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A CARRIER DEPLOYMENT MODEL

by

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A Carrier Deployment Model

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ABSTRACT

Aircraft carriers are and will continue to be highly important to the United States as she safeguards her interests globally. Today's budget environment, however, demands efficient use of these carrier assets in meeting their station coverage assignments. In a peacetime environment, a carrier's ability to cover a station is constrained by depot maintenance, training cycles, and the Chief of Naval Operations personnel and operating tempo program (PERSTEMPO / OPTEMPO).

To aid in satisfying this demand on carriers, a mixed integer programming model is developed. The output from the model provides optimal station coverage assignments for a given level of coverage under constraints associated with carrier operations. When implemented in conjunction with the General Algebraic Modeling System (GAMS), the model requires minimal user inputs and is implementable on a personal computer. Other applications of the model are also demonstrated in several examples.

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The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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I. INTRODUCTION

Since early in World War II, the importance of U.S. Naval aircraft carriers has been proven repeatedly. These ships are used to project Naval air power, deter aggression, and preposition U.S. forces to quickly respond to crisis situations. Recently, the Chief of Naval Operations, Admiral Carlisle Trost stated: "The keelblock of our Navy is the carrier battle group. Our carrier forces with their airwings and support ships provide our President with the broadest possible range of policy options for an appropriate response to almost any crises." (Trost, 1990, p.69) Given the realities of our geostrategic position, fronting on two oceans, maritime superiority over any potential adversary is essential to support our alliance relationships. Our Naval forces deployed in the Mediterranean Sea as well as the Pacific and Indian Oceans assist in protecting our growing strategic and economic interests, and supporting allies and friends in Asia and Europe. (National Security Strategy, 1988, p. 19)

Despite radical world change and peace overtures by the Soviets, world conflict is still widely prevalent. Numerous Third World countries remain extremely unstable as they struggle with economic and political upheaval. Low intensity conflict (LIC) -- terrorism, insurgency, and subversion -- is a major threat to the U.S.and her allies. Today, many high-tech and excessively deadly weapons are available on the open market to any country that can afford them. The growing potential for an unstable country to strike out with lethal weapons requires increased U.S. attention in these regions.

The growing technological sophistication of the Third World will prove to be a major challenge to U.S. forces, thus, the United States will continue to need the ability to make its presence known around the world. As Secretary Cheney put it: " We are a superpower and we're always going to want to have the capacity to deploy military force to safeguard American interests and preserve our capacity to influence events in the world." (Baltimore Sun, November 27, 1989) In particular, the aircraft carrier will continue to assume a major role as an instrument of U.S. foreign policy. It provides a unique ability to project U.S. force in troubled areas while remaining uncommitted in International waters.

In recent days, budget considerations have prompted a desire to more effectively utilize these assets to maximize carrier coverage. To provide for world presence, carriers are stationed in various world theaters (Mediterranean Sea, Pacific, and Indian oceans) to provide "coverage" of these areas. Coverage by a carrier is constrained by several factors. They are: (a) work-up cycles and transit times associated with carrier operations, (b) maintenance periods, and (c) Personnel and Operating Tempo (PERSTEMPO/OPTEMPO). This thesis incorporates these constraints into a real-world carrier deployment model which minimizes the number of ships needed to cover the Mediterranean Sea.

A. CARRIER OPERATIONS

Prior to deployment, each carrier's crew and airwing must first raise their level of proficiency to enable them to complete any assigned mission in any region of the world. To do so, carriers, conventional (CV) or nuclear powered (CVN), employ a "work-up" cycle that lasts approximately eight months and consists of four major at-sea periods. The first period is a short sea-trial period designed to ensure proper operation of ship systems. The next sea period is an Independent Steaming Evolution (ISE). This period is used primarily to train new ships' company and airwing pilots to replace the more experienced personnel who have departed since the last deployment. The third period is Refresher Training (REFTRA). During this period, the ships' crew is integrated into a highly competent team. This at-sea time is used in preparation for the Advanced Phase Work-up period in which the carrier is tested under battle conditions to ensure the readiness of the ship and its crew. This Advanced Phase work-up period is the last at-sea period in the work-up cycle. (COMNAVAIRLANTINST 3500.24H, MARCH 1989)

Following the work-up cycle and a pre-deployment leave period, the carrier departs on cruise. These deployments are used to provide coverage to various regions whose security is important to the United States. Coverage of the Mediterranean Sea and Atlantic ocean is provided by carriers from the east coast, i.e., those homeported in Mayport, Florida and Norfolk, Virginia. Similarly, coverage of the Western Pacific (WESTPAC) and the Indian Ocean (IO) is provided by carriers from the west coast, i.e., those homeported in San Diego and San Francisco, California; Bremerton, Washington; and Yokosuka, Japan. Occasionally, during periods of heightened tension, carriers from the east coast will aid in coverage of the Indian Ocean or ships from the west coast will augment forces in the Mediterranean Sea.

During a normal six month deployment, a ship must be on station in an assigned area or in transit to and from homeport. However, only the time during which the ship is on station counts as coverage time. An east coast ship is on station in the Mediterranean Sea when it transits the Straights of Gibraltar. A west coast carrier is on station in WESTPAC when it passes 160 degrees west longitude. A ship is on station in the Indian Ocean once it reaches the Straights of Malacca. So in addition to the work-up cycle, transit time is another factor in carrier operations which further restricts the amount of coverage supplied by a ship. Typical transit times are given in Table 1.

TABLE 1

CARRIER TRANSIT TIMES
(OP-642C1, 1990)

Coast	Station	Transit time
East	Mediterranean (Gibraltar)	11-14 days
	Indian Ocean (via Suez Canal)	25-30 days
West	Western Pacific	12-15 days
	Indian Ocean (via Straights of Malacca)	33-45 days
Yokosuka Japan	Indian Ocean	17 days

B. MAINTENANCE

As with any highly sophisticated and technical piece of equipment, proper maintenance is important to ensure continued system reliability for years to come. Aircraft carriers must be maintained properly so they are capable of accomplishing their assigned mission as well as being fully capable of meeting any threat, expected or unexpected. There are three levels of ship maintenance: Organizational, Intermediate, and Depot. The first two levels of maintenance involve minor repairs and can be performed either pierside or while underway. Hence, these two levels have negligible effect on the availability of carriers. On the other hand, depot level maintenance has a great effect on carrier availability. It is defined by Chief of Naval Operations Instruction 4700.7H (OPNAVINST 4700.7H) as

> ... that maintenance which requires skills and facilities beyond the level of the organizational and intermediate levels and is performed at Naval Shipyards, private shipyards, Naval Ship Repair Facilities, or other shore-based activities. During depot availabilities large scale maintenance and repairs requiring industrial facilities are performed. Approved alterations and modifications, which update and improve the ship's military and technical capabilities, are accomplished. (OPNAVINST 4700.7H, 1987, enclosure 5)

According to this OPNAV instruction, typical maintenance activities at the depot level consist of the following:

- <u>Complex Overhaul (COH)</u>-- overhaul that, because of funds, time, manpower constraints , or complexity requires extraordinary coordination and extensive management of the planning and industrial phases to ensure with a high level of confidence that the overhaul will be satisfactorily completed. For conventional carriers, a COH is performed every 60 months and lasts approximately 12 months. For nuclear carriers, a COH is performed every 84 months and lasts approximately 18 months.

- <u>Reactor Core Overhaul (RCOH)</u>-- utilized by nuclear powered aircraft carriers to "refuel" the cores of the reactors. These occur notionally every 182 months (every other COH), and last approximately 30 months.

- <u>Selected Restricted Availability (SRA)</u>-- These availabilities are assigned to accomplish work that is required to sustain the material condition of the ship between overhauls, particularly those ships on extended operating cycles. SRA's are short, labor-intensive availabilities that are generally scheduled at specific times throughout the operating cycle. SRA's follow each deployment and are approximately three months in duration.

- <u>Docking Selected Restricted Availability (DSRA)</u>-- an SRA extended to include drydocking the ship. Nuclear carriers utilize DSRA's which last approximately four months. The second of the three SRA's that occur between overhauls includes docking services.

- <u>Service Life Extension Program (SLEP)</u>-- A depot level program designed to extend the service life of a ship beyond that for which it was originally designed. Following SLEP the ships are maintained and modernized through normal overhaul procedures. To date, only the older conventional carriers have been SLEPed. SLEP's occur once in the life of a carrier and last approximately 30 months.

The Commander of Naval Sea Systems Command, COMNAVSEASYSCOM, assigns and schedules overhauls and SRA's. The Surface Warfare Division, OP-32, promulgates notional durations, notional intervals, and approved schedules for depot availabilities. These notional maintenance durations are used for long range planning and at the Annual Fleet Depot Maintenance Scheduling Conference. The overhauling shipyard commander assesses his capacity and ability to perform the work in the allotted time. Any increase or decrease in expected time needed to complete maintenance is officially addressed as soon as possible after the conference. SRA durations normally do not require adjustments in time to complete the assigned work. It may be necessary, however, to increase durations to accommodate urgent alterations that are essential to improving the mission capability of the ship or to accomplish necessary repairs. (OPNAVINST 4700.7H, 1987, enclosure 5)

Depot maintenance is usually performed at the ships homeport. However, there are circumstances when maintenance must be completed elsewhere. For example, some specialized maintenance, such as docking SRA's and reactor core overhauls, must be performed at specific shipyards. Also, homeports can become unavailable unexpectedly due to political pressures or unforseen extensions in durations for other carriers.

C. PERSONNEL TEMPO / OPERATING TEMPO

In the late 1970's and early 1980's , events such as the Iranian Hostage crises, hijackings, subversive acts in Central America, Grenada, and the beginning of the tanker war in the Persian Gulf dramatically increased the requirements for U.S. aircraft carrier presence in these regions. Due to this, deployment lengths were increased dramatically and time between deployments was shortened to meet these growing commitments. As a result, the money spent on keeping carriers at sea and the hardships experienced by sailors rose to unacceptable levels. Because of these longer deployments, many sailors departed the Navy in hopes of finding an easier life. In 1985, the Chief of Naval Operations initiated a program to counter these increased costs to the Navy in the form of money, manpower, and morale. The Navy implemented the Personnel and Operating tempo (PERSTEMPO and OPTEMPO) programs.

PERSTEMPO is an administrative set of standards designed to balance a ship's ability to support national objectives while still maintaining high morale through a reasonable home life. The PERSTEMPO program is composed of three criteria:

- Maximum deployment length will not exceed six months (180 days), homeport to homeport
- Minimum of 2 to 1 turn around ratio (TAR). Essentially, this means that there must exist a minimum of 12 months between consecutive 6-month deployments.

- Over a five year cycle (3 years historical, 2 years projected), 50 percent of time must be spent in homeport. The accounting for time is day for day with exception of extended depot level maintenance periods (i.e., over six months in duration), which is administratively counted as 90 days homeport time. (OPNAVINST 3000.13, 1990).

Any carrier not satisfying the above three PERSTEMPO criteria cannot deploy. This, therefore, restricts the availability of carriers. OPTEMPO, however, is the percentage of time that a ship is budgeted to be underway each fiscal quarter. This thesis focuses on developing a model to determine the optimal number of carriers required to cover the station as driven by other constraints. As a result, OPTEMPO does not directly affect the results of the model. If the money does not exist to fund deployment of the optimal number of carriers, the coverage will not be met.

D. PRIOR WORK

The Office of the Chief of Naval Operations, Program Resource Appraisal Division (OP-81) presently utilizes a mathematical model consisting of simple algebraic relationships to approximate the minimum number of carriers required to provide theater coverage specified by the Navy. To facilitate this computation, Lotus 1-2-3 spreadsheet software is used to obtain a solution to the model. The spreadsheet requires data inputs such as:

- The desired level of coverage in various theaters. Often, this level is measured as the average number of carriers present in a given theater over a specified period, and

- The available number of carriers, conventional and nuclear, in each of the two fleets: West Coast and East Coast. The output is the number of carriers required to achieve the desired level of coverage.

It was clear to the analysts at OP-81 that this algebraic model is rather limited and contains many restrictive assumptions. Examples of the limitations of the model include:

- The model produces a non-integer number of carriers. It is possible to round up or down the non-integer solution. The financial implications, however, of incorrectly rounding could be in billions of dollars.

- The model uses average durations for depot level maintenance and does not include the availability of the shipyards. It is therefore possible that the solution provided by the model is inoperable when OP-32's notional schedules for maintenance is taken into account.

- In calculating PERSTEMPO, the model uses percentages to determine the maintenance which is completed at the ship's homeport. This effect is averaged over all ships and cannot be attributed to particular ships. Thus the PERSTEMPO may appear more favorable than it actually is.

E. PROBLEM SCOPE

The above limitations prompted the analysts at OP-81 to seek an alternative model which captures the underlying problem more realistically. As an attempt to accomplish this task, this thesis proposes to model the problem of determining the minimum number of carriers to provide the specified level of coverage as a mixed integer program (MIP). The advantages of this approach are:

- MIP models provide integer solutions.

- Notional maintenance schedules can be incorporated into the model in a flexible manner. Hence, the resulting model would always provide a solution based on a given maintenance schedule. The flexibility factor also facilitates any modification should the notional schedule need adjustment.

- PERSTEMPO criteria are taken into account in a more realistic manner.

- More importantly, the model can be solved by commercially available software -- General Algebraic Modeling System (GAMS).
- Allows for sensitivity or "what if" analysis. By simply changing the input parameters, several scenarios can be analyzed. (e.g., effects of SLEPs or CV phased maintenance)

The following chapter describes the basic structure of the model formulation as well as provides formal mathematical representation of the model. Chapter III will describe the user interface required to implement the model. Chapter IV will illustrate example analysis that can be performed utilizing this model. Chapter V presents the conclusions and lists areas for possible future research. Appendices A and B list the computer programs used to generate the model. In addition, Appendix C describes various parts if the GAMS code.

II. A CARRIER DEPLOYMENT MODEL

The goal of this thesis is to create an optimal carrier model that produces an integer solution which minimizes carrier assets while realistically representing real-world constraints. However, to make the model mathematically and computationally tractable, the following conditions are assumed:

- Peacetime model - the results of this model are based on known constraints such as maintenance and perstempo that exist in a peacetime environment. It does not try to predict contingency operations or effects if a carrier is unexpectedly unable to perform its mission. The model, however, is sufficiently flexible to incorporate the effects of such scenarios once the situation arises. Additionally, probable contingencies can be tested and analyzed in advance to predict minimal carrier force sizes required to successfully meet any eventuality.

- Coverage and geography - coverage of the Mediterranean Sea is obtained by East Coast carriers only. This is realistic since in any peacetime scenario, coverage can be obtained in the Mediterranean without utilizing west coast carriers to augment existing forces.

- Work-up cycle length - Based on COMNAVAIRLANTINST 3500.24H, eight months is required to "work-up" a carrier under peacetime conditions. Because of this, this model does not allow a carrier to be considered for deployment until the ninth month following a maintenance period.

- Time in months vice days - to limit the model to a size that can be solved on a PC, time segments are in months instead of days. This dramatically reduces the number of variables associated with the model, which in turn reduces the memory and time required to produce a solution.

- Coverage Percentage - PERSTEMPO requires deployments to be limited to six months (180 days homeport to homeport). Of this six months, it is assumed that only five months is available for coverage. The other month is used for transiting to the Mediterranean and returning to the carriers homeport.

- Coverage - Coverage is calculated as the average of the number of carriers on station during each month over the planning period.
- PERSTEMPO - If a carrier is 'idle' then it is assumed to be at homeport which would therefore have a positive effect on the calculation of personnel tempo. The term 'idle' means that a carrier is neither on-station nor in some form of maintenance. Carriers usually become idle when the desired level of coverage is low.

A. SCHEDULE CONSTRUCTION

The Overhaul Schedule for Advanced Planning listed in Chief of Naval Operations Notice 4710 (OPNAV NOTE 4710) is used to motivate the integer programming model. The plan balances the durations of each ships required maintenance with shipyard availabilities. Figure 1 lists a small example of the larger notional schedule listed in OPNAV NOTICE 4710. The month number in this figure is a sequential representation of the months in the planning cycle. Shaded boxes in Figure 1 depicts periods of depot level maintenance. Ships are not deployable during these times. Plain boxes denote nonmaintenance periods. If a nonmaintenance period is at least 14 months long then there is sufficient time for a carrier to conduct a full work-up cycle and complete a cruise before going into the next scheduled maintenance. Thus, a nonmaintenance period with a length of at least 14 months is called a deployable period. Shorter nonmaintenance periods are nondeployable. In Figure 1, the plain box with label '(1)' is a nondeployable period. Depending on various maintenance considerations, a carrier averages two to three deployable periods each planning cycle. Since the first eight months of a deployable period is for work-ups, the earliest time that a carrier can be on station is in the ninth month

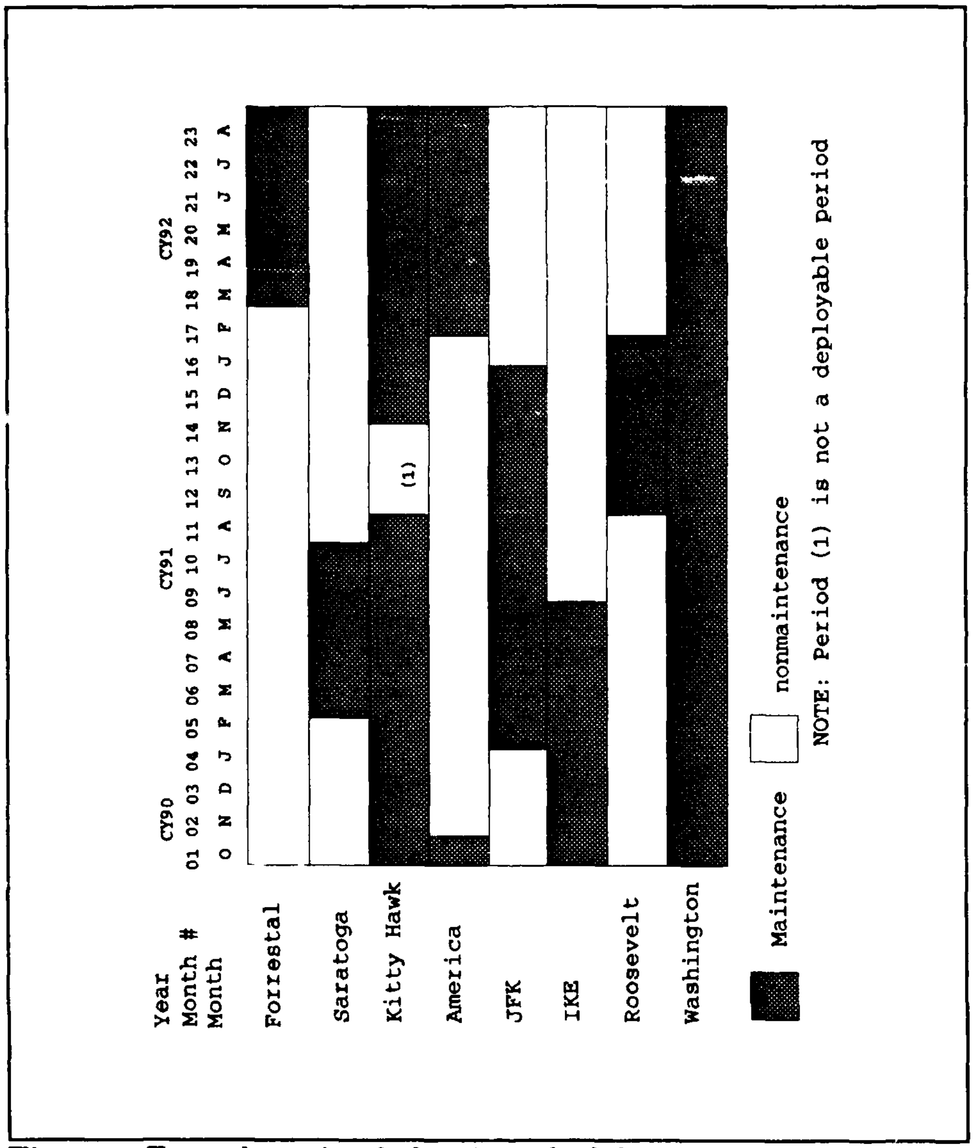

Figure 1 Example notional planning schedule

of the deployable period. By assumption, the on-station time lasts exactly five months and by convention the month immediately following the last month on station is considered as the time in transit. In practice, users only have to shift the on-station time backward half a month to obtain a workable plan. This observation leads to the definition of the term 'on-station schedules' as periods of five consecutive months in a deployable period. If a deployable period is exactly 14 months long, then there is only one on-station schedule which exactly begins on the ninth month and ends on the thirteenth month. (Recall that the fourteenth month is reserved for transit.) Longer deployable periods would have more on-station schedules since the carrier can delay being on-station by at least one month.

Figure 2 contains a small example of possible schedules that could exist in two deployable periods for USS America and one deployable period for USS Eisenhower. Each vertical vector of '1's represents a potential on-station schedule. (Note: The schedules for the first period for USS America and USS Eisenhower in Figure 2 correspond to the deployable periods shown in Figure 1). The calendar year dates and the corresponding month numbers in the planning period covered by a particular schedule are listed in the left hand column. Notice in Figure 2 that a selection of USS America's schedule '1' in period 1 and schedule '3' in period 2 results in coverage of months 10-14 in the planning cycle (Jul-Nov, 1991) and months 29-33 (Feb-Jun, 1993) respectively. A selection of schedule '2' for USS Eisenhower results in coverage of months 18-22 (Mar-Jul, 1992).

Mos. No.	CY Date	AMER SCHED PERIOD 1			AMER SCHED PERIOD 2				IKE SCHED PERIOD 1		
		1	2	3	1	2	3	4	1	2	3
01	90 O										
02	N										
03	D										
04	91 J										
05	F										
06	M										
07	A										
08	M										
09	J										
10	J	1									
11	A	1	1								
12	S	1	1	1							
13	O	1	1	1							
14	N	1	1	1							
15	D		1	1							
16	92 J			1							
17	F								1		
18	M								1	1	
19	A								1	1	1
20	M								1	1	1
21	J								1	1	1
22	J									1	1
23	A										1
24	S										
25	O										
26	N										
27	D				1						
28	93 J				1	1					
29	F				1	1	1				
30	M				1	1	1	1			
31	A				1	1	1	1			
32	M					1	1	1			
33	J						1	1			

Figure 2 Integer matrix representation of deployable schedules

B. CONSTRAINTS

The 2 to 1 turnaround ratio, one of the PERSTEMPO requirements, is calculated by introducing two coefficients, a_i and b_i. Figure 3 depicts a graphical example. The coefficient a_i represents the number of months after each schedule until the beginning of the next depot period. The coefficient b_i represents the number of months from the beginning of the depot period until the beginning of the schedule in the next deployable period. The model ensures that the sum of these two numbers, the time between consecutive on-station schedules, allows for at least 13 months to transpire between successive deployments. Thirteen months between on-station schedules allows for twelve months in homeport and an additional month for transit to and from the assigned station (2 weeks each way). That is, the model will not choose schedules that fail to allow a ship to be home for at least 12 months following a six month deployment. The first deployment period of the planning cycle is "hot-started" by allowing schedules to be considered only if 12 months have passed since the end of the last known deployment. Figure 4 illustrates an example. Following the "hot-start", a_i and b_i, illustrated in Figure 3, are used in the remaining deployment periods in the planning cycle.

To satisfy the fifty percent homeport time requirement for PERSTEMPO, number p_i is assigned to each schedule i. Schedules belonging to the same deployable period have exactly the same p_i. The calculation of p_i assumes that the carrier will be deployed. Under this assumption, p_i is then the number of months at

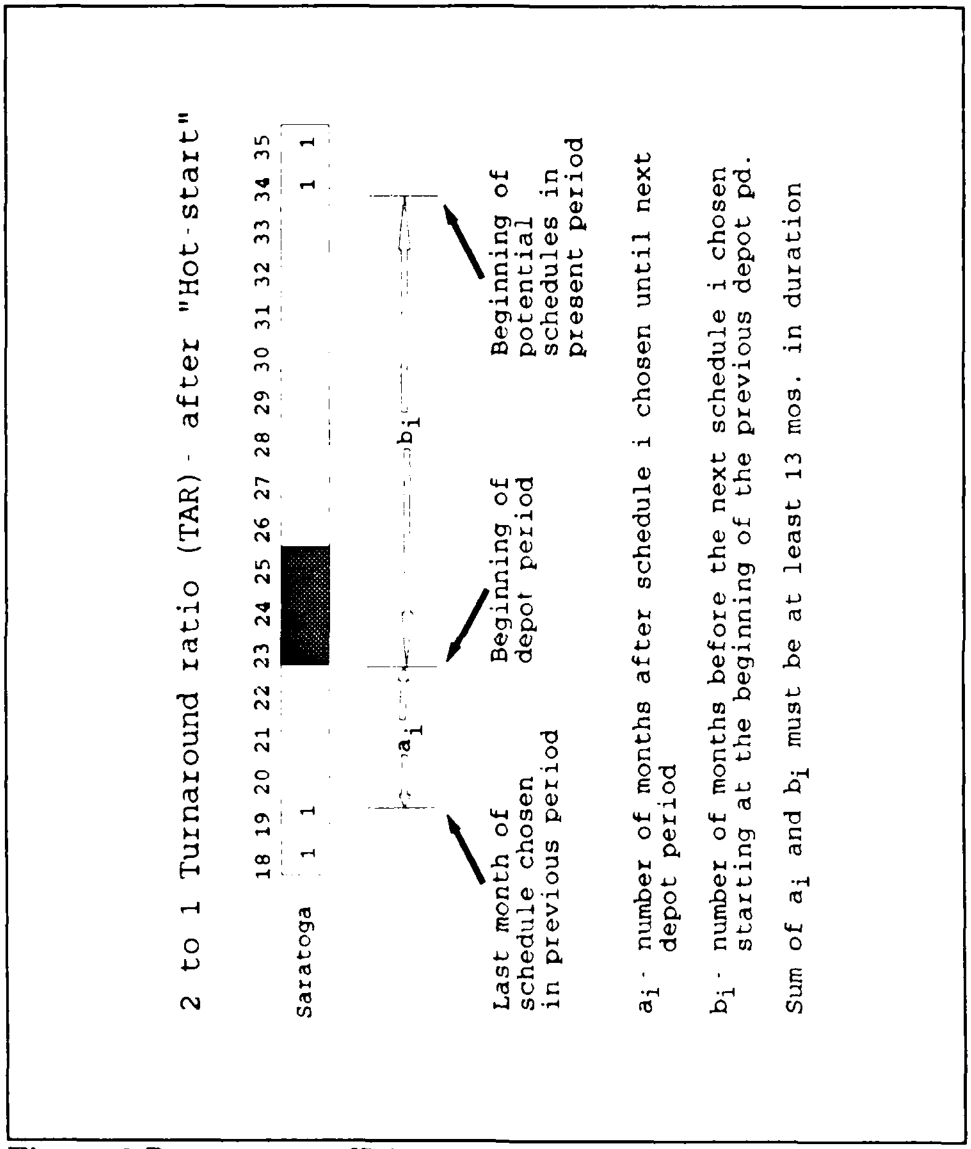

Figure 3 Perstempo coefficient representation

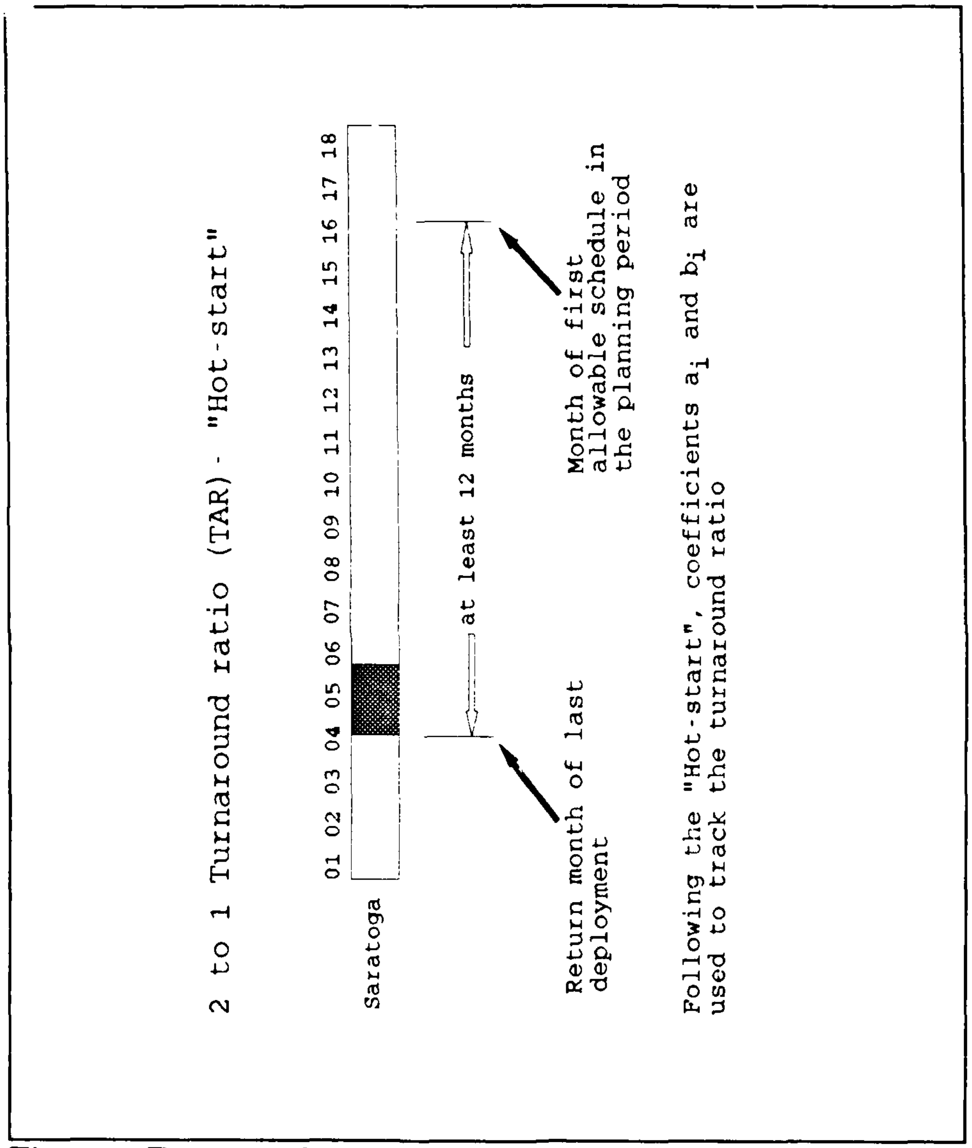

Figure 4 Turnaround representation for the "hot-start"

homeport minus the number of months not at homeport from the end of a deployable period to the end of the next deployable period. Thus p_i may be negative for some schedules. In the model below, if a carrier is not selected to deploy, then the carrier is assumed to be at homeport during the entire period. The formulation below will ensure that the homeport time is at least as large as the non-homport time, thereby satisfying the PERSTEMPO requirement.

In addition to the above constraints, there are other constraints to ensure details such as select only one on-station schedule per deployable period and an on-station schedule of a carrier can be selected only when the carrier is to be used to provide coverage.

C. LINEAR INTEGER PROGRAM MODEL FORMULATION

Considering the factors and constraints discussed in the last section, the complete carrier deployment model requires the following:

Indices:

c = 1,....,C	carriers
i = 1,....,I	on-station schedules
j = 1,....,J	deployable periods
k = 1,....,K	months, where K = months in the planning cycle

Data:

S_{cj}	set of schedule indices for carrier c in deployable period j
a_i	the number of months in homeport after the deployment for on-station schedule i, i.e., the difference between the end of deployment for on-station schedule i and the beginning of the maintenance period following on-station schedule i. (See Figure 3)
b_i	the number of months in homeport before the deployment for on-station schedule i, i.e., the difference between the start of deployment for schedule i and the beginning of the maintenance period preceding on-station schedule i. (See Figure 3)
p_i	personnel tempo for schedule i if the carrier is deployed
q_i	personnel tempo for schedule i if the carrier is not deployed
N_c	number of deployable periods for carrier c in the planning cycle
f	the desired coverage factor
d_{ik}	binary indicator, 1 if schedule i covers month k; 0 otherwise (See Figure 2)

Variables

x_i	1 if schedule i is selected; 0 otherwise
y_k	coverage in month k
z_c	1 if carrier c is selected to provide coverage; 0 otherwise

Formulation:

$$\textit{Minimize} \quad \sum_c Z_c$$

Subject to:

$$\sum_{i \in S_{cj}} x_i \leq 1 \qquad \forall \ j \text{ and } c \tag{1}$$

$$\sum_{j=1}^{N_c} \left[\sum_{i \in S_{cj}} x_i \right] \leq N_c * Z_c \qquad \forall \ c \tag{2}$$

$$L_{cj} * (1 - \sum_{i \in S_{cj-1}} x_i) + \sum_{i \in S_{cj-1}} a_i x_i + \sum_{i \in S_{cj}} b_i x_i \geq 13 \qquad \forall \ j = 2,..,N_c \quad \forall \ c = 1,..,C \tag{3}$$

$$\sum_{j=1}^{N_c} \sum_{i \in S_{cj}} (p_i x_i + q_i \ (1 - x_i)) \geq 0 \qquad \forall \ c \tag{4}$$

$$\sum_k \sum_i d_{ik} x_i \geq f * K \tag{5}$$

In the above formulation, the objective function is to minimize the number of aircraft carriers needed to cover the assigned station. Constraint (1) ensures that a maximum of one schedule is assigned to a carrier during each deployment period. Constraint (2) allows schedules to be assigned to those carriers which are selected to provide coverage. Constraint (3) allows a schedule to be selected only if it satisfies the 2 to 1 Turn Around Ratio (i.e., 12 months between each 6 month deployment -- 13 is listed to allow one month for transit, two weeks each way). Constraint (4) ensures that the number of months at homeport minus the number of months not at homeport is no smaller than zero in order to guarantee the fifty percent homeport time requirement. Recall that the calculation of p_i assumes that the carrier will be deployed. If the carrier is not selected to deploy, it is assumed to be at homeport for the duration of the deployable period. Thus, the term involving q_i in Equation (4) represents the homeport time when the carrier is not deployed. Constraint (5) ensures that the average coverage over the planning period satisfies the desired coverage level.

The next chapter describes how the model is implemented computationally and Chapter IV illustrates several applications.

III. IMPLEMENTATION

The carrier coverage model described in the previous chapter is implemented in GAMS, the General Algebraic Modeling System (See Brooke et al., 1988). The major portion of the input data required by the model is the carrier on-station schedules and their attributes, i.e., the number of months in homeport before deployment (b_i), the number of months in homeport after deployment and before the next scheduled maintenance (a_i), and personnel tempo (p_i). In an effort to minimize the amount of data preparation by the users, a FORTRAN program ,listed in Appendix A, is developed to generate the inputs to GAMS. (see Appendix B)

Table 2 depicts a sample input file into the FORTRAN program which generates the necessary GAMS input file. This input file is constructed from the OPNAV NOTICE 4710 notional schedule. The first line in the input specifies the desired level of coverage. For this example, 1.0 coverage is desired, i.e., on the average there should be one carrier present in the Mediterranean. The second line of input consists of 3 pieces of data: the available number of carriers and the beginning and end of the planning cycle. The rest of the input file is separated into groups, one for each carrier and each has the same input format. In Table 2, the first group of data is for the carrier Forrestal. The first line in this group of inputs consists of an abbreviation for the name of the carrier which must be exactly four characters long enclosed in two quotation marks. If the abbreviation is shorter

TABLE 2

SAMPLE INPUT FILE

```
1.0
8, 9010, 9807
    'FORR', 3, 8912
      9010, 9205, 0
      9310, 9506, 3
      9511, 9708, 4
    'SARA', 3, 9101
      9108, 9303, 5
      9308, 9412, 4
      9603, 9708, 3
    'KHWK', 3, 8912
      9109, 9307, 6
      9310, 9501, 2
      9506, 9708, 4
    'AMER', 3, 9004
      9010, 9111, 0
      9204, 9309, 5
      9403, 9508, 5
    ' JFK', 2, 9010
      9108, 9212, 3
      9601, 9807, 6
    ' IKE', 3, 9009
      9104, 9205, 5
      9301, 9404, 3
      9409, 9609, 4
    'THEO', 3, 9003
      9201, 9307, 5
      9312, 9503, 4
      9611, 9806, 3
    'WASH',3 , 0
      9306, 9409, 3
      9502, 9607, 4
      9701, 9806, 5
```

than four characters, blank characters are inserted in front of the abbreviation to complete a four character set, e.g., ' JFK'. The two numbers following the abbreviations of the carrier are the number of deployable periods and the date of the end of the carrier's last deployment prior to the planning cycle. Each of the next sequence of input lines contain three numbers. The first two numbers are the beginning and ending dates (in CY YYMM format) for a given deployable period. The third number is the number of months at homeport minus the number of months not at homeport form the end of the preceding deployable period to the beginning of the next one. For the first deployable period following commissioning of a new ship, this number must be set to three (i.e., 90 days) according to OPNAVINST 3000.13. For ships with an extended depot maintenance period in homeport (in excess of six months), the number must be set to six according to the above OPNAV instruction.

Using the input in Table 2, the FORTRAN program generates the GAMS file listed in Appendix B. When this file is executed using GAMS, it solves the mixed integer program using the zero/one Optimization Method (ZOOM). The resulting output is displayed in Tables 3 and 4.

The results depicted in Table 3 starts with the "Solve Summary" which shows that the model is a mixed integer program (MIP) and that the Zero/One Optimization Method (ZOOM) is the solver. Following this, the solver and model status as well as the objective value are listed. In this case, the solver completed normally while the model solution is integer with an objective value of 8.0 carriers.

Next, the Resource Usage, Iteration Count, and their current limits are shown. The next item that should be noticed by the user is the best non-integer solution, or lower bound, that exists for the problem. The best non-integer solution is 6.5. This means that the minimum number of carriers required for the desired coverage is either 7 or 8 and GAMS found a feasible solution which requires 8 carriers. (The output in Appendix D confirms the 8 carriers is indeed optimal.) If one desires a truly optimal solution, the GAMS option called OPTCR or OPTCA must be set to zero (see page 164 of Brooks and Appendix E). However, for the carrier deployment problem, it is not advisable to do so because there are a large number of variables and ZOOM may take an extremely long time to produce a solution, if it can successfully do so. In this implementation, OPTCR is set to 0.001 (in Table 3, this number is listed as the relative tolerance) which corresponds to terminating ZOOM when it finds an integer solution with less than .1% error.

TABLE 3

SAMPLE OUTPUT

```
        S O L V E     S U M M A R Y

MODEL   LANT                 OBJECTIVE  Z
TYPE    MIP                DIRECTION  MINIMIZE
SOLVER  ZOOM                 FROM LINE  718

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      8 INTEGER SOLUTION
**** OBJECTIVE VALUE             8.0000

RESOURCE USAGE, LIMIT         287.340      1000.000
ITERATION COUNT, LIMIT      24178         25000

Courtesy of Dr Roy E. Marsten,
   Department of Management Information Systems,
   University of Arizona,
   Tucson      Arizona 85721,  U.S.A.

Work space needed(estimate)  --        25355 words.
Work space available          --      25355 words.
Maximum obtainable            --      423166 words.

No solution better than    6.5071323     can exist.
(relative and absolute distance: 0.229   1.4928677)
(relative and absolute tolerances: 0.100E-02)

The LU factors occupied 1343 slots (estimate 5266).
the branch and bound tree contained 127 nodes


**** REPORT SUMMARY :
                          0    NONOPT
                          0 INFEASIBLE
                          0  UNBOUNDED
```

Table 4 shows the solution produced by ZOOM for the carrier deployment model. The first column lists the sequential months in the planning cycle. The second column lists the date in calendar year (YYMM) format. The four letter identifiers of the carriers chosen are listed across the top of the page. The on-station schedules chosen for each carrier are listed vertically under the ships name and are depicted by vertical vectors of '1's". The final column lists the total coverage in each month. In the example listed in Table 4, all eight carriers are chosen. In the short example depicted in Table 4, America has two on-station schedules listed. The first schedule covers June 1990 to October 1990 (months 9-13 in the planning cycle) while the second schedule covers April 1992 to August 1992 (months 31-35 in the planning cycle).

TABLE 4

SCHEDULE AND CARRIER LISTING

	DATE	FORR	SARA	KHWK	AMER	JFK	IKE	THEO	WASH	TOTAL
9	9006				1					1
10	9007				1					1
11	9008				1					1
12	9009				1					1
13	9010				1					1
14	9011	1								1
15	9012	1								1
16	9101	1								1
17	9102	1								1
18	9103	1								1
19	9104		1							1
20	9105		1							1
21	9106		1							1
22	9107		1			1				2
23	9108		1			1				2
24	9109					1				1
25	9110					1				1
26	9111					1		1		2
27	9112							1		1
28	9201							1		1
29	9202							1		1
30	9203							1		1
31	9204				1					1
32	9205				1					1
33	9206				1					1
34	9207				1					1
35	9208				1					1
36	9209						1			1
37	9210						1			1
38	9211						1			1
39	9212						1			1
40	9301						1			1
41	9302								1	1
42	9303								1	1
42	9304								1	1

IV. APPLICATIONS

This chapter illustrates several applications for the model developed in earlier chapters. The main goal is to illustrate how the model can be used as a decision aid. As a caution, it must be remembered that the conclusion drawn in each example is purely based on the results obtained from the model only. No tactical, political, strategic, or economic considerations are taken into account since such analysis would be beyond the scope of this thesis. Also, the data for examples are for the east coast. The west coast model is different, but similar. Below are four applications of the carrier deployment model.

1) Coverage Effectiveness of the NAVSEANOTE 4710 Notional Maintenance Schedule

As indicated previously, one of the factors constraining carriers from being on-station is the maintenance. This application of the carrier deployment model shows how a given maintenance schedule affects the number of carriers required to provide a certain level of coverage. Table 5 gives the results produced by the model using the Ship Overhaul Schedule for Advanced Planning, May 1989. For each level of coverage, there are two numbers: one is the optimal integer answer and the other is noninteger. Note at 0.75 coverage, rounding up the noninteger answer which is 4.7 does not equal the integer answer. This partially invalidates the practice of rounding up answers from LOTUS 1-2-3 model.

TABLE 5

CARRIER COVERAGE USING NAVSEADET NOTIONAL SCHEDULE

Level of Coverage	Optimal Integer Carriers	Optimal Non-integer Carriers
0.5	4	3.133
0.6	4	3.76
0.75	6	4.7
1.0	8	6.5
1.1	8	7.06
1.2	8	7.28

It is interesting to note that the model says that eight carriers are needed to provide a 1.0 coverage in the Mediterranean. This answer is much different from the LOTUS 1-2-3's answer of five carriers. It is hypothesized that this difference is due to the fact that the mixed integer program does not average the major depot level maintenance periods experienced by the carriers. Averaging the length of maintenance decreases the effect of long and overlapping periods such as Service Life Extension Program (SLEP's) and Reactor Core Overhauls (RCOH's). When there are long maintenance periods such as SLEP's and RCOH's, carriers are unavailable for a long period, thereby increasing the need for more carriers to maintain the same level of coverage. In an effort to reduce the number of carriers, the remaining applications investigate the effect of replacing all SLEP's with complex overhauls (COH's) for CV's, using phased maintenance to lengthen service life between major overhauls of CV's, and using all CV's or all CVN's to cover the Mediterranean.

2) Replacing SLEP's with COH's

In this scenario, the SLEP's for America and John F. Kennedy scheduled for September 1995 to January 1998 and January 1993 to May 1995, respectively, are replaced with a standard 12 month overhaul from August 1995 to August 1996 and from January 1993 to January 1994, respectively. The results of this change is summarized in Table 6.

TABLE 6

CARRIER COVERAGE -- SLEP REPLACED WITH COH

Level of Coverage	Optimal Integer Carriers	Optimal Non-integer Carriers
0.5	3	2.8
0.6	4	3.42
0.75	5	4.36
1.0	7	5.93
1.1	7	6.65
1.2	8	7.18
1.3	8	7.91

Compared with the results in Table 5, the COH's allow more coverage with the same number of carriers.

3) Phased maintenance for conventional carriers

Phased maintenance allows for a carrier to use many short, pier-side maintenance periods to replace some of the complex overhauls. When phased maintenance is used, the cycle between major overhauls is greatly extended. Presently, only the Yokosuka based carrier is maintained in this manner.

In this scenario, the notional schedule for the nuclear carriers is left unchanged. The SLEP durations for the carriers America and John F. Kennedy are reduced to regular overhaul lengths as described in Example 2 above. A COH is replaced by SRA's for the remaining three CV's. This increased the number of deployable periods from three to four for America and John F. Kennedy. The results of these changes are listed in Table 7. Again, when compared to Table 5, more coverage is obtainable with fewer assets.

TABLE 7

PHASED MAINTENANCE AND NO SLEPS

Level of Coverage	Optimal Integer Carriers	Optimal Non-integer Carriers
0.5	3	2.35
0.6	4	2.57
0.75	5	3.54
1.0	6	5.21
1.1	7	5.37
1.2	7	5.84
1.3	7	6.4
1.4	8	7.2

4) Coverage effectiveness of Conventional vs. Nuclear carriers

This application examines how effective a CV or CVN is at providing coverage. The minimum number of carriers of a particular type is used as a measure of coverage effectiveness. To do so, the standard maintenance cycles listed in OPNAV NOTICE 4700 are assumed. Therefore, each conventional carrier had a 72 month cycle from the end of one overhaul to the end of the next. The nuclear carriers had 102 month cycles which is typical for the CVN 68 class nuclear carriers. The maintenance periods for carriers are scheduled to avoid overlap as much as possible. In this manner, there would be more carriers available for exercises at any given moment. Table 8 compares the minimum numbers of CV's and CVN's for each level of coverage. The results from this table suggest that CV's are more effective since fewer CV's are required to provide the same level of coverage. However, upon a closer examination of the maintenance cycle, CVN's have noticeably longer overhaul periods, in particular the 30 month RCOH. Thus, CVN's are less available for cruises than CV's. Besides these longer overhaul periods, other and perhaps more important factors are not taken into account here since the object is to demonstrate possible uses of the model. In practice, one would expect the optimal carrier force to consist of both CV's and CVN's.

TABLE 8

COVERAGE EFFECTIVENESS OF CV'S AND CVN's

Maximum Coverage	Optimal Integer CV's	Optimal Integer CVN's
0.5	3	3
0.6	4	4
0.75	4	5
1.0	5	6
1.2	6	7

V. CONCLUSION

This thesis addresses the usage of one of the most capable yet expensive assets in the US Navy -- aircraft carriers. It proposes a mixed integer programming (MIP) model which determines the minimum number of aircraft carriers to provide a specified level of coverage in a particular theater. This MIP model is different from the LOTUS 1-2-3 model currently in use at OP-81 in several aspects. They are:

- The MIP model provides integer solution while LOTUS does not.
- The MIP model uses actual maintenance schedule while LOTUS uses average maintenance cycles.
- The MIP model allows for more accurate accounting of factors determining the personnel tempo (PERSTEMPO) and LOTUS does not.

Other features which makes the MIP model a more effective tool as decision aid include the use of commercially available software - GAMS, and the ease of data input. This latter feature also facilitates sensitivity analysis to answer the "what if" questions.

In addition, the MIP model can also be used as a tool for analysis other than determining the minimum number of carriers. Chapter IV depicted four possible analyses involving the east coast carriers and the Mediterranean station. These analyses include: (1) Coverage effectiveness of the NAVSEANOTE 4710 notional maintenance schedule, (2) Analysis of replacing SLEP's with COH's, (3) Analysis of a phased maintenance approach for conventional carriers, and (4) Coverage effectiveness of conventional vs. nuclear carriers.

This thesis also points out other areas for future research:

- This thesis demonstrated that the determination of the minimum number of carriers satisfying coverage requirements can be stated as a mixed integer program. However, there was sufficient time to model only the east coast portion. Modelling the west coast portion is an area for future work. This model would be similar, but would have to include the carrier homeported in Yokosuka, Japan.

- One important factor in determining the availability of carriers for cruises is the individual carrier's maintenance schedule. Better coordination of the individual carriers maintenance schedule would allow carriers to be available for more cruises thereby reducing the number of carriers to provide the same level of coverage. It is quite possible that the problem of coordinating these maintenance schedules in order to maximize carrier availability can also be modeled as a mixed integer program, hence should be investigated.

- One question which was raised in one of the four applications discussed in Chapter IV concerns the optimal numbers of CV's and CVN's in a carrier force. Again, it is possible that this question can also be answered through the use of a mathematical programming model.

- All of the above assume that the given data are deterministic which may not be realistic. It is therefore important to examine cases where some data are not known deterministically. As an example, the starting and the finishing dates of a maintenance period are in reality nondeterministic.

APPENDIX A FORTRAN PROGRAM LISTING

This FORTRAN program uses an input file provided by the user to generate a carrier optimization model in the modelling language GAMS-- General Algebraic Modelling System. The GAMS model solves for the minimum carrier assets required to cover the Mediterranean Ocean based on desired coverage. The model is constrained by maintenance and PERSTEMPO requirements. This model has been composed as a result of Thesis research at the Naval Postgraduate School conducted by:

```
* Mark L. Stone, LT, USN
*Thesis Advisor: Dr. Siriphong Lawphongpanich

      PROGRAM ATCOM6
      REAL COVER, UU, LL
      INTEGER SHP, BKS, BKE, SCH, PRS, SRA
      PARAMETER (SHP=1, BKS=2, BKE=3, SCH=4, PRS=5, SRA=6)
      INTEGER BEGYR, BEGCY, BEGDAT, ENDYR, ENDDAT, BEGMO,
     +ENDMO, MONTH,
     +        NOBLOK, BINDEX, SINDEX, NUMSHP, N1, N2, DIFF,
     +        STMO, STYR, FNYR, FNMO, ALLSCH, TOTAL
      INTEGER BLOCK(100,6), TOTSCH(20) ,TOTBLK(20) ,BSCH(20),
     +ESCH(20)
      INTEGER BEF(300), AFT(300)
      INTEGER IN, OUT
      CHARACTER*4 SNAME(20), SHIP
*
      IN = 9
      OUT = 10
      CALL EXCMS('FILEDEF 9 DISK LANT3A DATA A1')
      CALL EXCMS('FILEDEF 10 DISK OUT6 GAMS A1')
*
      READ(IN,*) COVER
      READ (IN,*) NUMSHP, BEGDAT, ENDDAT
      BEGYR = BEGDAT / 100
      ENDYR = ENDDAT / 100
      BEGMO = BEGDAT - BEGYR*100
      ENDMO = ENDDAT - ENDYR*100
      MONTH = (ENDYR - BEGYR)*12 + (ENDMO - BEGMO) + 1
      BEGCY = BEGYR - 1
*
      SINDEX = 1
      BINDEX = 1
      TOTAL  = 0
```

```
      ALLSCH = 0
*
*---------------------------------CALCULATE MONTHS SINCE LAST
*                            DEPLOYED FOR FIRST DEPLOYABLE PERIOD
*
      DO 20 I = 1, NUMSHP
         READ (IN, *) SHIP, NOBLOK , NLAST
         SNAME(SINDEX) = SHIP
         TOTBLK(SINDEX) = NOBLOK
*        WRITE(OUT,*) TOTBLK(SINDEX)
         STYR = NLAST / 100
         STMO = NLAST - STYR * 100
         LDEPLY = (STYR-BEGYR)*12 + STMO - BEGMO + 1
*
*------------ GENERATE INDEXES ASSOCIATED WITH EACH CARRIER
*      AND START AND BEGIN MONTHS FOR EACH DEPLOYABLE PERIOD
*
         DO 10 J = 1, NOBLOK
            READ (IN, *) N1, N2 , NPERS
            STYR = N1 / 100
            STMO = N1 - STYR*100
            FNYR = N2 / 100
            FNMO = N2 - FNYR*100
*
            BLOCK(BINDEX, SHP) = SINDEX
            BLOCK(BINDEX, BKS) = (STYR - BEGYR)*12 + (STMO -
     +        BEGMO) + 1
            BLOCK(BINDEX, BKE) = (FNYR - BEGYR)*12 + (FNMO -
     +        BEGMO) + 1
*
*----------------CALCULATE MONTHS AFTER LAST DEPLOYMENT  TO
  *                                START OF NEXT DEPLOYABLE PERIOD
*
            IF (J .EQ. 1) THEN
               BLOCK(BINDEX,SRA) =
     +            MIN0(BLOCK(BINDEX,BKS)-LDEPLY-1,12)
            ELSE
               BLOCK(BINDEX,SRA) = BLOCK(BINDEX,BKS) -
     +                               BLOCK(BINDEX-1,BKE) - 1
            ENDIF
*
* ------------------ CHECK IF THE LENGTH OF EACH DEPLOYABLE
*                                      PERIOD IS LONGER THAN  13
*
            IF (BLOCK(BINDEX,BKE) - BLOCK(BINDEX,BKS) .GE. 13)
     +        THEN
               BLOCK(BINDEX,SCH) =
     +                   (BLOCK(BINDEX,BKE)-5) -
                                      (BLOCK(BINDEX,BKS)+8)+1
*
```

```
*------------------------------- CALCUIATE PERSTEMPO TO DATE
*
               BLOCK(BINDEX,PRS) = BLOCK(BINDEX,BKE) -
     +               BLOCK(BINDEX,BKS) - 19 + NPERS
*
               TOTAL = TOTAL + BLOCK(BINDEX,SCH)
               BINDEX = BINDEX + 1
             ENDIF
  10      CONTINUE
          TOTSCH(SINDEX) = TOTAL
          ALLSCH = ALLSCH + TOTAL
          TOTAL = 0
          SINDEX = SINDEX + 1
  20  CONTINUE
      BINDEX = BINDEX - 1
      BSCH(1) = 1
      LAST = 0
      DO 30 I = 1, NUMSHP
         ESCH(I) = TOTSCH(I) + LAST
         BSCH(I + 1) = ESCH(I) + 1
         LAST = ESCH(I)
*        WRITE(OUT,*) BSCH(I), ESCH(I)
  30  CONTINUE
*     DO 40  K = 1, BINDEX
*        WRITE(OUT,9100) (BLOCK(K,I), I = 1, 6)
*9100    FORMAT(' ', 7I4)
* 40  CONTINUE
*     SINDEX = SINDEX -1
*     DO 50 K = 1, SINDEX
*        WRITE(OUT,*) SNAME(K), TOTSCH(K)
* 50  CONTINUE
*
*-------------SET UPPER/LOWER BOUNDS BASED ON COVERAGE DESIRED
*     IF (COVER .GE. 1.0) THEN
         UU = 2.0
         LL = 1.0
      ELSE
         UU = 1.0
         LL = 0.0
      ENDIF
************************************************************
   GAMS PROGRAM GENERATION
************************************************************
      WRITE(OUT,7000)
 7000 FORMAT('$TITLE EAST COAST CARRIER OPTIMIZATION MODEL')
      WRITE(OUT,8000)
 8000 FORMAT('$OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF')
      WRITE(OUT,8001)
 8001 FORMAT(1X,'OPTIONS LIMCOL = 0, LIMROW = 0, SOLPRINT =
     + OFF,',3X,
```

```
     + 'ITERLIM = 25000;')
      WRITE (OUT,8002) COVER, UU, LL
 8002 FORMAT(1X,'OPTIONS OPTCR = 0.001;'/
     +3X, 'SCALAR FRA /',F3.1,'/, UU /',F3.1,'/, LL /',F3.1,'/
     + ;')
      WRITE(OUT,8003)
 8003 FORMAT('  SETS'//)
      WRITE(OUT,8004) NUMSHP
 8004 FORMAT(5X,'C',4X,'CARRIERS',10X,'/1 * ',I1,' /')
      WRITE(OUT,8005) ALLSCH
 8005 FORMAT('     I   SHIP-SCHEDULE PAIR /1 * ',I4,'/')
      WRITE(OUT,8006) MONTH
 8006 FORMAT('     K   MONTH              /1 * ',I3,'/')
*
*---------GENERATE FEASIBLE DEPLOYMENT SCHEDULES IN MONTHS
*                      FOR EACH SHIP AND DEPLOYABLE PERIOD
*
      WRITE(OUT,8007)
 8007 FORMAT('     ICOVER(I,K) COVERAGE INDICATOR /')
      ISCH = 0
      DO 60 K = 1, BINDEX
         DO 60 I = 1, BLOCK(K,SCH)
            ISCH = ISCH + 1
            N1 = 7 + BLOCK(K,BKS) + I
            N2 = N1 + 4
            BEF(ISCH) = 7 + I + BLOCK(K,SRA)
            AFT(ISCH) = BLOCK(K,BKE) - N2 - 1
            WRITE(OUT,8008) ISCH, N1, N2
 8008       FORMAT(10X,I4,'.(',I3,'*',I3,')')
 60   CONTINUE
      WRITE(OUT,8009)
8009  FORMAT(10X,' /')
      ILAST = 1
      ISCH = 0
      ISHIP = 1
      J = 0
*
* --------------WRITE SCHEDULES ASSOCIATED WITH A PARTICULAR
*                                SHIP FOR ALL DEPLOYABLE PERIODS
*
      DO 70 I = 1, BINDEX
         IF ( ISHIP .NE. BLOCK(I,SHP) ) THEN
            WRITE(OUT,8010) SNAME(ISHIP),ILAST, ISCH
8010        FORMAT(3X,A4,'(I) /',I3,'*',I3,'/')
            ILAST = ISCH + 1
            J = 0
            ISHIP = BLOCK(I,SHP)
         ENDIF
         J = J + 1
         N1 = ISCH + 1
```

```
         N2 = BLOCK(I,SCH) + ISCH
*
* ----------------------- WRITES SCHEDULES ASSOCIATED WITH A
*         PARTICULAR SHIP FOR A PARTICULAR DEPLOYABLE PERTOD
*
         WRITE(OUT,8011) SNAME(ISHIP), J, N1, N2
8011     FORMAT(3X,A4,I1,'(I) /',I3,'*',I3,'/')
            ISCH = N2
70    CONTINUF
         WRITE(OUT,8010) SNAME(ISHIP),ILAST, ISCH
         WRITE(OUT,8012)
8012     FORMAT(10X, ';')
*
*------------------------WRITE PERSTEMPO ASSOCIATED WITH A
*              PARTICULAR CARRIER IN EACH DEPLOYABLE PERIOD
*
      WRITE(OUT,8013)
8013  FORMAT(3X,'PARAMETER PERS(I) /')
      ISCH = 0
      DO 80 I = 1, BINDEX
         N1 = ISCH + 1
         N2 = BLOCK(I,SCH) + ISCH
         WRITE(OUT,8014) N1,N2, BLOCK(I,PRS)
 8014    FORMAT(5X,I3,'*',I3,2X,I3)
         ISCH = N2
 80   CONTINUE
      WRITE(OUT, 8015)
 8015 FORMAT(3X,' /')
      WRITE(OUT,8016)
*
* --------WRITE THE NUMBER OF 'BEFORE' MONTHS ASSOCIATED  WITH
     EACH SCHEDULE FOR ALL CARRIERS AND EACH DEPLOYABLE PERIOD
*
8016  FORMAT(5X,' BFR(I) /')
      ISCH = 0
      DO 90 K = 1, BINDEX
         DO 90 I = 1, BLOCK(K,SCH)
            ISCH = ISCH + 1
            WRITE(OUT,8017) ISCH, BEF(ISCH)
8017        FORMAT(5X,2I4)
90    CONTINUE
      WRITE(OUT, 8015)
*
* -------WRITE THE NUMBER OF 'AFTER' MONTHS ASSOCIATED  WITH
   EACH SCHEDULE FOR ALL CARRIERS AND EACH DEPLOYABLE PERIOD
*
      WRITE(OUT,8019)
8019  FORMAT(5X,' AFT(I) /')
      ISCH = 0
      DO 100 K = 1, BINDEX
```

```
         DO 100 I = 1, BLOCK(K,SCH)
            ISCH = ISCH + 1
            WRITE(OUT,8017) ISCH, AFT(ISCH)
100   CONTINUE
      WRITE(OUT, 8020)
8020  FORMAT('     /;')
*
      WRITE(OUT,8021)
 8021 FORMAT(3X,'PARAMETER EMPTY(K) EMPTY MONTH;'/
     +10X,'EMPTY(K) = SUM(I $ ICOVER(I,K), 1);'/
     +3X,'VARIABLES'//
     +10X,'X(I)     SELECT ITH SCHEDULE FOR SHIP C'/
     +10X,'Y(K)      COVERAGE FACTOR IN MONTH K'/
     +10X,'Z         MAX COVERAGE;'/
     +3X,'BINARY VARIABLE SL(C) , X(I);'/
     +3X,'POSITIVE VARIABLE Y(K);'/
     +10X,'Y.LO(K)$(EMPTY(K)) = LL;'/
     +10X,'Y.UP(K)$(EMPTY(K)) = UU;'/
     +10X,'Y.UP(K)$(EMPTY(K) EQ 0) = 0;')
*--------------------------------------SET BOUNDS ON FIRST
*                                            BLOCK FOR TAR
      DO 110  I = 1, NUMSHP
            J =1
            WRITE (OUT,8022) SNAME(I),J,SNAME(I),J
8022        FORMAT(8X,'X.FX(',A4,I1,')$(BFR(',A4,I1,') LT 12)
     +        = 0;')
110   CONTINUE
*
* -------------------------------------  GENERATE EQUATIONS
      WRITE(OUT,8023)
8023  FORMAT(3X,'EQUATIONS'/)
      J = 0
      ISHIP = 1
      DO 120 I = 1, BINDEX
         IF ( ISHIP .NE. BLOCK(I,1) ) THEN
            J = 0
            ISHIP = BLOCK(I,1)
         ENDIF
         J = J + 1
         WRITE(OUT,8024) SNAME(ISHIP), J
 8024    FORMAT(5X,A4,I1,'SLC')
 120  CONTINUE
      WRITE(OUT,8025)
 8025 FORMAT(5X,'OBJ'/ 5X,'COVERAGE(K)')
      DO 130 I = 1, NUMSHP
         WRITE(OUT,8026) I
 8026    FORMAT(5X,'SHIP',I1)
 130   CONTINUE
      DO 150 I = 1, NUMSHP
         DO 140 J = 2, TOTBLK(I)
```

```
            WRITE(OUT,8027) SNAME(I), J
8027        FORMAT(5X,A4,I1,'TAR')
140       CONTINUE
150    CONTINUE
      DO 160 I = 1, NUMSHP
         WRITE(OUT,8028) SNAME(I)
8028     FORMAT(5X,A4,'PERS')
160   CONTINUE
      WRITE(OUT,8029)
8029  FORMAT(5X,'FACTOR  ;'/)
*---------------------------------------GEN SHIPSLC EQUATIONS
      J = 0
      ISHIP = 1
      DO 170 I = 1, BINDEX
         IF ( ISHIP .NE. BLOCK(I,SHP) ) THEN
            J = 0
            ISHIP = BLOCK(I,SHP)
         ENDIF
         J = J + 1
         WRITE(OUT,8030) SNAME(ISHIP), J, SNAME(ISHIP), J,
     +      SNAME(ISHIP), J
8030FORMAT(3X,A4,I1,'SLC..',5X,'SUM(',A4,I1,',X(',A4,I1,'))
     +   =L= 1;')
170   CONTINUE
*---------------------------------------GEN SHIP EQUATIONS
      DO 180 I = 1,NUMSHP
         WRITE(OUT,8031) I, BSCH(I), ESCH(I), TOTBLK(I), I
8031     FORMAT(3X,'SHIP',I1,'..',/
     +   5X,'SUM(I $(ORD(I) GE ',I3,' AND ORD(I) LE ',I3,
     +   '), X(I)) =L= ',I3,' *SL("',I1,'");')
180   CONTINUE
*---------------------------------------GEN TAR EQUATIONS
      IC = 0
      DO 200 I = 1, NUMSHP
         UPTO = TOTBLK(I)-1
         DO 190 J = 1, UPTO
            DIFF = BLOCK(IC+J,BKE) - BLOCK(IC+J,BKS) +1
*           WRITE(OUT,*) DIFF
            WRITE(OUT,8032) SNAME(I),J+1,DIFF,SNAME(I),J,
     +      SNAME(I),J,
     +      SNAME(I),J,SNAME(I),J,SNAME(I),  J,SNAME(I),J+1,
     +      SNAME(I),J+1, SNAME(I),J+1
8032        FORMAT(3X,A4,I1,'TAR..',/
     +      5X,I3,'*(1 - SUM(',A4,I1,',X(',A4,I1,'))) + ',/
     +      5X,'SUM(',A4,I1,',AFT(',A4,I1,')*X(',A4,I1,')) +
     +      SUM(',
     +      A4,I1,' ,BFR(',A4,I1,')*X(',A4,I1,')) =G= 13;')
190      CONTINUE
         IC = IC +TOTBLK(I)
200   CONTINUE
```

```
*------------------------------------GEN PERSTEMPO EQUATIONS
      IC = 0
      DIFF = 0
      DO 220 I = 1, NUMSHP
         WRITE(OUT,8033) SNAME(I)
 8033       FORMAT(3X,A4,'PERS..')
        DO 210 J = 1, TOTBLK(I)
          DIFF = BLOCK(IC+J,BKE) - BLOCK(IC+J,BKS) +1
          IF(J .EQ. TOTBLK(I)) THEN
            WRITE(OUT,8034)SNAME(I),J,SNAME(I),J,SNAME(I),J,
     +      DIFF, SNAME(I),J,SNAME(I),J
 8034       FORMAT(5X,'SUM(',A4,I1,',
     +        PERS(',A4,I1,')*X(',A4,I1,')) + ',
     +      I2,'*(1-SUM(',A4,I1,', X(', A4,I1,'))))')
          ELSE
            WRITE(OUT,8035)SNAME(I),J,SNAME(I),J,SNAME(I),J,
     +      DIFF, SNAME(I),J,SNAME(I),J
 8035       FORMAT(5X,'SUM(',A4,I1,',
     +        PERS(',A4,I1,')*X(',A4,I1,')) + ',
     +      I2,'*(1-SUM(',A4,I1,', X(', A4,I1,'))) +')
          ENDIF
210      CONTINUE
         WRITE(OUT,8036)
8036     FORMAT(5X,'=G= 0;')
         IC = IC +TOTBLK(I)
220   CONTINUE
      WRITE(OUT,8037)
 8037 FORMAT(3X,'OBJ..      Z =E= SUM(C, SL(C));'/
     +3X,'COVERAGE(K)$(EMPTY(K))..
     +Y(K)=L=SUM(I$ICOVER(I,K),X(I));'/
     +3X,'FACTOR..',4X,'SUM(K,Y(K)) =G= FRA * CARD(K);'
     +//
     +3X,'MODEL LANT /ALL/;'/
     +3X,'SOLVE LANT USING MIP MINIMIZING Z;')
      WRITE(OUT,8038)
 8038 FORMAT(3X,'OPTION Y:2:0:1;'/)
      WRITE(OUT,8039)
 8039 FORMAT(3X,'PARAMETER NCOVER(I,K);'/
     +5X,'NCOVER(I,K) = 1$ICOVER(I,K);',/
     +3X,'PARAMETER REPORT(K,*);'/
     +3X,'OPTION REPORT: 0;')
*
*----------------- ------------------------- GENERATE REPORT
*
      WRITE(OUT,8040) BEGCY
8040  FORMAT(3X,'REPORT(K,"DATE") =
     +(',I2,'+TRUNC((ORD(K)+8)/12))*'
     +1X,'100+MOD(ORD(K)+8,12)+1;')
      DO 230 I = 1,NUMSHP
         WRITE(OUT,8041) SNAME(I), BSCH(I),ESCH(I)
```

```
8041      FORMAT(3X, 'REPORT(K," ',A4,' ") = ',/
     +    5X,'SUM(I $(ORD(I) GE ',I3, ' AND ORD(I) LE ',I3,
     +    2X,'), X.L(I)*NCOVER(I,K));')
230    CONTINUE
       WRITE(OUT,8042)
8042   FORMAT(1X,'REPORT(K,"TOTAL") = SUM(I,
     +  X.L(I)*NCOVER(I,K));',/
     +1X,'DISPLAY REPORT;')
       STOP
       END
```

APPENDIX B GAMS MODEL LISTING

```
$TITLE EAST COAST CARRIER OPTIMIZATION MODEL
$OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
 OPTIONS LIMCOL = 0, LIMROW = 0, SOLPRINT = OFF,   ITERLIM = 25000;
 OPTIONS OPTCR = 0.001;
*------------------------------------------------------------
* INDICES
*------------------------------------------------------------

   SCALAR FRA /1.0/, UU /2.0/, LL /1.0/ ;
  SETS


    C    CARRIERS          /1 * 8 /
    I  SHIP-SCHEDULE PAIR /1 *  145/
    K   MONTH             /1 *  94/
    ICOVER(I,K) COVERAGE INDICATOR /
             1.(  9* 13)
             2.( 10* 14)
             3.( 11* 15)
             4.( 12* 16)
             5.( 13* 17)
             6.( 14* 18)
             7.( 15* 19)
             8.( 45* 49)
                  .
                  .
                  .
            145.( 88*92)
        /

   FORR1(I) /  1*  7/
   FORR2(I) /  8* 15/
   FORR3(I) / 16* 24/
   FORR(I) /  1* 24/
   SARA1(I) / 25* 31/
   SARA2(I) / 32* 35/
   SARA3(I) / 36* 40/
   SARA(I) / 25* 40/
            .
            .
            .
   WASH1(I) /133*135/
   WASH2(I) /136*140/
   WASH3(I) /141*145/
```

```
WASH(I) /133*145/
        ;
PARAMETER PERS(I) /
    1*  7     0
    8* 15     4
   16* 24     6
   25* 31     5
         .
         .
         .
  126*132     3
  133*135    -1
  136*140     2
  141*145     3
 /

   BFR(I) /
     1  17
     2  18
     3  19
     4  20
     5  21
     6  22
       .
       .
       .
   143  15
   144  16
   145  17
 /
   AFT(I) /
     1   6
     2   5
     3   4
     4   3
     5   2
     6   1
         .
         .
         .
   143   2
   144   1
   145   0
 /;
PARAMETER EMPTY(K) EMPTY MONTH;
       EMPTY(K) = SUM(I $ ICOVER(I,K), 1);
```

```
*----------------------------------------------------------------
* VARIABLES
*----------------------------------------------------------------
   VARIABLES

          X(I)    SELECT ITH SCHEDULE FOR SHIP C
          Y(K)     COVERAGE FACTOR IN MONTH K
          Z        MAX COVERAGE;
   BINARY VARIABLE SL(C) , X(I);
   POSITIVE VARIABLE Y(K);
          Y.LO(K)$(EMPTY(K)) = LL;
          Y.UP(K)$(EMPTY(K)) = UU;
          Y.UP(K)$(EMPTY(K) EQ 0) = 0;
        X.FX(FORR1)$(BFR(FORR1) LT 12) = 0;
        X.FX(SARA1)$(BFR(SARA1) LT 12) = 0;
        X.FX(KHWK1)$(BFR(KHWK1) LT 12) = 0;
        X.FX(AMER1)$(BFR(AMER1) LT 12) = 0;
        X.FX( JFK1)$(BFR( JFK1) LT 12) = 0;
        X.FX( IKE1)$(BFR( IKE1) LT 12) = 0;
        X.FX(THEO1)$(BFR(THEO1) LT 12) = 0;
        X.FX(WASH1)$(BFR(WASH1) LT 12) = 0;
*----------------------------------------------------------------
* FORMULATION
*----------------------------------------------------------------

   EQUATIONS

     FORR1SLC
     FORR2SLC
     FORR3SLC
     SARA1SLC
     SARA2SLC
     SARA3SLC
         .
         .
     OBJ
     COVERAGE(K)
     SHIP1
     SHIP2
        .
        .
     FORR2TAR
     FORR3TAR
     SARA2TAR
     SARA3TAR
     KHWK2TAR
     KHWK3TAR
         .
         .
     FORRPERS
```

```
  SARAPERS
      .
      .
  FACTOR  ;

FORR1SLC..      SUM(FORR1,X(FORR1)) =L= 1;
FORR2SLC..      SUM(FORR2,X(FORR2)) =L= 1;
FORR3SLC..      SUM(FORR3,X(FORR3)) =L= 1;
SARA1SLC..      SUM(SARA1,X(SARA1)) =L= 1;
SARA2SLC..      SUM(SARA2,X(SARA2)) =L= 1;
SARA3SLC..      SUM(SARA3,X(SARA3)) =L= 1;
KHWK1SLC..      SUM(KHWK1,X(KHWK1)) =L= 1;
KHWK2SLC..      SUM(KHWK2,X(KHWK2)) =L= 1;
KHWK3SLC..      SUM(KHWK3,X(KHWK3)) =L= 1;
AMER1SLC..      SUM(AMER1,X(AMER1)) =L= 1;
AMER2SLC..      SUM(AMER2,X(AMER2)) =L= 1;
AMER3SLC..      SUM(AMER3,X(AMER3)) =L= 1;
 JFK1SLC..      SUM( JFK1,X( JFK1)) =L= 1;
 JFK2SLC..      SUM( JFK2,X( JFK2)) =L= 1;
 IKE1SLC..      SUM( IKE1,X( IKE1)) =L= 1;
 IKE2SLC..      SUM( IKE2,X( IKE2)) =L= 1;
 IKE3SLC..      SUM( IKE3,X( IKE3)) =L= 1;
THEO1SLC..      SUM(THEO1,X(THEO1)) =L= 1;
THEO2SLC..      SUM(THEO2,X(THEO2)) =L= 1;
THEO3SLC..      SUM(THEO3,X(THEO3)) =L= 1;
WASH1SLC..      SUM(WASH1,X(WASH1)) =L= 1;
WASH2SLC..      SUM(WASH2,X(WASH2)) =L= 1;
WASH3SLC..      SUM(WASH3,X(WASH3)) =L= 1;
SHIP1..
  SUM(I $(ORD(I) GE   1 AND ORD(I) LE  24), X(I)) =L=   3 *SL("1");
SHIP2..
  SUM(I $(ORD(I) GE  25 AND ORD(I) LE  40), X(I)) =L=   3 *SL("2");
SHIP3..
  SUM(I $(ORD(I) GE  41 AND ORD(I) LE  67), X(I)) =L=   3 *SL("3");
SHIP4..
  SUM(I $(ORD(I) GE  68 AND ORD(I) LE  78), X(I)) =L=   3 *SL("4");
SHIP5..
  SUM(I $(ORD(I) GE  79 AND ORD(I) LE 100), X(I)) =L=   2 *SL("5");
SHIP6..
  SUM(I $(ORD(I) GE 101 AND ORD(I) LE 116), X(I)) =L=   3 *SL("6");
SHIP7..
  SUM(I $(ORD(I) GE 117 AND ORD(I) LE 132), X(I)) =L=   3 *SL("7");
SHIP8..
  SUM(I $(ORD(I) GE 133 AND ORD(I) LE 145), X(I)) =L=   3 *SL("8");
FORR2TAR..
   20*(1 - SUM(FORR1,X(FORR1))) +
  SUM(FORR1,AFT(FORR1)*X(FORR1)) + SUM(FORR2 ,BFR(FORR2)*X(FORR2)) =G=
FORR3TAR..
   21*(1 - SUM(FORR2,X(FORR2))) +
  SUM(FORR2,AFT(FORR2)*X(FORR2)) + SUM(FORR3 ,BFR(FORR3)*X(FORR3)) =G=
```

```
SARA2TAR..
   20*(1 - SUM(SARA1,X(SARA1))) +
  SUM(SARA1,AFT(SARA1)*X(SARA1)) + SUM(SARA2 ,BFR(SARA2)*X(SARA2)) =G=
SARA3TAR..
   17*(1 - SUM(SARA2,X(SARA2))) +
  SUM(SARA2,AFT(SARA2)*X(SARA2)) + SUM(SARA3 ,BFR(SARA3)*X(SARA3)) =G=
KHWK2TAR..
   23*(1 - SUM(KHWK1,X(KHWK1))) +
  SUM(KHWK1,AFT(KHWK1)*X(KHWK1)) + SUM(KHWK2 ,BFR(KHWK2)*X(KHWK2)) =G=
KHWK3TAR..
   16*(1 - SUM(KHWK2,X(KHWK2))) +
  SUM(KHWK2,AFT(KHWK2)*X(KHWK2)) + SUM(KHWK3 ,BFR(KHWK3)*X(KHWK3)) =G=
AMER2TAR..
   14*(1 - SUM(AMER1,X(AMER1))) +
  SUM(AMER1,AFT(AMER1)*X(AMER1)) + SUM(AMER2 ,BFR(AMER2)*X(AMER2)) =G=
AMER3TAR..
   18*(1 - SUM(AMER2,X(AMER2))) +
  SUM(AMER2,AFT(AMER2)*X(AMER2)) + SUM(AMER3 ,BFR(AMER3)*X(AMER3)) =G=
 JFK2TAR..
   17*(1 - SUM( JFK1,X( JFK1))) +
  SUM( JFK1,AFT( JFK1)*X( JFK1)) + SUM( JFK2 ,BFR( JFK2)*X( JFK2)) =G=
 IKE2TAR..
   14*(1 - SUM( IKE1,X( IKE1))) +
  SUM( IKE1,AFT( IKE1)*X( IKE1)) + SUM( IKE2 ,BFR( IKE2)*X( IKE2)) =G=
 IKE3TAR..
   16*(1 - SUM( IKE2,X( IKE2))) +
  SUM( IKE2,AFT( IKE2)*X( IKE2)) + SUM( IKE3 ,BFR( IKE3)*X( IKE3)) =G=
THEO2TAR..
   19*(1 - SUM(THEO1,X(THEO1))) +
  SUM(THEO1,AFT(THEO1)*X(THEO1)) + SUM(THEO2 ,BFR(THEO2)*X(THEO2)) =G=
THEO3TAR..
   16*(1 - SUM(THEO2,X(THEO2)`\ +
  SUM(THEO2,AFT(THEO2)*X(THE(   ) + SUM(THEO3 ,BFR(THEO3)*X(THEO3)) =G=
WASH2TAR..
   16*(1 - SUM(WASH1,X(WASH1))) +
  SUM(WASH1,AFT(WASH1)*X(WASH1)) + SUM(WASH2 ,BFR(WASH2)*X(WASH2)) =G=
WASH3TAR..
   18*(1 - SUM(WASH2,X(WASH2))) +
  SUM(WASH2,AFT(WASH2)*X(WASH2)) + SUM(WASH3 ,BFR(WASH3)*X(WASH3)) =G=
FORRPERS..
  SUM(FORR1, PERS(FORR1)*X(FORR1)) + 20*(1-SUM(FORR1, X(FORR1))) +
  SUM(FORR2, PERS(FORR2)*X(FORR2)) + 21*(1-SUM(FORR2, X(FORR2))) +
  SUM(FORR3, PERS(FORR3)*X(FORR3)) + 22*(1-SUM(FORR3, X(FORR3)))
  =G= 0;
SARAPERS..
  SUM(SARA1, PERS(SARA1)*X(SARA1)) + 20*(1-SUM(SARA1, X(SARA1))) +
  SUM(SARA2, PERS(SARA2)*X(SARA2)) + 17*(1-SUM(SARA2, X(SARA2))) +
  SUM(SARA3, PERS(SARA3)*X(SARA3)) + 18*(1-SUM(SARA3, X(SARA3)))
  =G= 0;
```

```
KHWKPERS..
  SUM(KHWK1, PERS(KHWK1)*X(KHWK1)) + 23*(1-SUM(KHWK1, X(KHWK1))) +
  SUM(KHWK2, PERS(KHWK2)*X(KHWK2)) + 16*(1-SUM(KHWK2, X(KHWK2))) +
  SUM(KHWK3, PERS(KHWK3)*X(KHWK3)) + 27*(1-SUM(KHWK3, X(KHWK3)))
  =G= 0;
AMERPERS..
  SUM(AMER1, PERS(AMER1)*X(AMER1)) + 14*(1-SUM(AMER1, X(AMER1))) +
  SUM(AMER2, PERS(AMER2)*X(AMER2)) + 18*(1-SUM(AMER2, X(AMER2))) +
  SUM(AMER3, PERS(AMER3)*X(AMER3)) + 18*(1-SUM(AMER3, X(AMER3)))
  =G= 0;
 JFKPERS..
  SUM( JFK1, PERS( JFK1)*X( JFK1)) + 17*(1-SUM( JFK1, X( JFK1))) +
  SUM( JFK2, PERS( JFK2)*X( JFK2)) + 31*(1-SUM( JFK2, X( JFK2)))
  =G= 0;
 IKEPERS..
  SUM( IKE1, PERS( IKE1)*X( IKE1)) + 14*(1-SUM( IKE1, X( IKE1))) +
  SUM( IKE2, PERS( IKE2)*X( IKE2)) + 16*(1-SUM( IKE2, X( IKE2))) +
  SUM( IKE3, PERS( IKE3)*X( IKE3)) + 25*(1-SUM( IKE3, X( IKE3)))
  =G= 0;
THEOPERS..
  SUM(THEO1, PERS(THEO1)*X(THEO1)) + 19*(1-SUM(THEO1, X(THEO1))) +
  SUM(THEO2, PERS(THEO2)*X(THEO2)) + 16*(1-SUM(THEO2, X(THEO2))) +
  SUM(THEO3, PERS(THEO3)*X(THEO3)) + 20*(1-SUM(THEO3, X(THEO3)))
  =G= 0;
WASHPERS..
  SUM(WASH1, PERS(WASH1)*X(WASH1)) + 16*(1-SUM(WASH1, X(WASH1))) +
  SUM(WASH2, PERS(WASH2)*X(WASH2)) + 18*(1-SUM(WASH2, X(WASH2))) +
  SUM(WASH3, PERS(WASH3)*X(WASH3)) + 18*(1-SUM(WASH3, X(WASH3)))
  =G= 0;
OBJ..      Z =E= SUM(C, SL(C));
COVERAGE(K)$(EMPTY(K)).. Y(K)=L=SUM(I$ICOVER(I,K),X(I));
FACTOR..    SUM(K,Y(K)) =G= FRA * CARD(K);

MODEL LANT /ALL/;
SOLVE LANT USING MIP MINIMIZING Z;
OPTION Y:2:0:1;
PARAMETER NCOVER(I,K);
  NCOVER(I,K) = 1$ICOVER(I,K);
PARAMETER REPORT(K,*);
OPTION REPORT: 0;
REPORT(K,"DATE") = (89+TRUNC((ORD(K)+8)/12))* 100+MOD(ORD(K)+8,12)+1;
REPORT(K," FORR ") =
  SUM(I $(ORD(I) GE   1 AND ORD(I) LE  24  ), X.L(I)*NCOVER(I,K));
REPORT(K," SARA ") =
  SUM(I $(ORD(I) GE  25 AND ORD(I) LE  40  ), X.L(I)*NCOVER(I,K));
REPORT(K," KHWK ") =
  SUM(I $(ORD(I) GE  41 AND ORD(I) LE  67  ), X.L(I)*NCOVER(I,K));
REPORT(K," AMER ") =
  SUM(I $(ORD(I) GE  68 AND ORD(I) LE  78  ), X.L(I)*NCOVER(I,K));
REPORT(K,"  JFK ") =
```

```
    SUM(I $(ORD(I) GE  79 AND ORD(I) LE 100  ), X.L(I)*NCOVER(I,K));
  REPORT(K,"  IKE ") =
    SUM(I $(ORD(I) GE 101 AND ORD(I) LE 116  ), X.L(I)*NCOVER(I,K));
  REPORT(K," THEO ") =
    SUM(I $(ORD(I) GE 117 AND ORD(I) LE 132  ), X.L(I)*NCOVER(I,K));
  REPORT(K," WASH ") =
    SUM(I $(ORD(I) GE 133 AND ORD(I) LE 145  ), X.L(I)*NCOVER(I,K));
REPORT(K,"TOTAL") = SUM(I, X.L(I)*NCOVER(I,K));
DISPLAY REPORT;
```

APPENDIX C GAMS MODEL DESCRIPTION

The output listings can be changed by utilizing the "OPTION" statements. These statements are listed at the top of the GAMS listing. The OPTION statements are:

LIMCOL — Limits the number of columns that are listed in the equation listing for each equation. Default value is three. Specify zero to suppress equation listing totally. (Brooke, Kendrick, Merraus, 1988, p. 103)

LIMROW — Limits the number of rows that are listed in the equation listing for each equation. Default value is three. Specify zero to suppress equation listing totally. (Brooke, Kendrick, Merraus, 1988, p. 103)

SOLPRINT — Controls the printing of the solution.
ON - prints the solution following the solve.
OFF - solution details are not printed.
Note: Suppressing the list of the solution report is not recommended unless the model is understood well. (Brooke, Kendrick, Merraus, 1988, p. 199)

ITERLIM — Iteration Limit. Causes the solver to terminate the solution process after "n" iterations. Default is 1000. The more iterations, the better the solution, but the longer the runtime (Brooke, Kendrick, Merraus, 1988, p. 104)

OPTCR — Optimal Criteria. A real number between 0 and 1. Controls the termination of GAMS/ZOOM. OPTCR is a relative measure: If for instance OPTCR is set at .05, then GAMS will instruct the solver to continue until an integer solution, guaranteed to be not more than five percent from the best possible, is found. Default is .01.
Warning: Setting OPTCR = 0.0 can result in extremely long run times for even small problems. (Brooke, Kendrick, Merraus, 1988, pp. 164, 198, & 233)

Other "OPTION" statements are listed in GAMS: A User's Guide. An example follows in Table 9.

TABLE 9

USER INPUTS TO THE GAMS MODEL

```
OPTIONS LIMCOL = 0, LIMROW = 0, SOLPRINT = ON, ITERLIM =
25000;
OPTIONS OPTCR = 0.0001;
```

The model utilizes SETS as inputs to the equations. These SETS are:

1. The number of carriers, total deployable on-station schedules generated, and number of months in the planning period. See Table 10 for an example.

TABLE 10

SHIPS, SCHEDULES, & MONTHS

```
C   Carriers                 /1* 8 /
I   On-station schedules /1*  145/
K   Months                   /1 *  94/
```

2. The schedule number and the associated months in the planning period that are covered by that schedule. See Table 11 for an example.

TABLE 11

SCHEDULES AND MONTHS MATRIX

```
                ICOVER(I,K) COVERAGE INDICATOR /
                            1.(  9* 13)
                            2.( 10* 14)
Schedule # -------> 3.( 11* 15)  <--- months covered
                            4.( 12* 16)
                            5.( 13* 17)
```

3. The schedules from the ICOVER matrix for each deployable period followed by the total range of schedules attributed to a particular ship. See Table 12 for an example.

TABLE 12

SCHEDULES FOR EACH PERIOD AND TOTAL SCHEDULES

```
FORR1(I) /  1*  7/  <--- Schedules for first deployment
FORR2(I) /  8* 15/       period for Forrestal
FORR3(I) / 16* 24/
FORR(I) /  1* 24/   <--- Total schedules for Forrestal
```

4. PERSTEMPO, homeport time measured in months, associated with the schedules in each deployable period. See Table 13 for an example.

TABLE 13

PERSTEMPO FOR EACH DEPLOYMENT PERIOD

```
                 PARAMETER PERS(I) /
                      1*  7     0
                      8* 15     4
Schedules---->       16* 24     6   <---PERSTEMPO
                     25* 31     5
                     32* 35     1
                     36* 40     1
                     41* 50    10
```

5. The number of months available before schedule i from the beginning of the previous maintenance period. See Table 14 for an example.

TABLE 14

BEFORE MONTHS ASSOCIATED WITH A SCHEDULE

```
                 BFR(I) /
                    1  17
                    2  18
Schedule # --->     3  19   <----Months
                    4  20
                    5  21
```

6. The number of months available after the end of schedule i to the beginning of the next maintenance period. See Table 15 for an example.

TABLE 15

AFTER MONTHS ASSOCIATED WITH A SCHEDULE

```
                    AFT(I) /
                         1   6
                         2   5
Schedule # ---->         3   4 <---- Months
                         4   3
                         5   2
```

In addition to the SETS, Variables are used to produce the optimal decisions to the model. The variables in this model are: (1) the schedule number selected, (2) the coverage factor in month k, (3) the carriers selected, and (4) the coverage obtained. These are listed in Table 16.

TABLE 16

VARIABLES IN GAMS MODEL

```
VARIABLES

         SL(C)     select carrier c
         X(I)      select ith schedule
         Y(K)      coverage factor in month k
         Z         max coverage;
  Binary Variable SL(C) , X(I);
  Positive Variable Y(K);
```

Y(K), the coverage factor in month k, can not take on negative values. The schedule chosen and the carrier selected are binary variables.

The schedules selected in the first deployable period are fixed so that no schedule is considered if there is not at least 12 months between the last deployment and that schedule. This "hot-starts" the turnaround ratio calculation. An example for Forrestal, Saratoga, and Kitty Hawk is listed in Table 17.

TABLE 17

TAR CONSTRAINT FOR FIRST DEPLOYABLE PERIOD

```
X.FX(FORR1)$(BFR(FORR1) LT 12) = 0;
X.FX(SARA1)$(BFR(SARA1) LT 12) = 0;
X.FX(KHWK1)$(BFR(KHWK1) LT 12) = 0;
```

The equations which use the SETS as input and the Variables as decision makers are utilized to produce the final solution. The first equation ensures that not more than one schedule is picked from any deployable period. An example for the three deployable periods for Forrestal is listed in Table 18. The GAMS equations are represented formally by equation (1), Chapter II.

TABLE 18

SCHEDULE CONSTRAINT

```
FORR1SLC..     SUM(FORR1,X(FORR1)) =L= 1;
FORR2SLC..     SUM(FORR2,X(FORR2)) =L= 1;
FORR3SLC..     SUM(FORR3,X(FORR3)) =L= 1;
```

The second equation guarantees that a schedule is considered for each of the deployable periods associated with each ship. An example for the first ship, Forrestal, is listed in Table 19. The GAMS equations are represented formally by equation (2), Chapter II.

TABLE 19

MAXIMUM SCHEDULES

```
SHIP1..
  SUM(I $(ORD(I) GE   1 AND ORD(I) LE 24),
             X(I))  =L=   3 * SL("1");
```

The third equation ensures that a schedule is picked in the deployable periods following the first period only if the 2 to 1 turnaround ratio is satisfied. Table 20 illustrates an example. The GAMS equations are represented formally by equation (3), Chapter II.

TABLE 20

2 TO 1 TURNAROUND RATIO CONSTRAINT

```
FORR2TAR..
   20*(1 - SUM(FORR1,X(FORR1))) +
           SUM(FORR1,AFT(FORR1) * X(FORR1)) + SUM
              (FORR2,BFR(FORR2) * X(FORR2)) =G= 13;
FORR3TAR..
   21*(1 - SUM(FORR2,X(FORR2))) +
           SUM(FORR2,AFT(FORR2) * X(FORR2)) + SUM
              (FORR3 ,BFR(FORR3) * X(FORR3)) =G= 13;
```

The fourth equation allows a schedule to be considered in each period only if the PERSTEMPO is met. Table 21 lists an example. The GAMS equations are represented formally by equation (4), Chapter II.

TABLE 21

HOMEPORT TIME CONSTRAINT

```
FORRPERS..
   SUM(FORR1, PERS(FORR1)*X(FORR1))
    + 20*(1-SUM(FORR1,X(FORR1))) + SUM(FORR2, PERS(FORR2)
    * X(FORR2)) + 21*(1-SUM (FORR2,X(FORR2))) +
    SUM(FORR3, PERS(FORR3) * X(FORR3)) + 22*(1-SUM(FORR3,
    X(FORR3))) =G= 0;
```

The fifth equation assures that a schedule is picked that allows for coverage of month 'k' in the planning cycle. Table 22 exhibits an example. The GAMS equations are represented formally by equation (5), Chapter II.

TABLE 22

COVERAGE CONSTRAINT

```
COVERAGE(K)$(EMPTY(K))..
     Y(K)=L= SUM(IJ$ICOVER(I,K),X(I));
```

Finally, the objective function determines the number of carriers required to cover the assigned stations. Table 23 shows this. The GAMS equations are represented formally by the minimize equation, Chapter II.

TABLE 23

OBJECTIVE FUNCTION

```
OBJ..      Z =E= SUM(C, SL(C));
```

APPENDIX D SAMPLE OPTIMAL OUTPUT LISTING

```
           S O L V E      S U M M A R Y

 MODEL    LANT                      OBJECTIVE  Z
 TYPE     MIP                       DIRECTION  MINIMIZE
 SOLVER   ZOOM                      FROM LINE  718

 **** SOLVER STATUS     1 NORMAL COMPLETION
 **** MODEL STATUS      1 OPTIMAL
 **** OBJECTIVE VALUE               8.0000

 RESOURCE USAGE, LIMIT       739.340      1000.000
 ITERATION COUNT, LIMIT     60368         100000

Courtesy of Dr Roy E. Marsten,
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    University of Arizona,
    Tucson     Arizona 85721,  U.S.A.

Work space needed(estimate)  --        25355 words.
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the branch and bound tree contained 127 nodes


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                             0 INFEASIBLE
                             0  UNBOUNDED
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