, no. 6, pp 46 - 52, 1992.
- GRC & Marcotte, J., *AMP-MIDAS Overview*, USTRANSCOM Conference Slides, Scott AFB, IL, 1992. Received from USALEA November 1994.
- Kaskin, J., *Information Brief on Strategic Sealift*, Information Briefing Slides, Naval Postgraduate School, Monterey, CA, 1995.

Military Sealift Command, *Military Sealift Command In Review 1992*, Government Printing Office, Washington, D C., 1992.

Military Traffic Management Command, *Logistics Handbook for Strategic Mobility Planning*, MTMC PAM 700-2, Newport News, VA, 1992.

Morton, D., Rosenthal, R., and Weng, L., *Optimization Modeling for Airlift Mobility*, Naval Postgraduate School Technical Report NPS-OR-95-007, Monterey, CA, 1995.

Pagonis, W., w/ Cruikshank, J., *Moving Mountains: Lessons in Leadership and Logistics from the Gulf War*, Harvard Business School Press, Boston, MA, 1992.

Schrage, L., *LINDO: An Optimization Modeling System*, The Scientific Press, San Francisco, CA, 1986

USTRANSCOM, *Joint Flow and Analysis System for Transportation (JFAST)-Capabilities Overview & Status Update*, JOPES Conference Atlanta, GA, November 1991.

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