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OPTIMAL LONG-TERM AIRCRAFT CARRIER DEPLOYMENT PLANNING WITH SYNCHRONOUS DEPOT LEVEL MAINTENANCE SCHEDULING

by

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March, 1998

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Forward deployment of Navy aircraft carrier battle groups is a primary means for the United States to achieve overseas interests. The Navy maintains the forward presence of aircraft carriers in three major Areas of Responsibility (AORs): the Mediterranean Sea, the Persian Gulf, and the Western Pacific. Considering the cost of carrier operations and the desire to maximize coverage of the AORs, planning deployments for the carriers not only significantly affects the achievement of U.S. defense strategy, but also impacts the Navy financially. Previous studies have maximized the deployment of aircraft carriers to the AORs while strictly adhering to the fixed, long-range maintenance schedules published by the Planning and Engineering for Repairs and Alterations Activity for Aircraft Carriers (PERA CV). This thesis optimizes aircraft carrier deployment planning while shifting the pre-scheduled maintenance availabilities well within limits allowed by the Chief of Naval Operations (CNO). This synchronous planning of deployments and major maintenance yields at least 15% more planned coverage in the AORs with the existing carrier fleet. Such an increase had heretofore been thought to require three additional aircraft carriers.

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OPTIMAL LONG-TERM AIRCRAFT CARRIER DEPLOYMENT PLANNING WITH SYNCHRONOUS DEPOT LEVEL MAINTENANCE SCHEDULING

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ABSTRACT

Forward deployment of Navy aircraft carrier battle groups is a primary means for the United States to achieve overseas interests. The Navy maintains the forward presence of aircraft carriers in three major Areas of Responsibility (AORs): the Mediterranean Sea, the Persian Gulf, and the Western Pacific. Considering the cost of carrier operations and the desire to maximize coverage of the AORs, planning deployments for the carriers not only significantly affects the achievement of U.S. defense strategy, but also impacts the Navy financially. Previous studies have maximized the deployment of aircraft carriers to the AORs while strictly adhering to the fixed, long-range maintenance schedules published by the Planning and Engineering for Repairs and Alterations Activity for Aircraft Carriers (PERA CV). This thesis optimizes aircraft carrier deployment planning while shifting the pre-scheduled maintenance availabilities well within limits allowed by the Chief of Naval Operations (CNO). This synchronous planning of deployments and major maintenance yields at least 15% more planned coverage in the AORs with the existing carrier fleet. Such an increase had heretofore been thought to require three additional aircraft carriers.

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EXECUTIVE SUMMARY

Forward deployment of Navy aircraft carrier battle groups and amphibious ready groups is a primary means for the United States to achieve overseas interests. As Department of the Navy, Naval Doctrine Publication 1 (NDP 1, 1994) states: "Overseas presence promotes national influence and access to global areas, builds regional coalitions and collective security, furthers stability, deters aggression, and provides initial crisis-response capability."

The carrier battle group, operating in international waters, does not need the permission of host countries for landing or overflight rights, nor to build or maintain bases in countries in which U.S. presence may cause political or other diplomatic complications. Aircraft carriers are sovereign U.S. territories that navigate anywhere in international waters (more than 70% of the earth's surface is ocean). This fact is not overlooked by those U.S. officials who make political and strategic decisions to use naval aircraft carriers as a powerful instrument of diplomacy to strengthen alliances and respond to potential and developing crises. As President Bill Clinton said during a recent visit to the aircraft carrier USS Theodore Roosevelt, "When word of crisis breaks out in Washington, it's no accident the first question that comes to everyone's lips is; where is the nearest carrier?"

The Navy attempts to maintain the forward presence of aircraft carriers in three Areas of Responsibility (AORs): the European Command (EUCOM), the Central Command (CENTCOM), and Western Pacific (WESPAC). Carriers from the Atlantic

Fleet (LANTFLT) fulfill forward presence requirements for the EUCOM (Mediterranean Sea) AOR. Pacific Fleet (PACFLT) carriers provide coverage for the CENTCOM (Persian Gulf) AORs. Occasionally, an Atlantic Fleet carrier will also assist in covering the Persian Gulf AOR. Finally, the carrier operating from Yokosuka, Japan, is responsible for WESTPAC.

Historically, the Navy has tried to maintain a continuous forward carrier presence in these principal AORs. The diminishing defense budget has limited the number of carriers available to meet this goal. Carrier availability is further constrained by scheduled maintenance, training requirements, and Chief of Naval Operation (CNO) Policy on Personnel Tempo of Operations (PERSTEMPO). These restrictions along with limited available assets have made continuous carrier *coverage* (percentage of time a carrier is available in an AOR) essentially impossible.

Providing a sufficient amount of coverage in the AORs through forward presence also helps to decrease *crisis response time*. Crisis response, the timely dispatch of naval forces to a specific area, allows the U.S. to render assistance or exert military force. Herein, crisis response time is defined as the expected time to send the closest carrier to a crisis location.

A new nuclear powered carrier costs over 3.4 billion dollars, and when deployed is manned by 3,200 ship's company personnel and 2,480 air wing personnel. The air wing consists of eight to nine squadrons (85 aircraft). A carrier normally operates as the centerpiece of a carrier battle group. A carrier battle group, commanded by a flag officer, normally consists of two guided missile cruisers, a guided missile destroyer, a destroyer, a frigate, two attack submarines, and a combined ammunition, oiler, and supply ship.

Considering the cost of carrier operations and the desire to maximize coverage of the AORs, planning deployments for these carriers not only significantly affects the achievement of U.S. defense strategy, but also impacts the Navy financially.

Previous studies have maximized the deployment of aircraft carriers to the AORs while strictly adhering to the fixed, long-range maintenance schedules published by the Planning and Engineering for Repairs and Alterations Activity for Aircraft Carriers (PERA CV). However, the Chief of Naval Operations (CNO) publishes guidelines by which alterations may be made to a planned maintenance schedule.

This thesis shows that long-term aircraft carrier deployment planning can be synchronized with long-term scheduled maintenance availabilities, and improved by shifting maintenance within the limits allowed by CNO guidelines. It also introduces optimization models to achieve this goal. As a result of improved long-range planning, AOR coverage achievable with existing carrier force structure is significantly improved, and average crisis response times by a first and second carrier are significantly shortened.

The synchronous planning of deployments and depot level maintenance creates new deployable periods and yields at least 15% more planned coverage of the AORs with the existing carrier fleet. Such an increase in coverage has heretofore been thought to require the availability of three additional aircraft carriers.

Moreover, this reasonable planning strategy decreases the average worldwide crisis response time of a first carrier by an average of about one day and of a second carrier by about two days. Decreasing crisis response time has both strategic and economic significance. In the case of the Gulf War of 1990, a delay of two days in crisis response time by a second carrier has been estimated to increase the price of U.S. oil imports by an amount between $0.73B and $2.3B. The two-day delay could also result in a decrease of the U.S. Gross Domestic Product between $13B and $39B.

Considering the strategic and economic significance of efficient planning of aircraft carrier fleet deployment, the decision-support optimization models here have much to recommend then.

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I. INTRODUCTION

A. BACKGROUND

1. Forward Presence by Aircraft Carriers

Forward deployment of Navy aircraft carrier battle groups and amphibious ready groups is a primary means for the United States (U.S.) to achieve overseas interests. "Overseas presence promotes national influence and access to global areas, builds regional coalitions and collective security, furthers stability, deters aggression, and provides initial crisis-response capability." [Department of the Navy 1994, pg. 20]. As U.S. Secretary of Defense William Cohen stated, "If you don't have that forward deployed presence, you have less of a voice, less of an influence." [U.S. Navy 1998a]

The carrier battle group, operating in international waters, does not need the permission of host countries for landing or overflight rights, nor to build or maintain bases in countries in which U.S. presence may cause political or other diplomatic complications. Aircraft carriers are sovereign U.S. territories that navigate anywhere in international waters. This fact is not overlooked by those U.S. officials who make political and strategic decisions to use naval aircraft carriers as a powerful instrument of diplomacy to strengthen alliances and respond to potential and developing crises. As President Bill Clinton said during a visit to the aircraft carrier USS Theodore Roosevelt, "When word of crisis breaks out in Washington, it's no accident the first question that comes to everyone's lips is; where is the nearest carrier?" [U.S. Navy 1998a]

In addition to being able to operate independently, the carrier battle group can also present a unique range of options to the President, Congress and Secretary of Defense. By using the oceans (more than 70% of the earth's surface is ocean) both as a means of geographical access and as a military base, forward-deployed Navy and Marine forces can be readily available to provide the U.S. with a variety of national response capabilities. These capabilities range from simply displaying the flag (a demonstration of U.S. presence) to an assertion of power ashore. The significance of aircraft carriers in terms of national and international security is highlighted by General John Shalikashvili, Chairman of the Joint Chiefs of Staff, during a recent visit to the USS Dwight D. Eisenhower: "I know how relieved I am each time when I turn to my operations officer and say, 'Hey, where's the nearest carrier?' and he can say to me, 'It's right there on the spot.' For United States' interests, that means everything." [U.S. Navy 1998a]

The Navy attempts to maintain the forward presence of aircraft carriers in three Areas of Responsibility (AORs): the European Command (EUCOM), the Central Command (CENTCOM), and Western Pacific (WESTPAC). Carriers from the Atlantic Fleet (LANTFLT) fulfill forward presence requirements for the EUCOM (Mediterranean Sea) AOR. Pacific Fleet (PACFLT) carriers provide coverage for the CENTCOM (Persian Gulf) AORs. Occasionally, an Atlantic Fleet carrier will also assist in covering the Persian Gulf AOR. Finally, the carrier operating from Yokosuka, Japan, is responsible for WESTPAC.

Historically, the Navy has tried to maintain a continuous forward carrier presence in these principal AORs. The diminishing defense budget has limited the number of carriers available to meet this goal. Carrier availability is further constrained by scheduled maintenance, training requirements, and Chief of Naval Operation (CNO) Policy on Personnel Tempo of Operations (PERSTEMPO). These restrictions along with limited available assets have made continuous carrier *coverage* (percentage of time a carrier is available in an AOR) essentially impossible.

Providing a sufficient amount of coverage in the AORs through forward presence also helps to decrease *crisis response time.* "Crisis response, the emergent, timely dispatch of naval forces to a specific area, allows the U.S. to render assistance or exert military force." [Department of the Navy 1994, pg. 20] Herein, crisis response time is defined as the expected time to send the closest carrier to a crisis location from its planned position en route to, during, or returning from a planned deployment.

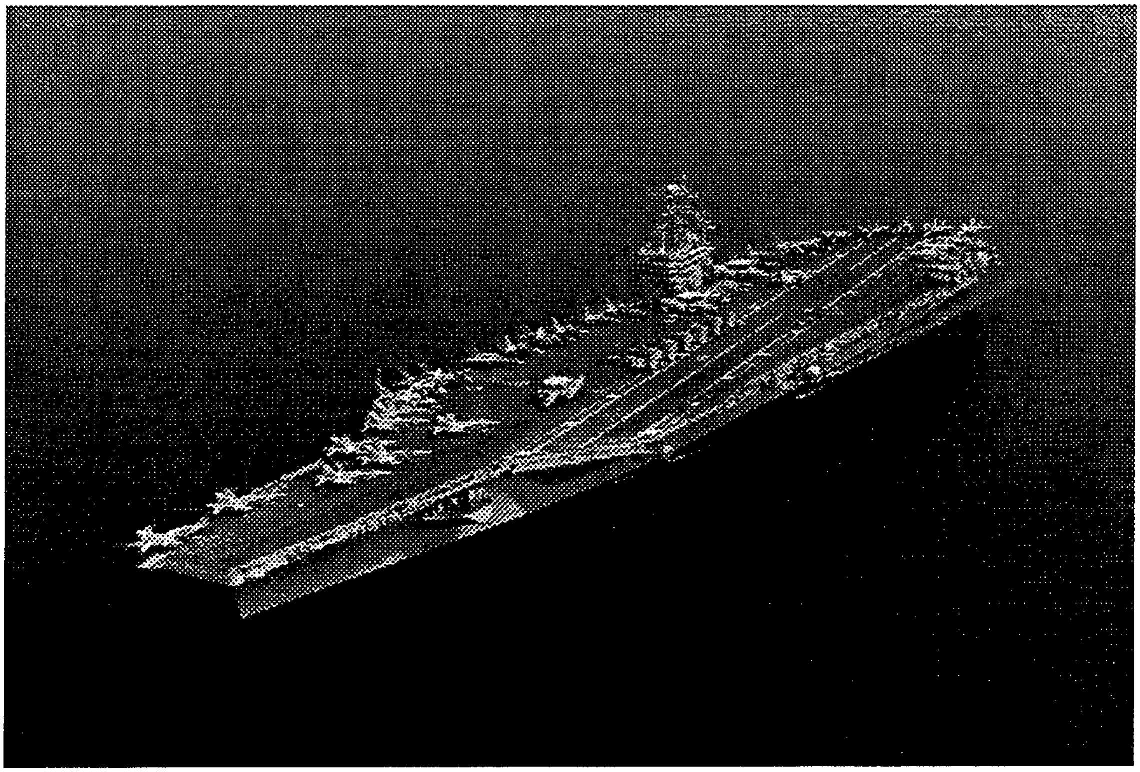

Figure 1. USS Nimitz (CVN 68), launched in 1975, has 3,200 crew in the ship's company and 2,480 for the air wing. The mission of Nimitz and her embarked air wing is to conduct sustained combat air operations. The air wing consists of eight to nine squadrons (85 aircraft). The ship normally operates as the centerpiece of a carrier battle group. The carrier battle group, commanded by a flag officer, consists of two guided missile cruisers, a guided missile destroyer, a destroyer, a frigate, two attack submarines, and a combined ammunition, oiler, and supply ship. [U.S. Navy 1998b]

2. The Significance of Deployment Scheduling of Aircraft Carriers

USS Nimitz (CVN 68) is a nuclear powered aircraft carrier in PACFLT, Figure 1, now (ca January 1998) operating in the Persian Gulf region. A new nuclear powered carrier costs over 3.4 billion dollars, and when deployed carries 3,200 crew members in the ship's company and 2,480 in the air wing. USS Nimitz has two nuclear reactors that give her virtually unlimited range and endurance and a top speed in excess of 30 knots.

The ship carries approximately 3 million gallons of fuel for her aircraft and escorts, and enough weapons and stores for extended operations without replenishment. The air wing consists of eight to nine squadrons (85 aircraft). Attached aircraft are the F/A-18 Hornet, F-14 Tomcat, EA-6B Prowler, S-3 Viking, E-2 Hawkeye, and SH-60 Seahawk. The air wing can destroy enemy aircraft, ships, submarines, and land targets, or lay mines hundreds of miles from the ship. Her aircraft are used to conduct strikes, support land battles, protect the battle group or other friendly shipping, and implement a sea or air blockade. The air wing provides a visible presence to demonstrate U.S. power and resolve in a crisis [US Navy 1998b].

A carrier normally operates as the centerpiece of a carrier battle group. The carrier battle group, commanded by a flag officer, normally consists of two guided missile cruisers, a guided missile destroyer, a destroyer, a frigate, two attack submarines, and a combined ammunition, oiler, and supply ship. [U.S. Navy 1998b]

Considering the cost of carrier operations and the desire to maximize coverage of the AORs, planning deployments for these carriers not only significantly affects the achievement of U.S. defense strategy, but also impacts the Navy financially. Inefficient forward deployment and unnecessary delays of the carriers wastes scarce resources and degrades combat power.

B. PREVIOUS WORK ON CARRIER FORWARD PRESENCE, COVERAGE, AND RESPONSE TIMES

A recent study by Brown, et.al [1997] analyzes the role of forward-deployed naval forces in U.S. national security strategy and joint military strategy. It addresses three major issues:

- The strategic value of forward-deployed naval forces within a security environment dominated by diffuse, relatively low-level threats, and within an operational environment driven by crises that are difficult or impossible to anticipate.
- The economic benefits of forward-deployed naval forces, as illustrated by the impact of naval crisis response on future oil prices during three recent crises in the Persian Gulf.
- The effectiveness of naval forces in providing forward presence, as measured by the amount of coverage or carrier presence in forward areas and by the response times of carriers to widely dispersed locations throughout the world. [Brown, et.al 1997, pg. i]

Both the strategic and economic advantages of forward-deployed naval forces depend upon their abilities to provide coverage for the areas of interest and to respond rapidly when U.S. interests are threatened. The abilities to provide coverage and respond rapidly are two measures of the level of forward presence which a naval force (particularly its carrier battle groups), can provide. This reference study developed an optimization-based model called the Coverage and Response Estimation model, or CoRE, in order to estimate the level of forward presence sustainable by various number of carriers.

There are several approaches for estimating the level of forward presence. One approach, e.g., the Navy's Force Presence Model (FPM), involves creating notional carriers with notional maintenance requirements and calculating average carrier coverage assuming steady state conditions [OPNAV 1996a]. Figure 2 is extracted from a memorandum of the Assessment Division Office Chief of Naval Operations (N81) [OPNAV 1996b] to give some specificity to the nature of FPM.

	TAR	= (TC - DL) / DL => TC = (TAR x DL)+ DL
	TC	= (2.85 x 6) + 6 = 23.1
	OPTEMPO	= 91.25 x [TC - (TC x PERSTEMPO) - DL] / [TC - DL]
==>	PERSTEMPO	= [(TC - DL) x (1 - (OPTEMPO / 91.25))] / TC
	PERSTEMPO	= [(23.1 - 6) x (1 - (28/91.25))] / 23.1 = 51.31 %
==>	All three CNO PERSTEMPO guidelines are maintained.	
	TAR	= Turn Around Ratio
	TC	= Tour Cycle
	DL	= Deployment Length
	PERSTEMPO	= Policy on Personnel Tempo of Operations
	OPTEMPO	= 28 non-deployed days per quarter

Figure 2. Forward Presence Model (FPM). "A Sample Calculation with FPM to Verify that a TAR of 2.85 Still Meets the CNO's PERSTEMPO Guidelines (maximum deployment length of 6 months, minimum TAR of 2.0, and minimum PERSTEMPO of 50%). 2.85 is plugged into the tour cycle (TC) and PERSTEMPO equations (other inputs - deployment length (DL) = 6 months and OPTEMPO = 28 non-deployed days per quarter)." [OPNAV 1996b]

Another approach [Price, et.al 1996] uses Monte Carlo simulation and Markov Chain models to estimate response times. These models rely on historical ship employment data for (probabilistic) input parameters such as length of maintenance and ship readiness status.

CoRE introduces a number of innovations. CoRE estimates coverage and response times by deterministically modeling the peacetime deployment of carriers over a long planning horizon (say, 10 years). It schedules the Navy's actual carriers for deployment in a manner that optimizes the amount of time that at least one carrier is present in each forward area in EUCOM and CENTCOM. CoRE also ensures that the optimal deployment schedules satisfy all operational constraints, such as the scheduled maintenance availability and PERSTEMPO. The resulting amount of time (or the corresponding percentage) with at least one carrier present in an AOR provides an estimate for long-term coverage there. The daily location of each carrier in the optimized long-range deployment schedule is then computed using a standard transit speed of 14 knots over a network of way points and ship sea-routes. CoRE estimates response times from the scheduled long-term daily carrier locations to thirty candidate locations throughout the world. [Brown, et.al 1997]

CoRE has been used to estimate coverage and response times for force structures with nine to sixteen carriers. It estimates that the current twelve-carrier force can be expected to achieve approximately 65% and 70% coverage in EUCOM and CENTCOM, respectively, during the period of 1997 to 2006.

C. A GENERALIZATION TO SCHEDULE MAINTENANCE TOO

To date, CoRE has honored pre-determined, exogenous, fixed scheduled maintenance periods for each carrier, stipulated by a long-range schedule published by the Planning and Engineering for Repairs and Alterations Activity for the Aircraft Carriers

(PERA CV). CoRE schedules the Navy's actual carriers for deployment around these fixed periods of availability in order to maximize the coverage in the AORs.

The ***Generalized CoRE*** **(GENCoRE)** models introduced here maximize the coverage in the AORs by adhering to all rules stipulated by CoRE, but shifting existing scheduled maintenance periods within allowable limits.

Figure 3 shows the first five years of a PERA CV maintenance schedule. In addition, CNO publishes guidelines by which alterations may be made to a planned maintenance schedule. These rules are summarized in Table 1.

Months from Start of Maintenance Cycle to Start of Maintenance Period	Allowable Months Deviation of Start of Maintenance Period
0-36 mo	+/- 3 mo
37-48 mo	+/- 4 mo
49-60 mo	+/- 5 mo
61-72 mo	+/- 6 mo
73-84 mo	+/- 7 mo
>84 mo	+/- 7 mo

Table 1. CNO Guidelines for Altering Scheduled Maintenance Periods. During a maintenance cycle, each scheduled maintenance period may be shifted forward, or backward by a number of months increasing as we progress into the far future. A *maintenance cycle* starts after the completion of a carrier's overhaul (or docking availability, when no overhaul availabilities are included in the maintenance plan) and ends after completion of the next overhaul or docking availability. For new construction ships, the maintenance cycle starts after completion of the post shakedown availability. [OPNAV 1996c, pg. 3-4]

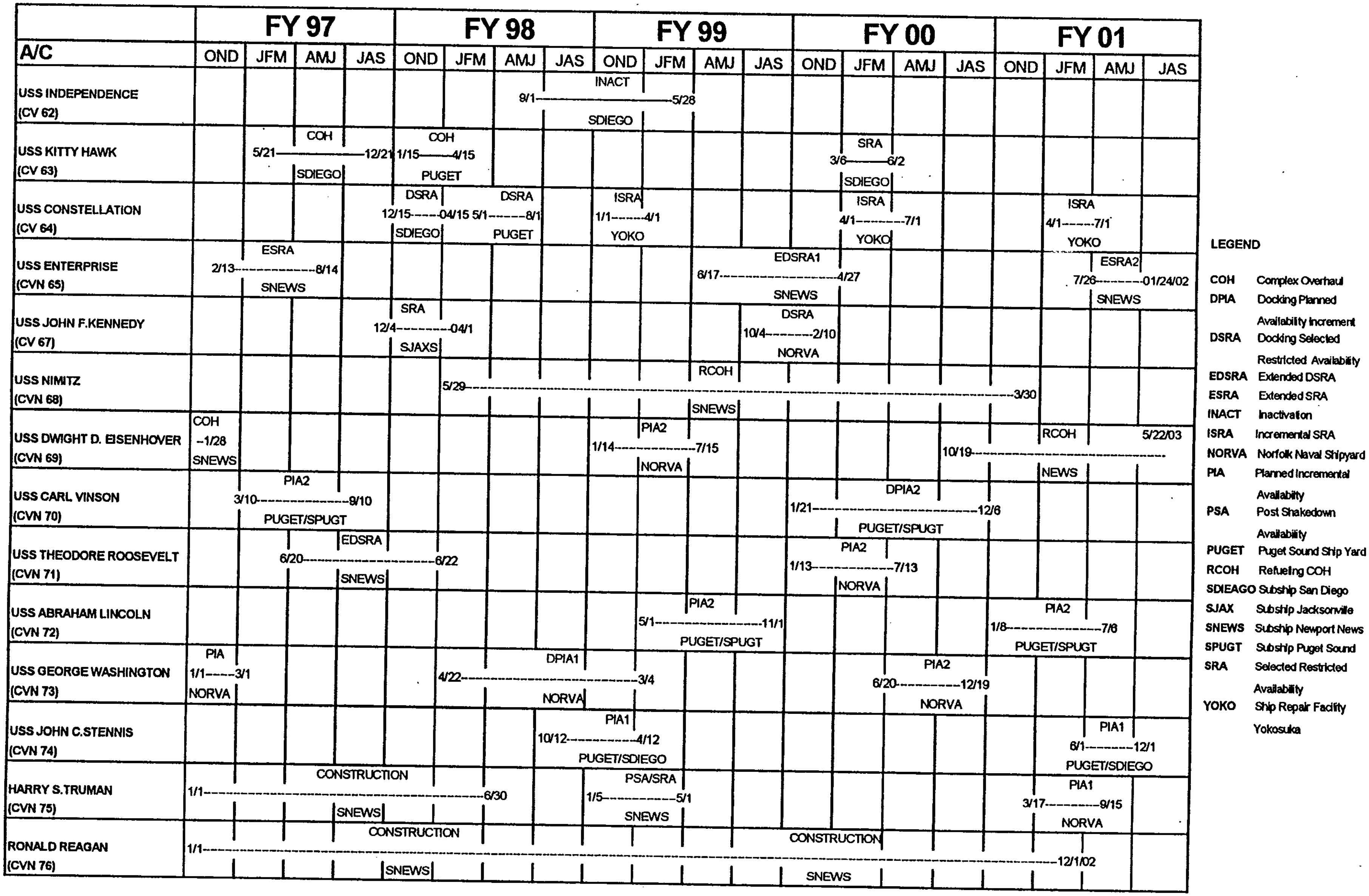

Figure 3. The first five years of a PERA CV maintenance schedule dated February 28, 1997. The dashed lines represent maintenance periods. The names above the dashed lines represent maintenance types, and the names below the lines represent the place of maintenance activities.

Although maintenance periods may be shifted more than one month, we limit our investigation to one-month shifts. These modest relaxations evaluate sensitivity of deployment planning to synchronous maintenance scheduling. Table 2 summarizes various GENCoRE scenarios.

Scenario	Model Description
SHIFT-ONCE	Over a ten-year horizon, at most one maintenance period per carrier may be shifted one month earlier, or later.
SHIFT-ALL	Any maintenance period may be shifted a month.
SHIFT-ONCE-IN-FUTURE	Only after the first three years, allow at most one maintenance shift of one month per carrier.
SHIFT-ALL-IN-FUTURE	Only after the first three years, allow any maintenance to be shifted one month.

Table 2. Generalized Core (GENCoRE) Scenarios. Shifting maintenance periods earlier, or later, relaxes the scheduling problem enough to permit better deployment planning. Shifts allowed here are very conservative with respect to CNO guidelines in Table 1.

II. AIRCRAFT CARRIER DEPLOYMENT SCHEDULING FACTORS AND OPERATIONS CONSTRAINTS

The deployment scheduling of carriers depends on five factors: (i) depot level maintenance, (ii) work-up cycle, (iii) PERSTEMPO, (iv) transit time, and (v) availability of LANTFLT carriers for CENTCOM. Each of these factors is described below.

A. DEPOT LEVEL MAINTENANCE

Depot level maintenance is defined as "that maintenance which requires skills or facilities beyond those of the organizational and intermediate levels and is performed by naval shipyards, naval ship facilities, or item depot activities" [OPNAV 1992]. While at depots, carriers undergo large-scale maintenance, repairs, approved alterations, and modifications to update and improve the carrier's technical and military capabilities. Each carrier periodically requires maintenance of differing durations. In general, these maintenance periods are for (i) incremental maintenance lasting approximately six months, (ii) incremental maintenance requiring drydocking, which lasts approximately twelve months, or (iii) complex overhaul and possibly refueling, with a duration exceeding two years.

U.S. Navy ships accomplish depot maintenance at the notional *intervals*, *durations*, and *repair mandays* set forth in OPNAVNOTE 4700 [OPNAV 1996c]. "Interval is defined as the period from the completion of one scheduled depot availability to the start of the next scheduled depot availability. Duration is defined as the period from the start of an availability to its completion. Repair mandays are those Type Commander maintenance mandays typically accomplished by the executing activity to satisfactorily complete the type of availability indicated." [OPNAV 1996c, pg. 3]

A sample notional depot maintenance cycle for a Nimitz Class aircraft carrier is provided in Figure 4:

Not in Maintenance | Notional Availability

PSA| ------------- |**SRA**| ------------- |**DSRA**| ------------- |**SRA**| ------------- |**COH**|

0 | 18 21 | 39 44.5 | 62.5 65.5 | 84 102

PSA : Post Shakedown Availability
SRA : Selected Restricted Availability
DSRA : Docking SRA
COH : Complex Overhaul

Figure 4. Sample Notional Depot Maintenance Availability for a Nimitz Class (CVN 68) Aircraft Carrier. The dashed time lines indicate periods not in maintenance. The time line numbers indicate months. A Post Shakedown Availability (PSA) may require only a few months, while a Complex Overhaul (COH) may take years.

To ensure compatibility between the ship's employment schedules and depot workloads, CNO authorizes deviation from the notional depot availability interval as shown in Table 1.

Figure 5 shows the allowable deviation durations corresponding to the notional depot maintenance availabilities, provided in Figure 4, for a Nimitz Class (CVN-68) aircraft carrier.

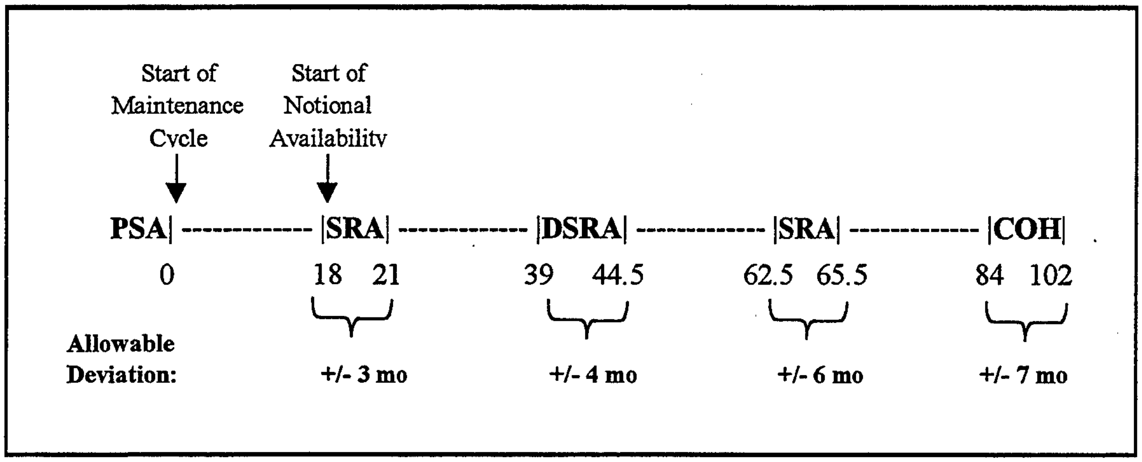

Figure 5. Allowable Deviations Corresponding to the Notional Depot Maintenance Availabilities for the Nimitz Class (CVN 68). This maintenance cycle begins at period 0. Notional start time for the first scheduled maintenance, a Selected Restricted Availability (SRA), is 18 months from the beginning of the maintenance cycle, and can be shifted forward or delayed by up to three months.

Depot maintenance of aircraft carriers is conducted at four major repair facilities: (i) Puget Sound Naval Shipyard (PUGET), (ii) Norfolk Naval Shipyard (NORVA) (Figure 6), (iii) Yokosuka Ship Repair Facility (YOKO), and (iv) Newport News Shipbuilding Company (NEWS).

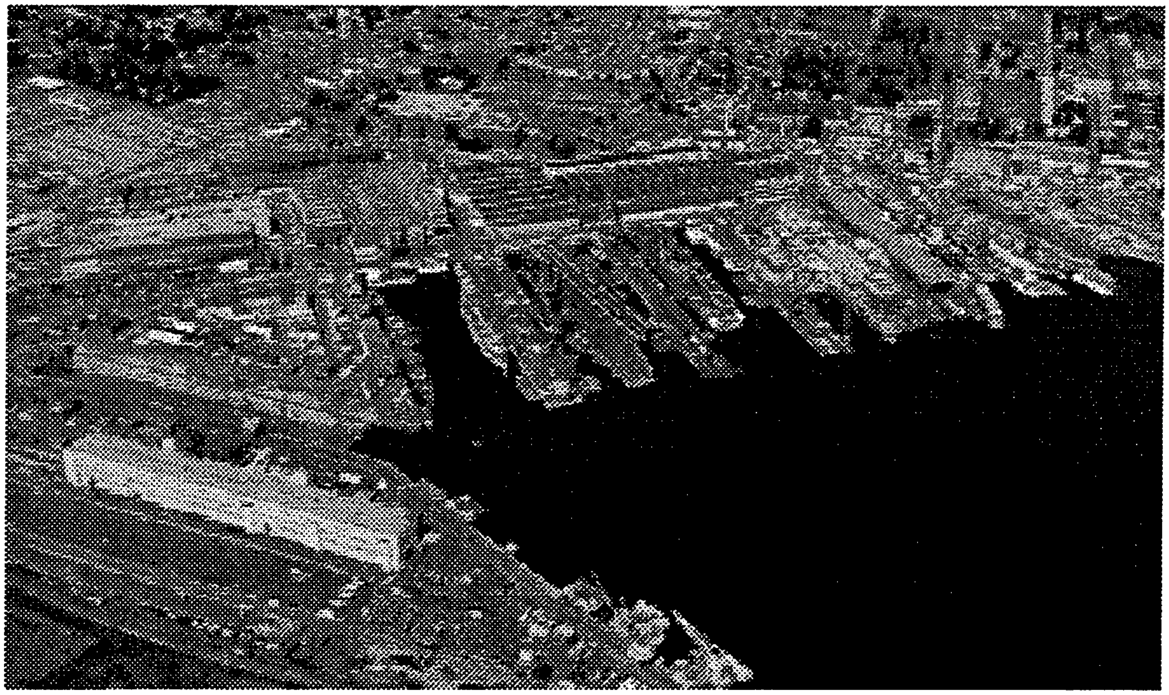

Figure 6. Norfolk Naval Shipyard Aerial View. The NORFOLK NAVAL SHIPYARD in Portsmouth, Virginia, is one of the largest shipyards in the world specializing in repairing, overhauling and modernizing ships and submarines. It is the oldest and largest industrial facility belonging to the U.S. Navy, and is also the most multifaceted. At the extreme left-center is an empty drydock that can accommodate an aircraft carrier.

Scheduling depot maintenance availabilities for aircraft carriers requires consideration of four factors: (i) repair requirements for the ship, (ii) forward deployment requirements by the Navy, (iii) availability of the shipyards, and (iv) capacity of the shipyards. The limitations associated with shipyard capacity and availability are as follows:

1. Drydocking Capacity and Availability

PUGET has two drydocks that can handle aircraft carriers. There is one large drydock for all carriers (nuclear or non-nuclear), and a second slightly smaller one that can handle only non-nuclear carriers. NORVA has one drydock that can handle either nuclear or non-nuclear carriers. NEWS has two drydocks available which can handle any size carrier. NEWS also has several building docks that are used for carrier construction.

> Drydocking can be conducted at any time during a docking availability, and normally takes one quarter of the total availability period to complete. By coordinating drydocking schedules, a shipyard may be able to accommodate simultaneous overhauls. [Brown 1998]

Figure 7 shows the drydocking of USS Dwight D. Eisenhower (CVN-69) in NEWS.

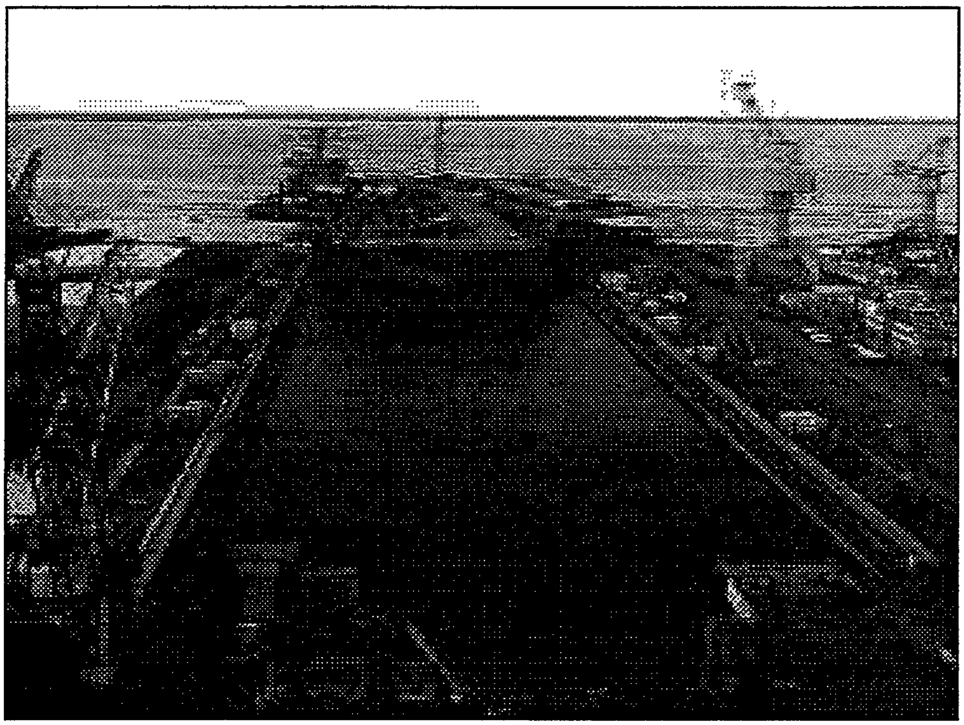

Figure 7. Drydocking of USS Dwight D. Eisenhower (CVN 69) at the Newport News Shipbuilding (NEWS). NEWS is the only private shipyard to perform overhaul and refueling work on Navy submarines and Nimitz-class aircraft carriers. NEWS completed the overhaul of Eisenhower in January, 1997, and began a year-long overhaul of USS Theodore Roosevelt (CVN 71) in July, 1997. NEWS also performs naval surface overhauls and repairs.

2. Repair Manday Availability

Repair mandays are an important secondary consideration when scheduling maintenance. While there is no limitation on manday availability, excessive manday requirements are avoided by staggering depot level maintenance periods to minimize overlaps. Current scheduling practice is to limit the overlap of simultaneous carrier maintenance periods at a given shipyard to 3 months or less in order to avoid manday shortfalls. [Brown 1998]

Figure 8 depicts the overlap of maintenance periods in the same shipyard.

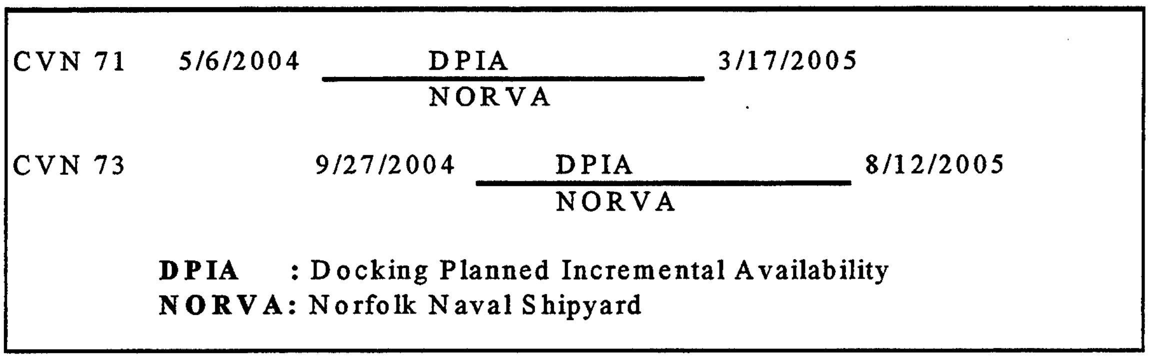

Figure 8. Overlap of Two Carrier Maintenance Periods in the Same Shipyard (taken from PERA CV schedule data provided in Appendix A). Scheduled DPIA for CVN 71 begins on May 6, 2004 and ends on March 17, 2005. The DPIA for CVN 73 begins on September 27, 2004 and ends on August 12, 2005. There is an overlap of approximately six months which may adversely affect the manday availability in the shipyard.

3. Refueling Availability

Refueling of nuclear-powered carriers must be conducted at NEWS. Due to the budget constraints, it is preferable to refuel one carrier at a time. However an overlap of at most six months can be accepted. [Brown 1998]

B. WORK-UP CYCLE

After depot level maintenance and prior to deployment, all ships are required to execute the Tactical Training Strategy (TTS) which takes place during the period known as the work-up cycle. This work-up cycle ensures that the crew is properly trained and that the ship is ready for deployment.

Conceptually, work-up begins after the completion of maintenance and lasts approximately 11.5 months. However, recent carrier deployments suggest that operational exigencies often curtail pre-deployment work-up. Therefore, the GENCoRE models schedule work-ups according to the following criteria: When the maintenance period is six months or less, the carrier can deploy fifteen months after the start of maintenance. If the maintenance period is between six and twelve months, then the carrier can deploy nineteen months after the start of maintenance. Finally, if the maintenance is a RCOH, or the carrier has just been commissioned, it cannot deploy for twelve months after the completion of maintenance or port-shakedown availability. [Brown, et.al 1997, pg. 37]

C. PERSONNEL TEMPO OF OPERATIONS (PERSTEMPO)

> In order to ensure a balance between the support of national objectives and reasonable operating conditions for Naval personnel, the CNO initiated the Personnel Tempo of Operations (PERSTEMPO) program. The PERSTEMPO program achieves this balance by placing peacetime utilization limitations on all Navy units deployed from their homeport. There are three utilization limitations:
>
> (1) The maximum length of a deployment cannot exceed six months (180 days).

(2) There must be a minimum of a 2-to-1 Turn Around ratio (TAR) between deployments. This means that a carrier must remain home for at least 12 months following a six-month deployment.

(3) Over the course of a five-year cycle (three years historical, two years projected), a carrier must spend a minimum of 50% of its time in homeport.

A carrier cannot deploy unless it satisfies these PERSTEMPO restrictions [OPNAV 1990].

A memorandum from N81 concludes that a TAR of 2.61 to 1 is more reasonable [Brown, et.al 1997, pg. 37].

D. TRANSIT TIME

Per OPNAV guidance, the transit time between San Diego and the Persian Gulf is 45 days [Brown, et.al 1997, pg. 37]. PACFLT carriers from Bremerton or Everett carriers must transit to San Diego to load the air wing before heading west toward the Persian Gulf. This adds six days to the transit time in both directions. For LANTFLT carriers, the transit time from Norfolk or Mayport to EUCOM is 13 days. However, it takes only eleven days for LANTFLT carriers to return to their homeports.

E. AVAILABILTY OF LANTFLT CARRIERS FOR CENTCOM

LANTFLT carriers can be deployed to CENTCOM to compensate for the loss of coverage due to the longer transit time required for PACFLT carriers to reach CENTCOM. A memorandum from N81 establishes that the LANTFLT carriers should provide 24% of CENTCOM coverage [Brown, et.al 1997, pg. 37].

III. MODEL INPUTS AND ASSUMPTIONS

A. SCHEDULE PERIODS

Figure 9 displays a sample two-year schedule for four carriers (A, B, C, and D).

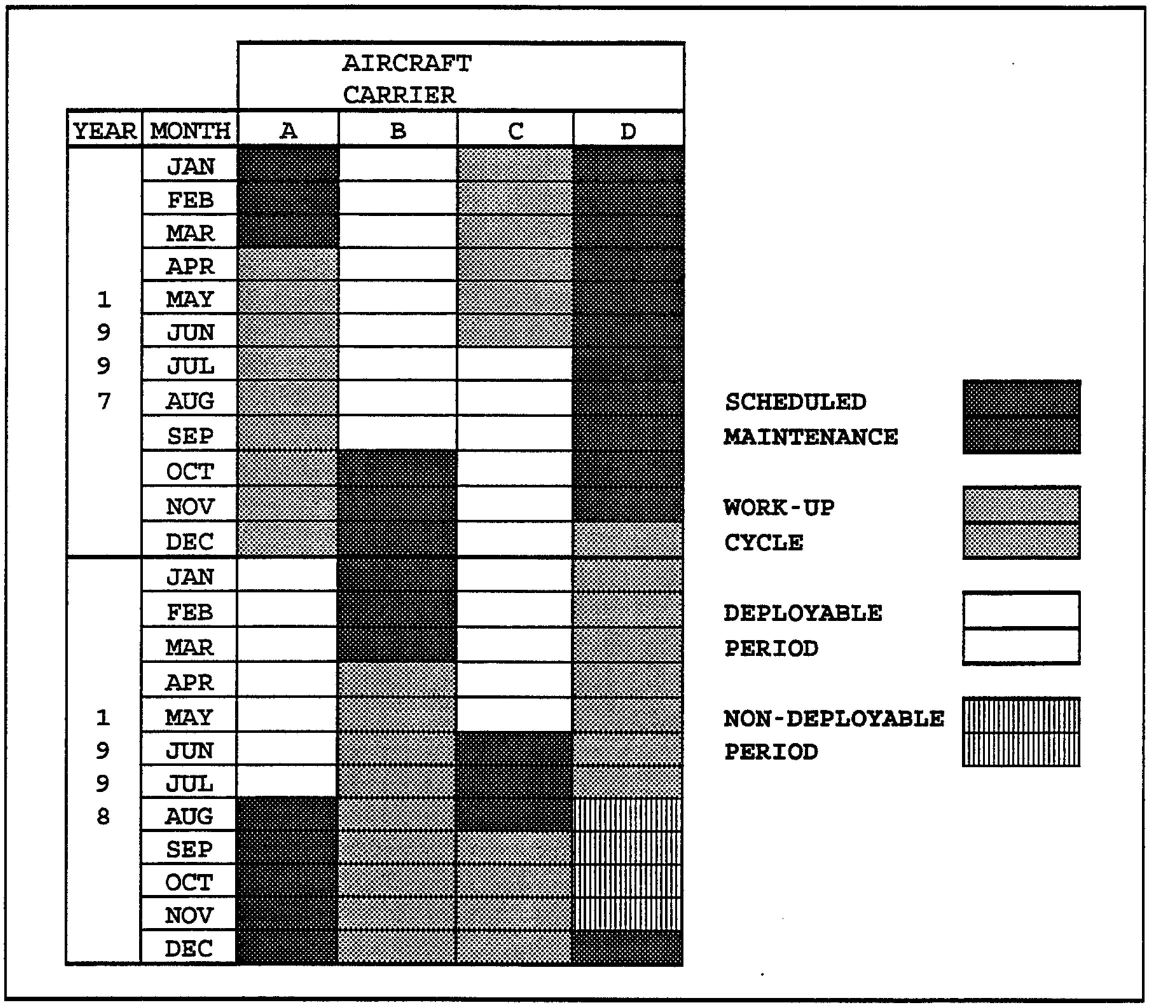

Figure 9. A Sample Two-year Schedule for Aircraft Carriers. The dark shaded cells represent time in maintenance. Following each maintenance period is a sequence of light shaded cells to indicate the required work-up period. Blank cells represent deployable periods, and vertical striped cells represent non-deployable periods.

In the GENCoRE models, a carrier is in one of the following states during each period: (i) maintenance, (ii) work-up, (iii) *deployable*, or (iv) *non-deployable*. When the amount of time between the end of one work-up period and the next maintenance period is at least 180 days, then a deployment is possible. This block of time is referred to as a deployable period. If the total number of such intervening available days is less than 180, it is a non-deployable period.

GENCoRE models use the same carrier availability schedule as CoRE.

> OPNAV Report 4710 [1996] provides maintenance schedules for all carriers for parts of the 1997-2006 period. Information concerning the depot level maintenance from OPNAVNOTE 4700 [1996] is used to complete the remaining maintenance. This maintenance information along with the planned decommissioning dates and commissioning dates are used to determine "open" periods during which carriers are available for deployment. [Brown, et.al 1997, pg. 35]

The maintenance availability schedule used as an input for the GENCoRE models is provided in Appendix A.

GENCoRE models have prototypically planned the decade beginning on December 29, 1996 and ending on December 31, 2006. This planning horizon has a duration of 523 weeks. A carrier may be scheduled to deploy at the beginning of every four-week interval. Four-week time resolution makes the scheduling problem computationally tractable, and offers sufficient fidelity for long-term planning purposes.

B. CARRIER FORCE STRUCTURE

The number of carriers considered here ranges from ten to fourteen. Since there are currently only twelve carriers, phantom carriers, suggested by Brown, et.al [1997], are provided for GENCoRE to augment beyond twelve carriers. The commissioning dates for the phantom carriers are varied to produce a realistic forecast force with diverse ages and maintenance requirements. Table 3 shows the commissioning and decommissioning dates of the real aircraft carriers from 1990 to 2006 along with active service years, and the total carriers available by fiscal year. The phantom carriers are created to supplement the carrier force shown in Table 3 by extending actual carriers beyond their decommissioning dates. Maintenance schedules used for the phantom carriers are based on the notional maintenance intervals, durations and cycles prescribed in OPNAVNOTE 4700 [OPNAV 1996c].

	Comm.	Decomm.	Status (as of October 1st of Each Fiscal Year)																
Carrier	Date	Date	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
CV 59		9/1/93	A	A	A														
CV 41		4/11/92	A	A															
CV 43		4/30/90																	
CV 60		8/20/94	A	A	A	A													
CV 61		7/10/93	A	A	A														
CV 62	1/1/59	9/1/98	A	A	A	A	A	A	A	A									
CV 63	4/1/61		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CV 64	10/1/61	4/1/03	A	A	A	A	A	A	A	A	A	A	A	A	A				
CV 66		8/9/96	A	A	A	A	A	A											
CV 67	1/1/89		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 65	11/1/61		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 68	5/1/75		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 69	10/1/77		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 70	2/1/82		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 71	10/1/86		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 72	12/1/89		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 73	7/1/92				A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
CVN 74	12/1/95								A	A	A	A	A	A	A	A	A	A	A
CVN 75	6/1/98										A	A	A	A	A	A	A	A	A
CVN 76	1/1/03															A	A	A	A
Total Number of Carriers			15	15	15	13	12	12	12	12	12	12	12	12	12	12	12	12	12

Table 3. Carrier Force. Commissioning and decommissioning dates are shown from 1990 to 2006 along with active service years, and the total carriers available by fiscal year. Status A represents a carrier in active service.

During the period 1997-2006, existing carriers will be decommissioned, and replaced by new construction carriers as they are commissioned. Also, carriers may change homeports during this period. Thus, when considering a force of a specific size, a combination of carriers may be considered as one *composite carrier*. For example, two different carriers (Independence and Kitty Hawk) are homeported in Yokosuka during stages of the 1997-2006 decade. Their maintenance availabilities while in Yokosuka are merged to create the maintenance availabilities of the composite carrier Independence/Kitty Hawk. The composite carrier force, suggested by Brown et.al [1997], is used as input by GENCoRE and listed in Appendix B.

"Although the Yokosuka carrier is part of Navy force structure, OPNAV guidance indicates that its main responsibility is to cover the Western Pacific" [Brown, et.al 1997, pg. 37]. Thus, GENCoRE does not schedule the Yokosuka carrier for deployment to CENTCOM. However, this carrier is considered when calculating response times.

C. CALCULATING COVERAGE PERCENTAGES AND CRISIS RESPONSE TIMES

Coverage percentage and crisis response time calculations are conducted according to the following criteria:

1. Coverage Calculation

According to OPNAV guidance, coverage for CENTCOM begins when there is a carrier within the 960-nautical-mile radius of the Straits of Hormuz. While on-station in CENTCOM, a carrier is located just inside the Straits at latitude 26.40N and longitude 56.30E. When leaving CENTCOM, the coverage is terminated when the carrier is outside the 960-nautical-mile radius.

Under OPNAV guidance, coverage for EUCOM begins when a carrier arrives at latitude 35.30N and longitude 25.10E, within the vicinity of Iraklion, Crete. When a LANTFLT carrier transits to CENTCOM, its coverage of EUCOM is temporarily interrupted while in the Suez Canal, and is terminated when the carrier reaches the 960-nautical-mile radius of the Straits of Hormouz — the start of its CENTCOM coverage. Upon returning to Iraklion's vicinity, EUCOM coverage is restored when the carrier is outside the 960-nautical-mile radius, and temporarily interrupted again during passage through the Suez Canal. [Brown, et.al 1997, pg. 38]

In both the CoRE and GENCoRE models, when a LANTFLT carrier covers both EUCOM and CENTCOM in a single deployment, the CENTCOM coverage is assumed to last six weeks. Both optimization models employ a weighting scheme that accentuates CENTCOM coverage more than EUCOM so as to generate deployment schedules in which LANTFLT carriers provide approximately 24% of CENTCOM coverage.

2. Crisis Response Time Calculation

While a carrier is deployed, its latitude/ longitude locations are computed at the beginning of each day. These daily latitude/longitude locations are based on port visits and ship routes constructed from a network of way points and routes developed by analysts at the Center for Naval Analyses. A transit speed of 14 knots is assumed as indicated by standard deployment norms.

Response times for deployed carriers are based on the shortest path routes from these daily latitude/ longitude locations to potential crisis locations (see Appendix C) using a conservative sprint speed of 20 knots. While on station, the carriers' response times are computed from their on-station locations.

Except for the Yokosuka carrier, it is assumed (as dictated by OPNAV guidance) that all carriers in homeport can respond to crises during the last 120 days of their work-up, and during the first 30 days after return from a deployment. In this situation, the response time for each potential crisis location includes the length of the shortest path from homeport, at a sprint speed of 20 knots and a 96-hour recall time. The Yokosuka carrier is assumed to be able to respond to crises at any time it is not in maintenance. Its response times are the lengths of the shortest paths from Yokosuka to potential crisis locations, at a transit speed of 20 knots. [Brown, et.al 1997, pg. 38]

IV. RELATED LITERATURE, CONCEPTUAL FRAMEWORK, AND IMPLEMENTATION

A. OPTIMIZATION LITERATURE

Carrier deployment planning suggests the notorious set-covering or set-partitioning problem. Many researchers have formulated the scheduling of transportation vehicles (e.g., delivery trucks, buses, oil tankers and ships) as a set covering or partitioning problem. Appelgren [1969, 1971] and Crawford and Sinclair [1977] suggest set-covering or partitioning problem to respectively schedule ships and beer tankers. Brown, Graves and Ronen [1987] schedule crude oil super tankers using the set partitioning.

Military applications of set-covering or partitioning include a program called SURFSKED developed by Wing [1986] to schedule surface combatants for inspections, training, and other events. Brown, Goodman, and Wood [1990] designed a similar program called CPSKED to assign combatants to deployments and previously scheduled naval exercises. Stone [1990] uses set covering to determine the minimum number of LANTFLT carriers necessary to provide coverage of the EUCOM AOR.

Researchers have also scheduled transportation with linear integer programs. Ronen [1983] and Bodin [1990] (see also references therein) have written two survey articles discussing various such models and their applications. Sibre's study [1977] analyzes ship scheduling when the interactions between the schedules are nonlinear.

Finally, Schauppner [1996] develops a model to schedule PACFLT aircraft carriers for deployment. Like the set partitioning approach, all possible schedules are generated as inputs to the optimization solver. However, instead of using an integer program to select an optimal set of schedules, the problem is formulated as a shortest path network model with side constraints---an integer linear program. Brown, et.al [1997] use this same approach in their CoRE model.

GENCoRE models follow Craig [1996] and Brown, et.al [1997] (CoRE), enhancing the fidelity of CoRE within the limits set by OPNAV guidance. These models can also be formulated as the set partitions. Appendix E provides a set partitioning formulation of CoRE. For the base case pursued here, there are 222,293 binary variables in this set partition. Accordingly, a set partition was not adopted for GENCoRE.

B. CONCEPTUAL FRAMEWORK

1. Shifting Maintenance Periods

GENCoRE shifts maintenance availabilities to increase AOR coverage as follows. Figure 10 depicts a deployment cycle of an aircraft carrier. If we shift the former maintenance period in Figure 10 one month earlier (to the left), then this maintenance period will be completed at the end of the second month. Therefore, the work-up period, and hence the deployable period, will also shift and begin one month earlier. Eventually, the new deployable period will last for 8 months, beginning in month 15 and ending in month 22. In addition, we can also increase the deployable period by one month by

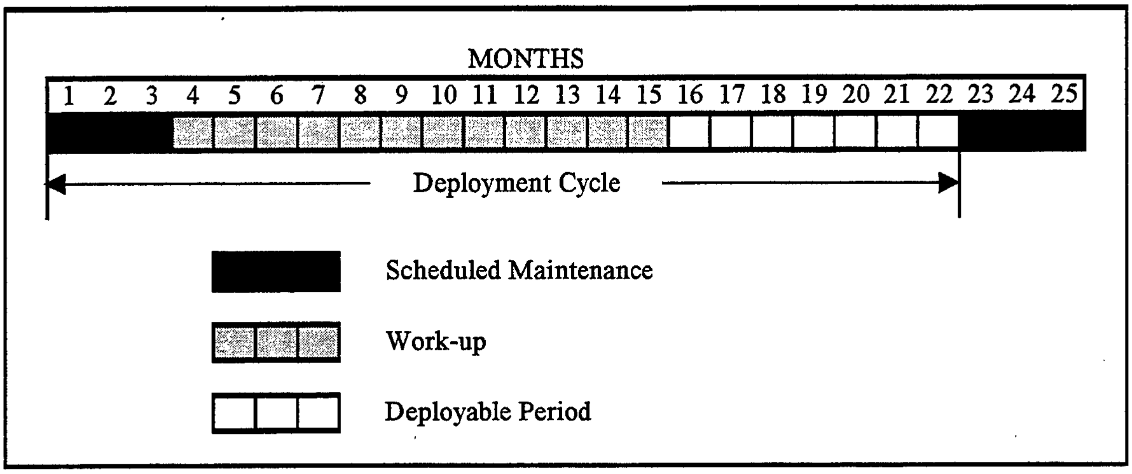

Figure 10. A Deployment Cycle for an Aircraft Carrier. The cycle begins with a maintenance period of three months, followed by a work-up period of twelve months, and ends with a deployable period of seven months beginning with month 16 and ending in month 22, after which another maintenance is scheduled.

shifting the later maintenance period (to the right) so that it begins one month later. Figure 11 depicts the effects of such shifting.

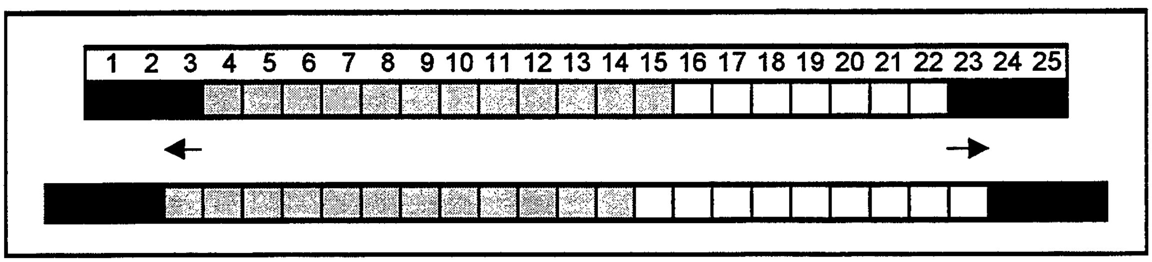

Figure 11. Shifting of Maintenance Periods. From Figure 10, the former (left) maintenance period is shifted one month earlier (to the left), and the second period one month later (to the right) increasing the length of the deployable period by two months.

Shifting maintenance periods may cause an undesirable overlap. This problem will arise if we shift one or both of any two maintenance periods towards each other causing an overlap which exceeds the allowable drydocking, refueling, or manday availability limits. GENCoRE does not permit any overlap violations. Potentially overlapping maintenance periods are called *critical maintenance pairs*. The maintenance period that starts earlier is called the *first element of the pair*, and the other maintenance period is called the *second element of the pair*. These labels are assigned in order to simplify the representation in the formulation. Figure 12 depicts a sample critical maintenance pair.

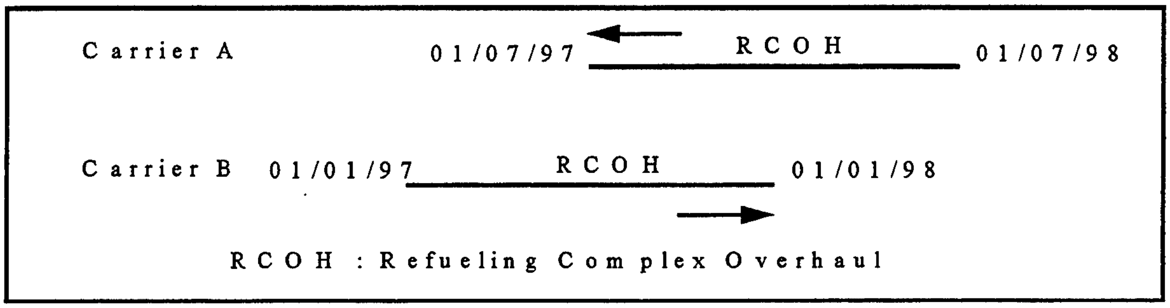

Figure 12. A Sample Critical Maintenance Pair. The overlap between two Refueling Complex Overhauls (RCOHs) is six months, which is the maximum allowable limit for refueling nuclear-powered aircraft carriers. If we shift one or both RCOHs towards each other, then the overlap will exceed this limit. However if we shift them in the same direction, the overlap will not change and the refueling constraint will not be violated. The RCOH of Carrier B is the first element of the pair, and the other RCOH is the second element.

2. Possible Deployment Schedules in a Deployable Period

a. For PACFLT Carriers

If we assume the carrier in Figure 10 to be a PACFLT carrier, then it can be deployed in only one possible way as shown in Figure 13.

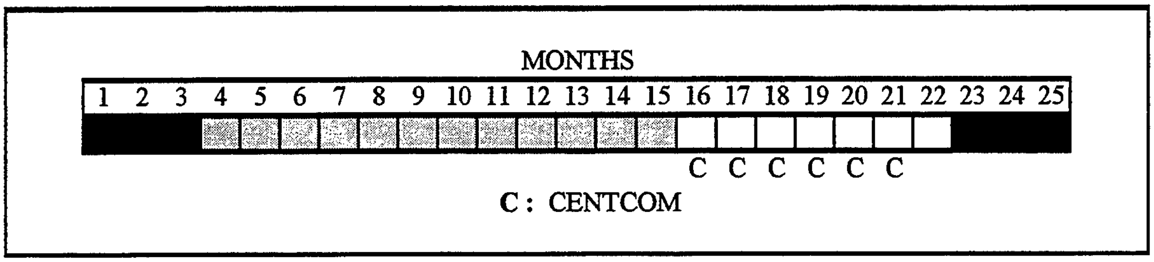

Figure 13. From Figure 10, a Possible PACFLT Deployment Schedule for a Deployable Period. The carrier can be deployed to CENTCOM from the beginning of the month 16 to the end of the month 21. The carrier is not deployed in month 22, because there should be at least a one-month delay between the end of a deployment period and the start of a maintenance period [Brown, et.al 1997, pg. 59].

After maintenance shifts of Figure 11, we can deploy this carrier in three alternate ways (Figure 14).

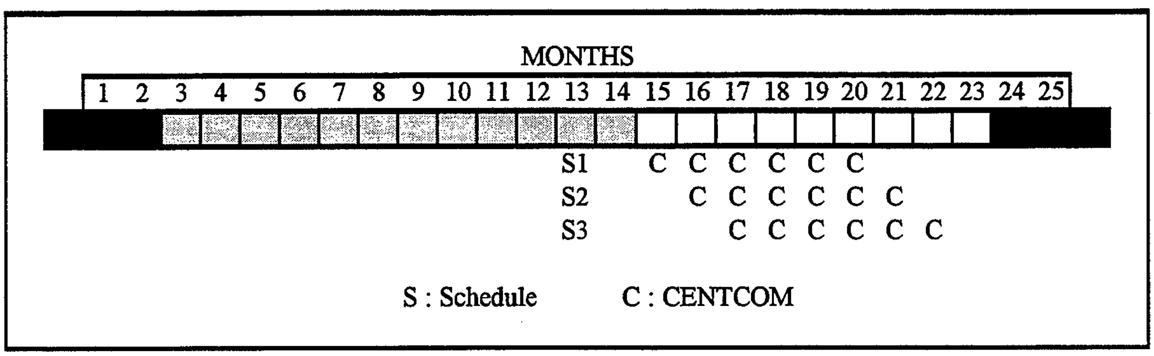

Figure 14. Alternate Candidate Schedules for the PACFLT Carrier in the Shifted Deployable Period of Figure 11. S1 is an early deployment, S2 is a normal deployment, and S3 is a late deployment.

GENCoRE defines the first deployment schedule (S1) in Figure 14 as an *early deployment*. It becomes available by shifting the preceding maintenance period one month earlier. The second schedule (S2) is called a *normal deployment*. This deployment schedule requires no maintenance shifting. The third schedule (S3), a *late deployment*, is obtained by shifting the following maintenance period one month later. For the special case of a seven-month deployable period, obtained by expanding a five-month non-deployable period by two months (one month from each end), the result is called an *early-or-late deployment*.

If we select an early deployment in an optimized solution, then the preceding maintenance period must be shifted to begin one month earlier. If a normal deployment is selected, no change is required. A late deployment requires that the following maintenance period begin one month later. Finally, if an early-or-late deployment is selected, both preceding and following maintenance periods must be shifted away one month.

b. For LANTFLT Carriers

A LANTFLT carrier can deploy to EUCOM for twenty-one weeks, or alternatively, to EUCOM for 15 weeks and CENTCOM for an additional six weeks. Figure 15 depicts possible schedules for a sample deployment cycle of a LANTFLT carrier, and also shows the scheme of EUCOM and CENTCOM coverage combinations. (For purposes of illustration using monthly increments, it is assumed in the figure that CENTCOM coverage is two months instead of six weeks.)

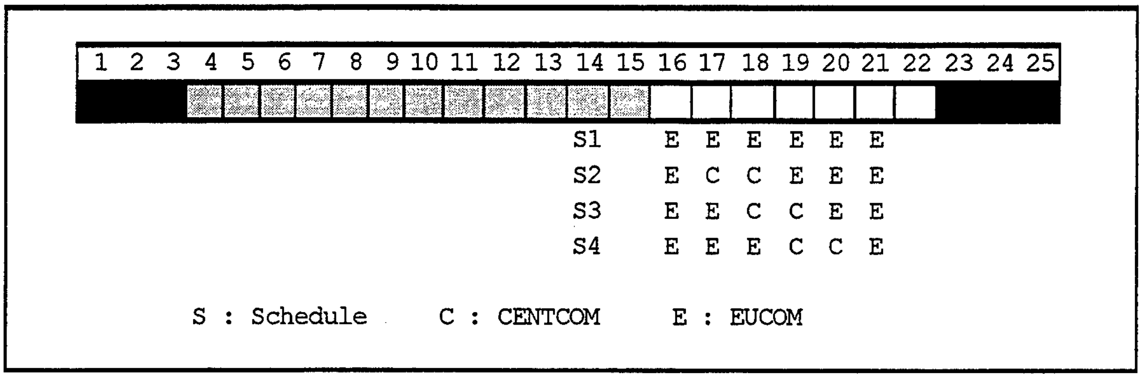

Figure 15. Possible Schedules for a Sample Deployment Cycle of a LANTFLT Carrier. The carrier can be deployed either for six months in EUCOM, or for a combination of two months of CENTCOM deployment and four months of EUCOM deployment.

3. Feasible Combination of Deployment Schedules

After generating all possible deployment schedules, the next step is to find all feasible combinations of these schedules. The coverage gaps between each pair of schedules should not exceed a specified length of time which is referred to as *max-gap* [Schauppner 1996, pg. 15].

When a feasible combination of schedules is sorted chronologically, every pair of successive schedules must belong to different deployable periods. If two successive schedules i and j belong to carriers A and B, respectively, in the same fleet, then carrier A should depart its homeport before carrier B. This ensures that the two carriers do not cover an AOR for exactly the same period. Two deployment schedules are said to be *compatible* when they satisfy these conditions.

Table 4, Figure 16, and Figure 17 illustrate compatible and incompatible pairs of deployment schedules. Table 4 shows a sample two-year schedule for four aircraft carriers. The first two are PACFLT carriers and the other two are from LANTFLT. The deployable periods of the carriers in Table 4 are already increased by shifting the associated maintenance and work-up periods. Figure 16 displays coverage gaps and *overlaps* (length of time in which more than one carrier is in an AOR) that will occur in CENTCOM for each pair of compatible deployment schedules. Figure 17 displays coverage gaps for EUCOM. For purposes of illustration only, the transit times to and from CENTCOM are assumed here to be 30 days each for PACFLT carriers. For LANTFLT carriers, the transit times to and from EUCOM are assumed here to be 15 days. The transit times between CENTCOM and EUCOM are not taken into account here.

MONTHS	AE1	AN2	AN3	AL4	BE1	BL2	CE1	CE2	CE3	CE4	CL5	CL6	CL7	CL8	DEL1	DEL2	DEL3	DEL4
1																		
2															E	E	E	E
3	C														E	C	E	E
4	C	C													E	C	C	E
5	C	C	C												E	E	C	C
6	C	C	C	C											E	E	E	C
7	C	C	C	C											E	E	E	E
8	C	C	C	C														
9		C	C	C														
10			C	C														
11				C			E	E	E	E								
12							E	C	E	E	E	E	E	E				
13							E	C	C	E	E	C	E	E				
14					C		E	E	C	C	E	C	C	E				
15					C	C	E	E	E	C	E	E	C	C				
16					C	C	E	E	E	E	E	. E	E	C				
17					C	C					E	E	E	E				
18					C	C												
19					C	C												
20						C												
21																		
22																		
23																		
24																		

Table 4. A Sample Two-year Schedule for Four Aircraft Carriers. Each row represents a month, and each column represents a deployment schedule. The first column is labeled *AE1*. *A* represents the carrier, *E* indicates that the schedule is an early deployment, and *1* is the schedule number for the carrier in this deployable period. A column label with second character *N*, represents a normal deployment, *L* means a late deployment, and *EL* an early-or-late deployment.

	AE1	AN2	AN3	AL4	BE1	BL2	CE1	CE2	CE3	CE4	CL5	CL6	CL7	CL8
AE1					7	8		4	5	6		5	6	7
AN2								3	4	5		4	5	6
AN3								2	3	4		3	4	5
AL4								1	2	3		2	3	4
BE1														
BL2														
CE1														
CE2					1	2								
CE3					0	1								
CE4					-1	0								
CL5														
CL6					0	1								
CL7					-1	0								
CL8					-2	-1								
DEL1														
DEL2	-1	0	1	2	10	11		7	8	9		9	10	11
DEL3	-2	-1	0	1	9	10		6	7	8		8	9	10
DEL4	-3	-2	-1	0	8	9		5	6	7		7	8	9

Figure 16. Coverage Gaps and Overlaps that Accrue in CENTCOM for Each Pair of Compatible Deployment Schedules. Each row indicates the first carrier in a pair, and each column the second. For example, cell (AE1, BE1), has a value of 7: if we first deploy carrier *A* with *AE1,* and then deploy carrier *B* with *BE1*, then there will be a coverage gap of seven months in CENTCOM, starting from the beginning of *AE1* and ending at the end of *BE1*. A negative number indicates overlap periods. For example, cell (*DEL2*, *AE1*) shows that carriers *D* and *A* will cover CENTCOM together for one month. Blank cells represent incompatible pairs or pairs for which one or both schedules do not provide any coverage of CENTCOM.

GENCoRE first calculates overlap values. Then, for the purposes of avoiding undesired amounts of overlap, the values which are longer than a specific maximum overlap value are eliminated. The remaining overlap values are assigned to zero, in order to represent them in terms of coverage gaps.

	CE1	CE2	CE3	CE4	CL5	CL6	CL7	CL8
CE1								
CE2								
CE3								
CE4								
CL5								
CL6								
CL7								
CL8								
DEL1	4	4	4	4	5	5	5	5
DEL2	6	6	6	6	7	7	7	7
DEL3	6	6	6	6	7	7	7	7
DEL4	6	6	6	6	7	7	7	7

Figure 17. EUCOM Coverage Gaps for Each Pair of Compatible Deployment Schedules. Unlike the situation shown in Figure 16, there are no overlaps here.

Note that Figures 16 and 17 are node-node adjacency matrices of a network [e.g., Ahuja, Magnanti, and Orlin 1993]. Figure 18 represents the network underlying Figure 17. Nodes *S1* and *T1* are added to represent the starting and termination of the planning horizon for EUCOM coverage. The other nodes correspond to deployment schedules for carriers. Costs associated with arcs originating from node *S1* and terminating at schedules *DEL1* to *DEL4* correspond to the coverage gap (in months) from the beginning of the planning horizon to the start of EUCOM coverage by carrier *D*. To simplify Figure 18, arcs from *S1* to nodes *CE1* through *CL8* are not shown. Similarly, costs associated with arcs from schedules *CE1* through *CL8* to node *T1* correspond to the coverage gap evident from the end of coverage by carrier *E* to the end of the planning horizon. A network corresponding to Figure 16 is similarly constructed with nodes *S2* and *T2* added to represent the start and termination of the planning horizon for CENTCOM.

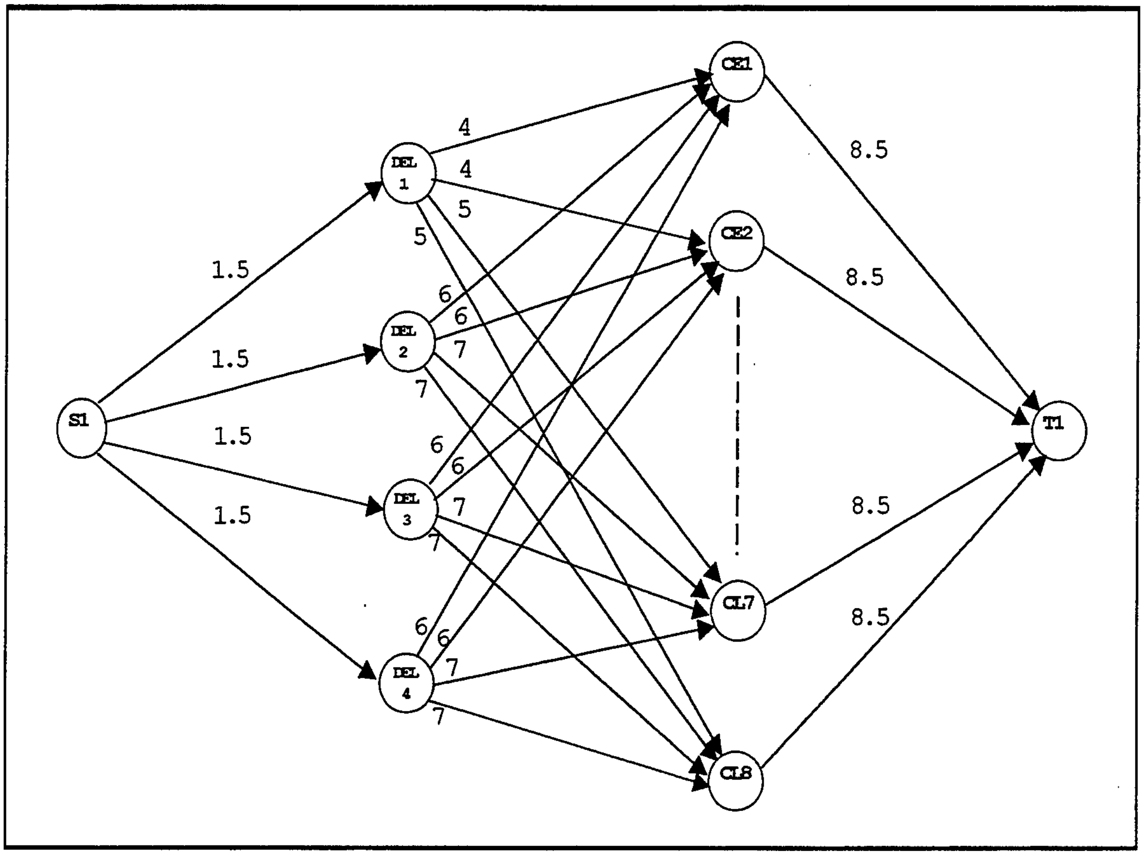

Figure 18. Network Depicting Possible Sequencing of Deployment Schedules for EUCOM. *S1* is the start node, and *T1* the termination node of the network indicating the beginning and end of the planning horizon, respectively. Any other node in the network represents a deployment schedule. Each arc length corresponds to the coverage gap between the two associated deployment schedules. Nodes *CE3*, *CE4*, *CL5*, and *CL6* exist, but are not displayed in the figure.

For each of the two networks (one for CENTCOM and one for EUCOM) described above, we can derive feasible paths beginning with *S1* or *S2*, visiting at most one node (or schedule) in each deployable period, and ending with *T1* or *T2*. Figure 19 depicts two sample feasible paths, one derived from the CENTCOM network, and the other from the EUCOM network. Since a LANTFLT carrier can cover both CENTCOM and EUCOM in the same deployment schedule, a feasible path from the CENTCOM network may have common nodes with another feasible path from the EUCOM network.

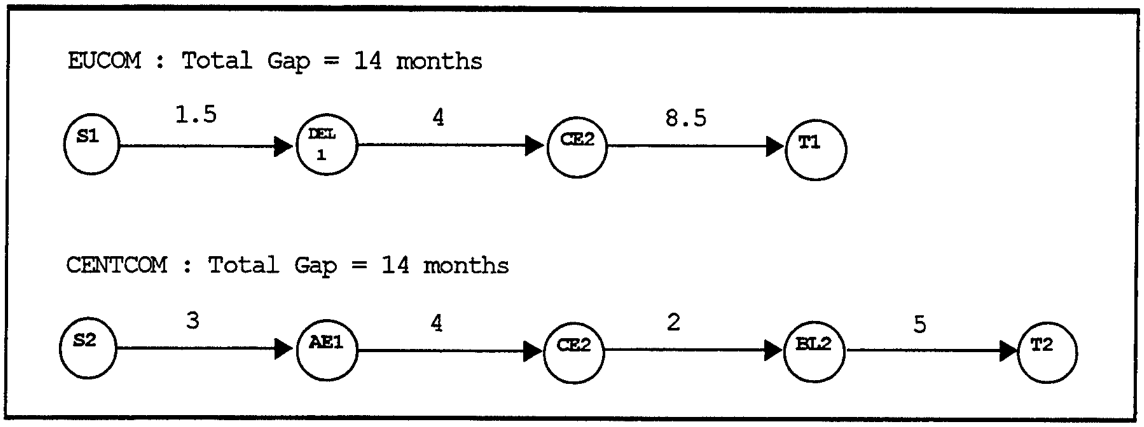

Figure 19. Two Sample Feasible Paths: One Derived from the EUCOM Network, and the Other from the CENTCOM Network. Node *CE2* is common to both paths, meaning that LANTFLT carrier covers both EUCOM and CENTCOM in the same schedule.

At this point, the carrier deployment problem is reduced to finding two paths that satisfy the conditions discussed above, and that yield a minimum gap. GENCoRE models this as a two-commodity network flow problem with side constraints.

C. IMPLEMENTATION

GENCoRE consists of the following three processes: (i) *Schedule Generator* (generates all possible deployment schedules and their feasible combinations), (ii) *Solver* (determines the optimal deployment schedules that maximize coverage in the AORs by solving a shortest path network problem using Integer Linear Programming), (iii) *Coverage Percentage and Crisis Response Time Calculator* (calculates the optimal coverage percentages and crisis response times using the advice of the solver).

1. Schedule Generator

The networks described above are constructed in the schedule generator. Possible deployment schedules are generated to construct the nodes of the networks. Each feasible pairwise combination is enumerated to construct an arc, and the coverage gap for each such feasible combination is calculated as the length of that arc. The generator also classifies each schedule in order to determine its deployable period, type (e.g., early, or late), and AOR (i.e. CENTCOM, EUCOM, or both). This is implemented in a Fortran program.

The generator automates the complicated calculations, provides a formatted input for the solver, and hence shortens scheduling time. Because we only generate possible schedules and their feasible combinations, the number of variables and constraints is minimized.

GENCoRE variants differ in some details. Shift-Once and Shift-All scenarios increase all the deployable and non-deployable periods by two months to allow shifting, and Shift-Once-in-Future and Shift-All-in-Future scenarios increase only the deployable and non- deployable periods existing after the first three years (see Table 2 GENCoRE Scenarios).

Table 5 shows the number of schedules and deployable periods generated by CoRE and by each of the GENCoRE variants for a force of twelve carriers in a base case. GENCoRE increases model size modestly.

Scenario	Number of Nodes	Number of Deployable Periods
CoRE	591	41
Shift-Once	872	50
Shift-All	872	50
Shift-Once-in-Future	786	49
Shift-All-Future	786	49

Table 5. The Number of Nodes and Deployable Periods Generated by CoRE and GENCoRE for a Base Case Force of Twelve Carriers. *There is a slight increase in the number of deployable periods between CoRE and GENCoRE because some new deployable periods result from shifting maintenance periods.*

2. Optimization Model

The two-commodity network problem with side constraints is mathematically formulated as follows:

a. Formulation for Shift-Once and Shift-Once-in-Future Scenarios

Indices:

a AORs (EUCOM and CENTCOM)

c carriers

d deployable periods (1, 2,..., D-1, D)

i, j nodes in the networks representing the schedules (Nodes S^a and T^a represent the beginning and the end of the planning horizon, respectively)

s drydocking or refueling shipyards (Newport News, Puget Sound, and Norfolk)

p critical maintenance period pairs (i.e. maintenance periods which will overlap more than the allowable drydocking, refueling, or manday availability limits when shifted towards each other)

Index Maps:

Φ^a = {c: carrier c can cover AOR a}

Ω_c^d = {i: schedule i belongs to deployable period d of carrier c}

Ψ_c^d = {i: schedule i belongs to early or late deployments of period d of carrier c}

Γ = {i: schedule i covers both AORs}

E_s^p = {i: schedule i belongs to early deployments of the deployable period right after the second element of critical maintenance period pair p (i.e. the maintenance period which starts later) for shipyard s }

L_s^p = {i: schedule i belongs to late deployments of the deployable period right before the first element of critical maintenance period pair p (i.e. the maintenance period which starts earlier) for shipyard s }

Data:

GAP_{ij}^a gap length in AOR a if node j follows node i in a path

$EXIST_{ij}^a$ equals 1 if there is an arc from node i to node j for AOR a

$WEIGHT^a$ weight for coverage gap in AOR a (e.g., a CENTCOM weight of 3, and a EUCOM weight of 1)

$CONST$ sufficiently small number to penalize the early or late deployments (units of months)

(Binary) Decision Variables

x_{ij}^{a} equal 1 if arc (i,j) belongs to the path from S^a to T^a and 0 otherwise

Formulation

$$\text{minimize} \sum_{a} WEIGHT^{a} \sum_{\{(i,j):EXIST_{ij}^{a}=1\}} GAP_{ij}^{a} * x_{ij}^{a} + \sum_{\{(a,c,d,i,j):c\in\Phi^{a},i\in\Psi_{c}^{d},EXIST_{ij}^{a}=1\}} CONST * x_{ij}^{a}$$

subject to

$$\sum_{\{j:EXIST_{ji}^{a}=1\}} x_{ji}^{a} - \sum_{\{j:EXIST_{ij}^{a}=1\}} x_{ij}^{a} = \begin{cases} -1 \text{ if } i = S^{a} \\ 1 \text{ if } i = T^{a} \\ 0 \text{ otherwise} \end{cases} \qquad \forall\, a, i \qquad (1.1)$$

$$\sum_{\{i\in\Omega_{c}^{d}\}} \sum_{\{j:EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \qquad \forall\, a, d, \text{ and } c \in \Phi^{a} \qquad (1.2)$$

$$\sum_{\{j:EXIST_{ij}^{EUCOM}=1\}} x_{ij}^{EUCOM} - \sum_{\{j:EXIST_{ij}^{CENTCOM}=1\}} x_{ij}^{CENTCOM} \ge 0 \qquad \forall\, i \in \Gamma \qquad (1.3)$$

$$\sum_{\{(i,j):i\in L_{s}^{p},EXIST_{ij}^{a}=1\}} x_{ij}^{a} + \sum_{\{(i,j):i\in E_{s}^{p},EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \qquad \forall\, a, \text{s, and } p \qquad (1.4)$$

$$\sum_{\{(d,i,j):i\in\Psi_{c}^{d},EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \qquad \forall\, a, c \in \Phi^{a} \qquad (1.5)$$

In the above formulation, the objective is to minimize the weighted coverage gaps in CENTCOM and EUCOM with a very small penalty assessed to the shifted maintenance schedules. Constraint (1.1), a flow balance constraint, ensures that there is a continuity of flow into and out of each node, and thus a path from S^a to T^a. Constraint (1.2) ensures that at most one schedule is selected from each deployable period. Constraint (1.3) ensures that the same schedule is selected, if it covers both AORs. Constraint (1.4) ensures that neither the drydocking, manday, nor refueling capacity of shipyard s is exceeded. Constraint (1.5) ensures that carrier c will depart its shipyard at most one month early, or one month late.

b. *Formulation for Shift-All and Shift-All-in-Future Scenarios*

Indices:

a	AORs (EUCOM and CENTCOM)
c	carriers
d	deployable periods (1, 2,..., D-1, D)
i, j	nodes in the networks representing the schedules (Nodes S^a and T^a represent the beginning and the end of the planning horizon, respectively)
s	drydocking or refueling shipyards (Newport News, Puget Sound, and Norfolk)
p	critical maintenance period pairs (i.e. maintenance periods which will overlap more than the allowable drydocking, refueling, or manday availability limits when shifted towards each other)

Index Maps:

Φ^a = {c: carrier c can cover AOR a}

Ω_c^d = {i: schedule i belongs to deployable period d of carrier c}

Θ_c^d = {i: schedule i belongs to early deployments of period d of carrier c}

Λ_c^d = {i: schedule i belongs to late deployments of period d of carrier c}

Γ = {i: schedule i covers both AORs}

Δ^c = {d: period d of carrier c is obtained as deployable by shifting maintenance periods}

E_s^p = {i: schedule i belongs to early deployments of the deployable period right after the second element of critical maintenance period pair p (i.e. the maintenance period which starts later) for shipyard s }

L_s^p = {i: schedule i belongs to late deployments of the deployable period right before the first element of critical maintenance period pair p (i.e. the maintenance period which starts earlier) for shipyard s }

Data:

GAP_{ij}^a gap length in AOR a if node j follows node i in a path

$EXIST_{ij}^a$ equals 1 if there is an arc from node i to node j for AOR a

$WEIGHT^a$ weight for coverage gap in AOR a (e.g., a CENTCOM weight of 3, and a EUCOM weight of 1)

$CONST$ sufficiently small number to penalize the early or late deployments (units of months)

(Binary) Decision Variables

x_{ij}^{a} equal 1 if arc (i,j) belongs to the path from S^a to T^a and 0 otherwise

Formulation

$$\text{minimize } \sum_{a} WEIGHT^{a} \sum_{\{(i,j):EXIST_{ij}^{a}=1\}} GAP_{ij}^{a} * x_{ij}^{a} + \sum_{\{(a,c,d,i,j):c\in\Phi^{a},i\in(\Theta_{c}^{d} or \Lambda_{c}^{d}),EXIST_{ij}^{a}=1\}} CONST * x_{ij}^{a}$$

subject to

$$\sum_{\{j:EXIST_{ji}^{a}=1\}} x_{ji}^{a} - \sum_{\{j:EXIST_{ij}^{a}=1\}} x_{ij}^{a} = \begin{cases} -1 \text{ if } i = S^{a} \\ 1 \text{ if } i = T^{a} \\ 0 \text{ otherwise} \end{cases} \quad \forall\, a, i \tag{2.1}$$

$$\sum_{\{i\in\Omega_{c}^{d}\}} \sum_{\{j:EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \quad \forall\, a, d, \text{ and } c \in \Phi^{a} \tag{2.2}$$

$$\sum_{\{j:EXIST_{ij}^{EUCOM}=1\}} x_{ij}^{EUCOM} - \sum_{\{j:EXIST_{ij}^{CENTCOM}=1\}} x_{ij}^{CENTCOM} \ge 0 \quad \forall\, i \in \Gamma \tag{2.3}$$

$$\sum_{\{(i,j):i\in L_{s}^{p},EXIST_{ij}^{a}=1\}} x_{ij}^{a} + \sum_{\{(i,j):i\in \mathrm{E}_{s}^{p},EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \quad \forall\, a, \text{s, and } p \tag{2.4}$$

$$\sum_{\{(i,j):i\in\Lambda_{c}^{d},EXIST_{ij}^{a}=1\}} x_{ij}^{a} + \sum_{\{(i,j):i\in\Theta_{c}^{d},EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \quad \forall\, a, d\in\{1,\ldots,\text{D-1}\}, \text{ and } c \in \Phi^{a} \tag{2.5}$$

$$\sum_{\{(i,j):i\in\Lambda_{c}^{d-1},EXIST_{ij}^{a}=1\}} x_{ij}^{a} + \sum_{\{(i,j):i\in\Lambda_{c}^{d},EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \quad \forall\, a, d\in(\Delta^{c} \text{ and } \{2,\ldots,\text{D}\}), \text{ and } c \in \Phi^{a} \tag{2.6}$$

$$\sum_{\{(i,j):i\in\Theta_{c}^{d},EXIST_{ij}^{a}=1\}} x_{ij}^{a} + \sum_{\{(i,j):i\in\Theta_{c}^{d+1},EXIST_{ij}^{a}=1\}} x_{ij}^{a} \le 1 \quad \forall\, a, d\in(\Delta^{c} \text{ and } \{1,\ldots,\text{D-1}\}), \text{ and } c \in \Phi^{a} \tag{2.7}$$

In the above formulation, the objective is to minimize the weighted coverage gaps in CENTCOM and EUCOM with a very small penalty assessed to the shifted maintenance schedules. Constraint (2.1), a flow balance constraint, ensures that there is a path from S^a to T^a. Constraint (2.2) ensures that at most one schedule is selected from each deployable period. Constraint (2.3) ensures that the same schedule is selected, if it covers both AORs. Constraint (2.4) ensures that the drydocking or refueling capacity of shipyard *s* is not exceeded. Constraint (2.5) ensures that a maintenance period is shifted in one direction only (i.e. a maintenance period cannot start one month late and simultaneously end one month early).

Constraint (2.6) ensures that a carrier cannot be deployed in deployable period *d* that was obtained from a non-deployable period, and at the same time deployed in a late deployment schedule of period (*d*-1). Constraint (2.7) ensures that a carrier cannot simultaneously be deployed in deployable period *d* that was obtained from a non-deployable period, and in an early deployment schedule of period (*d*+1). If we deploy a carrier in a late deployment schedule of period (*d*-1), then this will preclude deployment in period *d*. Therefore, a late deployment in (*d*-1) is mutually exclusive with any deployment in *d*.

3. Solver

The models have been implemented with the algebraic modeling language GAMS [Brooke, et.al 1992] and solved with OSL [IBM, 1992] using a 133 Mhz and 80MB Pentium personnel computer. Table 6 gives the model sizes resulting from GENCoRE scenarios. The optimality tolerance has been set to one percent. The solution times range from 45 minutes to 65 minutes.

Scenario	Number of Constraints	Number of Variables
Shift-Once	(1.1) 1600 (1.2) 50 (1.3) 437 (1.4) 5 (1.5) 21	
Total	**2113**	**45555**
Shift-All	(2.1) 1600 (2.2) 50 (2.3) 437 (2.4) 5 (2.5) 50 (2.6) 9 (2.7) 9	
Total	**2160**	**45675**
Shift-Once-in-Future	(1.1) 1439 (1.2) 49 (1.3) 392 (1.4) 4 (1.5) 18	
Total	**1902**	**36699**
Shift-All-in-Future	(2.1) 1439 (2.2) 49 (2.3) 392 (2.4) 4 (2.5) 35 (2.6) 8 (2.7) 8	
Total	**1935**	**36782**

Table 6. Model Sizes for a Force of Twelve Carriers, A Planning Horizon of Ten years, and a Time Resolution of One Month. A number in parenthesis indicates the constraint number in the mathematical formulation. For example, there are 1600 constraints for equation type (1.1) in the Shift-Once scenario.

4. Coverage Percentage and Crisis Response Time Calculator

There are two Fortran programs that use the solver output to respectively calculate average crisis response times and coverage percentages as described in Chapter

III. Figure 20 shows a sample output for a ten-year schedule generated by Shift-Once-in-Future for a twelve-carrier scenario.

```
        SHIFT-ONCE-IN-FUTURE WITH 12 CARRIERS
        PG = 77.35,  MED = 73.46
        PG BY LANTFLT = 31.77, PG BY PACFLT = 68.23

      <----97-----><----98-----><----99-----><---- 0-----><---- 1-----><---- 2-----><---- 3-----><---- 4-----><---- 5-----><---- 6-----
P.G.  44042344442442142444043444444441241424442 40-344242--14114133344441-42143444444444342444443--24014142144444344444444441-1434332444444

CONS  -----3442-------------------------------------------------------------------------------------------------------------------------
STEN  ----------------14440----------------------3442------------------------------2443-------------------------------4441--------------
KITA  440--------------------------------14440-------------------3442--------------------4441-------------------------------------------
REAG  ----------------------------------------------------------------------------------------------------------0444-------------------1
NIMI  ----------2442-----------------------------------------------------------3441-------------------------3441------------------0444--
VINS  -------------------------1443--------------------------------3441--------------------1443--------------------0444-----------------
LINC  ----------------------1443--------------------------------------------2442-------------------------1443------------------------344
ENTE  ---------------------42-------------------------------141------------------------42-----------------------------------------------
KENN  --------240--------------------240-----------------------33-----------------------------------141--------------------141----------
EISE  --------------141------------------------------42------------------------------------------------------------------------33-------
ROOS  ---42----------------------------141------------------------------42-----------------------240-------------------------240--------
WASH  ---------------------------------------240--------------------------141--------------------------42------------------------240----
AMER  ----------------------------141---------------------------------------------------------------------------------------------------
TRUM  ---------------------------------------------------141----------------------33---------------------------240----------------------

      <----97-----><----98-----><----99-----><---- 0-----><---- 1-----><---- 2-----><---- 3-----><---- 4-----><---- 5-----><---- 6-----
MED   444-14442-2-343-23244-140344344234224342-344444-3443-33-2444443444-12-24431410443-144400444444444-14004442-2344443344444443444442-

ENTE  ------------------244-140----------------------------33-243---------------------2-14440---------------------344443----------------
KENN  ----04442-2-----------------0442-32---------------------1104441----------------------------3443-2-----------------3443-2----------
EISE  ------------343-23-------------------------2444-10---------------------------------------------------------------------1410441----
ROOS  444-10--------------------------33-243------------------------2444-10------------------04442-2----------------------0442-32-------
WASH  -------------------------------------042-342------------------------2-2443--------------------244-140---------------------02-3442-
AMER  -------------------------3443-2---------------------------------------------------------------------------------------------------
TRUM  ------------------------------------------------3443-2--------------------1410441--------------------04442-2----------------------

              Legend:  '-'  :  No Coverage        P.G.            :  Persian Gulf  (CENTCOM
                       '0'  :  1  - 6  days       MED             :  Mediterranean (EUCOM
                       '1'  :  7  - 13 days       P.G. by LANTFLT :  P.G. Coverage Percentag
                       '2'  :  14 - 20 days                          by LANTFLT Carrier
                       '3'  :  21 - 27 days       P.G. by LANTFLT :  P.G. Coverage Percentag
                       '4'  :  28      days                          by LANTFLT Carrier
```

Figure 20. Sample Output of One-Future-Shift Deployment Schedule with Twelve Carriers. The carriers are represented by four-character abbreviations. The upper section of the schedule represents Persian Gulf (CENTCOM) coverage, and the lower section represents Mediterranean (EUCOM) coverage. Fiscal years are shown over each of these sections. Each fiscal year is divided into four-week periods. A four-week period is covered completely if the corresponding code is '4,' while less coverage is denoted by alternate codes. For instance, Eisenhower is assigned the codes '2444-10' in the Mediterranean section, and '42' in the Persian Gulf section of 2000. These codes indicate that Eisenhower is planned to deploy to the Mediterranean for the first fourteen weeks and then to the Persian Gulf for six weeks, and finally back to the Mediterranean for the last 8 to 18 days. This figure provides a concise graphical representation of a detailed, long-term deployment schedule. Underlying numerical outputs from the optimization models provide more detailed deployment schedules with exact dates.

V. RESULTS

This chapter presents achievable estimated coverage and response times derived from the following models: (i) *Modified CoRE* (a modification of the input data and the CoRE model generator, preserving the fidelity of the original model but repairing some errors and producing more accurate results), and (ii) GENCoRE.

Following recent exigent events in the Persian Gulf, the above models are also compared with a new scenario which allows Persian Gulf deployment by LANTFLT carriers to last either 4, 8, 12, or 16 weeks instead of fixing the length of these deployments at six weeks (Vary-Gulf). Unlike Modified CoRE and GENCoRE, CENTCOM and EUCOM are weighted equally in this scenario.

For the purposes of model validation, a statistical analysis is presented in Appendix D that seeks a relationship between shifting maintenance periods and the resulting planned duration of the following work-up period. The key idea is to see if shifting maintenance to make deployments more flexible comes at the cost of curtailed or hastened work-ups.

A. MODIFIED CORE – REPAIRS TO THE ORIGINAL MODEL

In the course of this research, we have discovered a few details in the original CoRE implementation that have needed to be changed. The result, called Modified CoRE here, has all these necessary repairs and may not exactly corroborate the base case results in Brown, et.al [1997].

A Refueling Complex Overhaul (RCOH) scheduled for USS Nimitz to end on 30 March, 2001, was found to be coded in the CoRE generator to end a year earlier. This one-year error is a relaxation that affects the results significantly.

A logic error in the CoRE generator did not require carriers with pre-scheduled work-up periods to return from deployment a month before their next scheduled maintenance. This relaxes the intended scheduling problem by four weeks and thus creates extra deployable periods. However, there were only five instances of this condition in the CoRE base case scenario, and not all of these were exploited in any optimized plan.

The 12-carrier scenario of Brown, et.al [1997] uses USS Phantom E to substitute for USS Truman and maintain the total planned force of twelve carriers. However, the last deployable period of Phantom E overlapped the first of USS Truman, relaxing the scenario briefly to thirteen carriers. This triviality is repaired by removing USS Phantom E from the fleet just as USS Truman arrives.

The nature of these repairs renders Modified CoRE as a *restriction* of CoRE.

B. AOR COVERAGE PERCENTAGES

Tables 7 through 12 and Figures 21 though 26 show the AOR coverages for each of the scenarios.

NO. CARRIERS	EUCOM	CENTCOM	CENTCOM BY LANTFLT	CENTCOM BY PACFLT
10	48.86	53.38	35.14	64.86
11	50.29	64.35	24.64	75.36
12	59.53	67.33	28.38	71.62
13	61.34	71.87	26.63	73.37
14	67.17	72.83	26.15	73.85

Table 7. AOR Coverage with Modified CoRE. The results shown include AOR coverage percentages, and distribution of CENTCOM coverage between LANTFLT and PACFLT carriers. For example, with a force of twelve carriers, coverage in EUCOM is 59.53% and coverage in CENTCOM is 67.33%. CENTCOM is covered by LANTFLT carriers 28.38% of the time, and by PACFLT carriers 71.62% of the time.

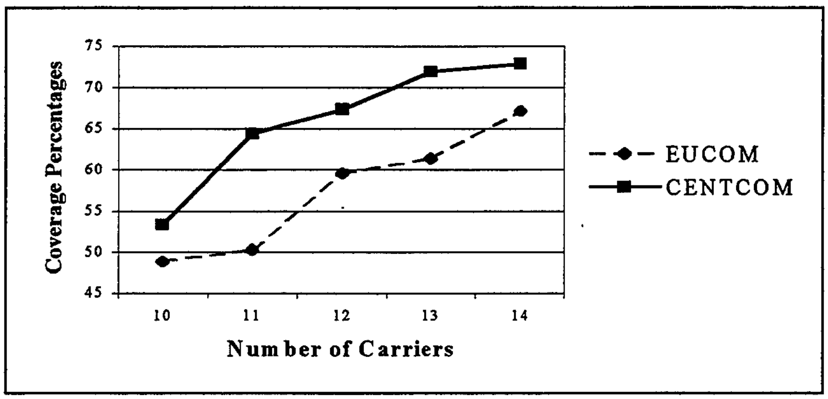

Figure 21. AOR Coverage with Modified CoRE. As the number of carriers increases, the coverage of both AORs also increases. The deployment of the eleventh carrier in PACFLT, results in a significant increase in CENTCOM coverage. Likewise, a significant increase in EUCOM coverage is due to the addition of the twelfth carrier to LANTFLT.

NO. CARRIERS	EUCOM	CENTCOM	CENTCOM BY LANTFLT	CENTCOM BY PACFLT
10	60.85	64.43	33.86	66.14
11	62.44	74.75	25.64	74.36
12	73.24	79.64	30.83	69.17
13	76.28	82.11	25.82	74.18
14	82.93	84.98	27.35	72.65

Table 8. AOR Coverage with GENCoRE-Shift-Once. This scenario allows a maintenance period shift of one month per carrier, only once over a ten-year horizon.

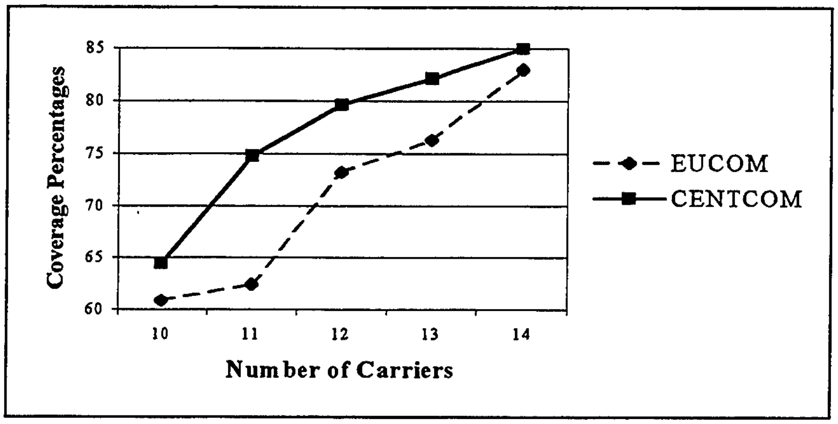

Figure 22. AOR Coverage with GENCoRE-Shift-Once.

NO. CARRIERS	EUCOM	CENTCOM	CENTCOM BY LANTFLT	CENTCOM BY PACFLT
10	63.61	67.72	35.32	64.48
11	62.52	80.38	29.54	70.46
12	75.98	83.97	32.52	67.48
13	78.44	87.11	27.23	72.77
14	82.19	89.82	30.54	69.46

Table 9. AOR Coverage with GENCoRE-Shift-All. This scenario allows an unlimited number of maintenance period shifts of one month per carrier, over a ten-year horizon.

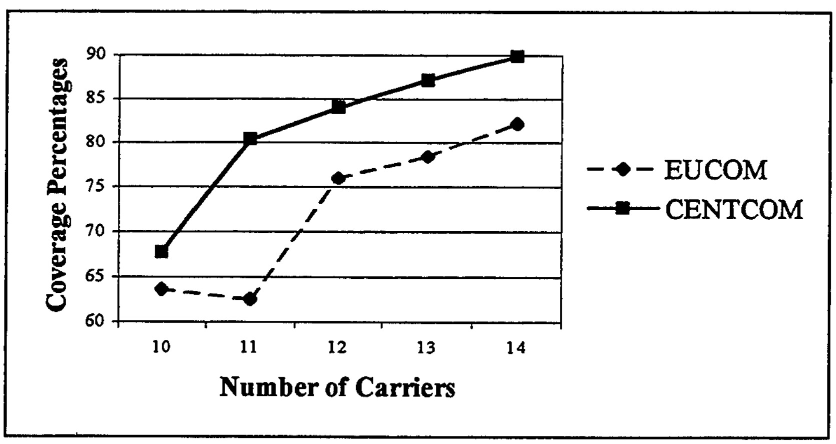

Figure 23. AOR Coverage with GENCoRE-Shift-All. Although the number of carriers increases from ten to eleven, the coverage percentage in EUCOM decreases by a small amount. This decrease follows the deployment of the eleventh carrier in PACFLT, and reflects the difference of the weights used for CENTCOM and EUCOM (CENTCOM coverage is three times more weighted than EUCOM coverage).

NO. CARRIERS	EUCOM	CENTCOM	CENTCOM BY LANTFLT	CENTCOM BY PACFLT
10	60.90	62.11	35.13	64.87
11	63.20	72.26	26.41	73.59
12	73.46	77.35	31.77	68.23
13	75.10	79.84	28.79	71.21
14	81.50	83.15	31.75	68.25

Table 10. AOR Coverage with GENCoRE-Shift-Once-in-Future. This scenario allows a maintenance period shift of one month per carrier, beginning with the fourth year of the ten-year planning horizon.

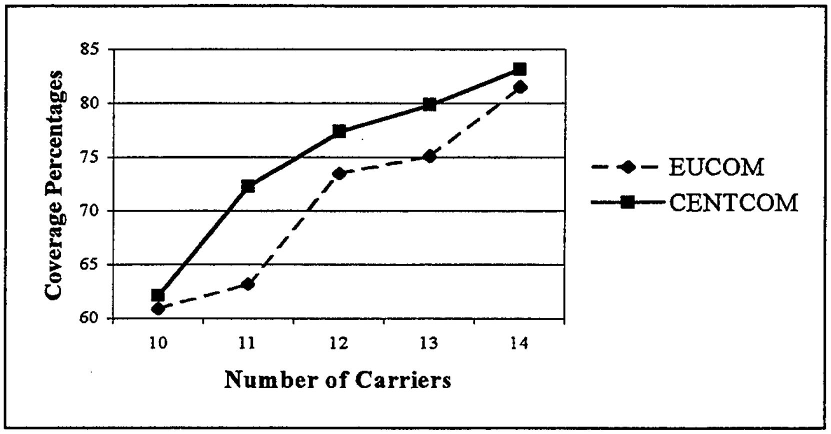

Figure 24. AOR Coverage with GENCoRE-Shift-Once-in-Future.

NO. CARRIERS	EUCOM	CENTCOM	CENTCOM BY LANTFLT	CENTCOM BY PACFLT
10	60.19	63.64	35.49	64.51
11	60.19	76.11	29.15	70.85
12	72.83	79.51	32.26	67.74
13	75.70	81.92	25.77	74.23
14	83.80	84.40	28.57	71.43

Table 11. AOR Coverage with GENCoRE-Shift-All-in-Future. This scenario allows an unlimited number of maintenance period shifts per carrier by one month, beginning with the fourth year of the ten-year planning horizon.

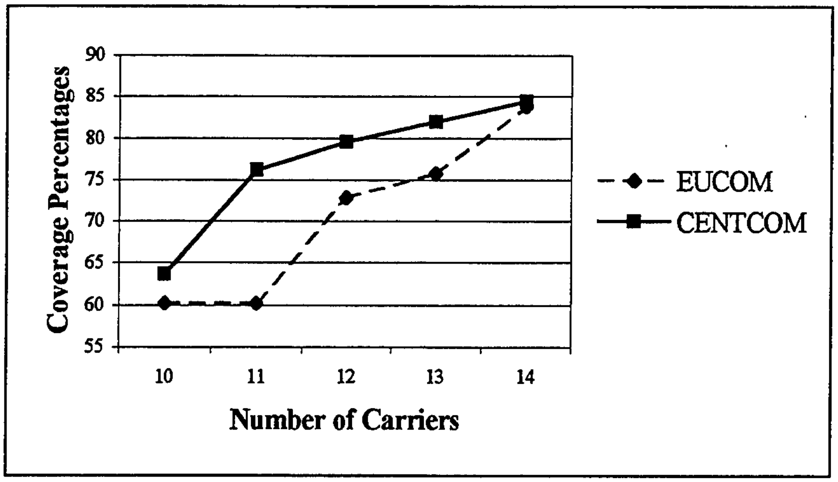

Figure 25. AOR Coverage with GENCoRE-Shift-All-in-Future.

Shift-Once-in-Future and Shift-All-in-Future scenarios are motivated by the realistic expectation that shifting of maintenance periods during the first three years of the planning horizon may complicate the coordination of deployment and maintenance scheduling.

NO. CARRIERS	EUCOM	CENTCOM	CENTCOM BY LANTFLT	CENTCOM BY PACFLT
10	44.38	58.25	41.26	58.74
11	49.82	65.01	30.22	69.78
12	60.77	67.33	28.04	71.96
13	63.94	67.58	24.51	75.49
14	73.84	72.12	26.59	73.41

Table 12. AOR Coverage with Vary-Gulf. This Modified CoRE scenario allows CENTCOM (Persian Gulf) deployment by LANTFLT carriers to last either 4, 8, 12, or 16 weeks instead of fixing the length of deployment at six weeks. Maintenance schedules are fixed.

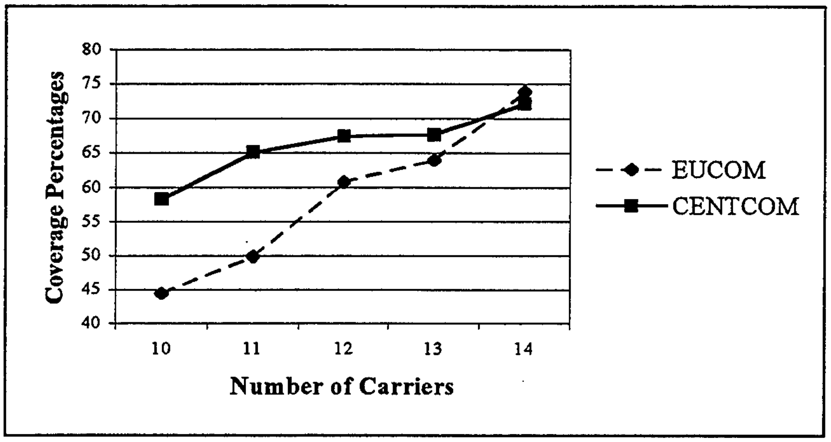

Figure 26. AOR Coverage with Vary-Gulf. For the fourteen carrier force, the EUCOM coverage is more than the CENTCOM coverage.

Figures 27 and 28 provide a comparison of all scenarios for EUCOM and CENTCOM, respectively.

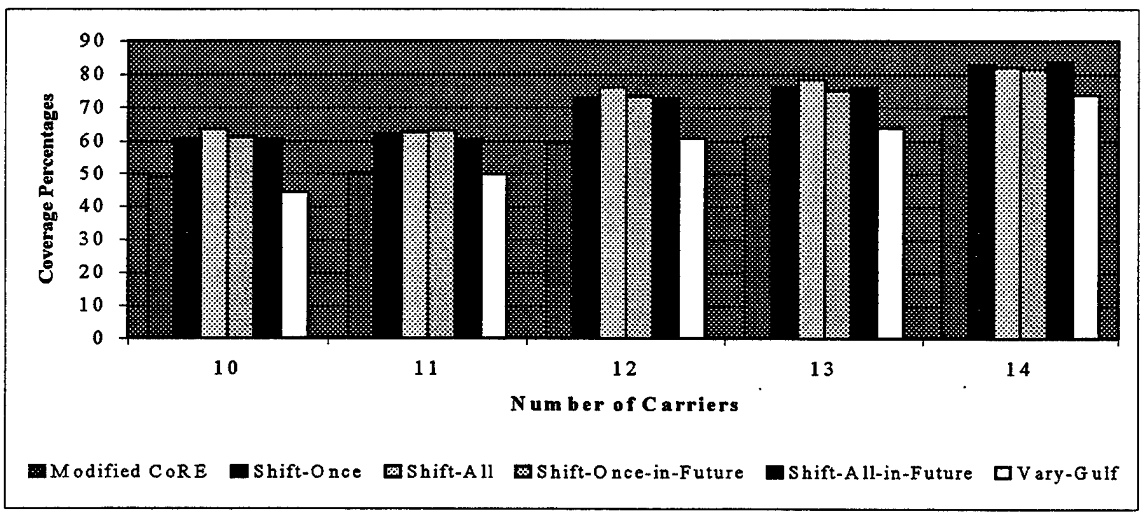

Figure 27. AOR Coverage for EUCOM. The legends are ordered from left to right. On average the best results are achieved with Shift-All. GENCoRE scenarios yield significantly better results than Modified CoRE. Modified CoRE and Vary-Gulf scenarios do not shift scheduled maintenance, and have approximately the same coverage.

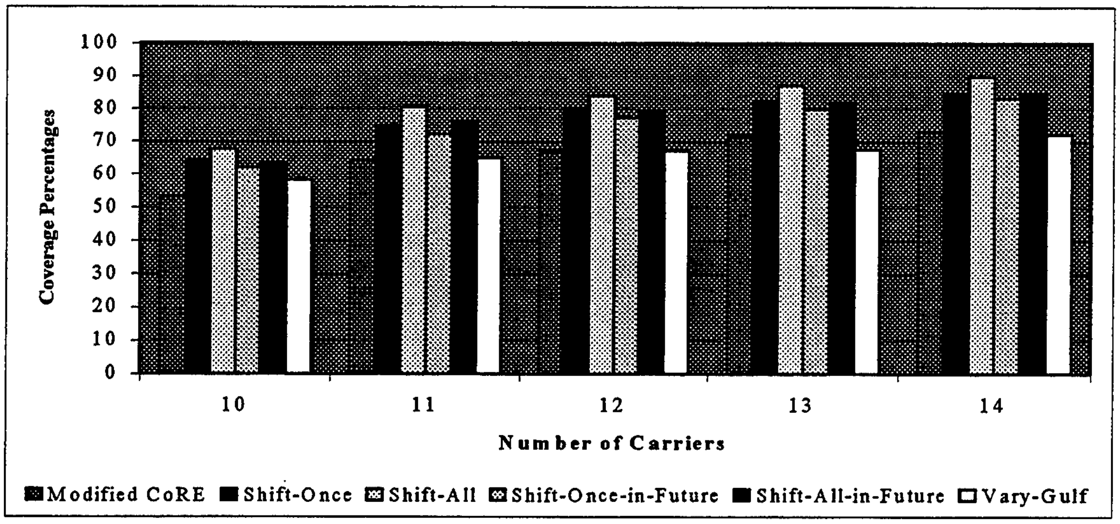

Figure 28. AOR Coverage for CENTCOM. The legends are ordered from left to right. GENCoRE scenarios yield significantly better results than Modified CoRE. Modified CoRE and Vary-Gulf do not shift scheduled maintenance, and yield approximately the same coverage.

The coverage percentages derived from GENCoRE for both AORs are significantly higher than those of Modified CoRE. For the most conservative Shift-Once-in-Future scenario, the coverage in CENTCOM with twelve carriers is 77.35% and the coverage in EUCOM 73.46%. For the Modified CoRE scenario, these percentages are 67.33% and 59.53%, respectively. This corresponds to a 10.02% of increase in CENTCOM, and a 13.93% increase in EUCOM. Significantly higher coverage percentages are achieved with just twelve carriers in Shift-Once-in-Future as compared to those coverage percentages yielded by the fourteen carrier Modified CoRE scenario. Moreover, Shift-All yields even better results with only eleven carriers.

The significant improvements in coverage derive from the new deployable periods obtained by shifting maintenance periods. Table 5 in Chapter IV shows that by shifting the maintenance periods one month earlier or later, *we obtain nine new deployable periods.*

These nine new deployable periods allow 116 more weeks of planned coverage in the AORs.

Vary-Gulf differs from Modified CoRE by allowing CENTCOM (Persian Gulf) deployment of a LANTFLT carrier to last either 4, 8, 12, or 16 weeks instead of fixing the length of deployment at six weeks. Like Modified CoRE, Vary-Gulf does *not* shift maintenance periods. Variable-length Persian Gulf coverage by a LANTFLT carrier is a relaxation, and might be expected to increase coverage percentages. However, Figures 26 and 27 show that Modified CoRE and Vary-Gulf scenarios yield approximately the same coverage percentages. Therefore, in order to reduce the size of each model (CoRE and GENCoRE) and to make larger scale future versions (e.g., allowing shifts more than one month) of these scenarios solvable, it is reasonable to fix the Persian Gulf deployment of a LANTFLT carrier at six weeks.

C. CRISIS RESPONSE TIMES

Table 13 and Figure 29 show the average crisis response times of the first carrier, derived from Modified CoRE and Shift-Once-in-Future scenarios with the existing carrier fleet. The locations shown are a representative sample from around the world (see Appendix C for the latitudes and longitudes of these points). These geographical locations are not meant to forecast a particular crisis during the 1997-2006 planning horizon, but rather to gauge the ability to reach diverse destinations when an optimally scheduled deployment plan is interrupted by a need for crisis response.

No.	Geographical Locations	Modified CoRE	Shift-Once-in-Future	Difference in the Response Times
1	Adriatic	4.1	2.5	1.6
2	Algiers	5.2	3.9	1.3
3	Baltic	7.1	6.1	1.0
4	Bugo, Philippines	6.4	5.7	0.7
5	Colombo	5.7	4.7	1.0
6	Dacca, Bangladesh	7.4	6.6	0.8
7	Djibouti	4.6	3.4	1.2
8	Ecuador	14.5	14.1	0.4
9	El Salvador	13.2	12.9	0.3
10	French Guyana	9.2	8.7	0.5
11	Haiti	7.8	6.5	1.3
12	Hong Kong	6.2	5.5	0.7
13	Iceland	8.3	7.5	0.8
14	Jakarta	7.3	6.5	0.8
15	Karachi	4.4	3.1	1.3
16	Korea	5.2	4.7	0.5
17	Kuwait	4.1	2.7	1.4
18	Lebanon	3.7	2.1	1.6
19	Liberia	9.4	8.5	0.9
20	Luanda	12.4	11.8	0.6
21	Madagascar	5.7	4.9	0.8
22	Malacca	6.9	6.1	0.8
23	Mombasa, Kenya	6.9	5.8	1.1
24	Montevideo, Uruguay	14.5	14.1	0.4
25	Sakhalin, Russia	7.5	7.2	0.3
26	Santiago, Chile	16.8	16.4	0.4
27	Somalia	6.2	5.1	1.1
28	Spratley Islands	6.4	5.7	0.7
29	Taiwan Strait	5.6	5.0	0.6
30	Tripoli	3.7	2.1	1.6
	Average	7.5	6.7	0.9

Table 13. Average Crisis Response Times (in days) of a First Carrier to World-wide Locations. Shift-Once-in-Future yields an average decrease of nearly a full day (numerically, the difference is 0.88, shown above truncated to 0.9) in the crisis response times of the first carrier.

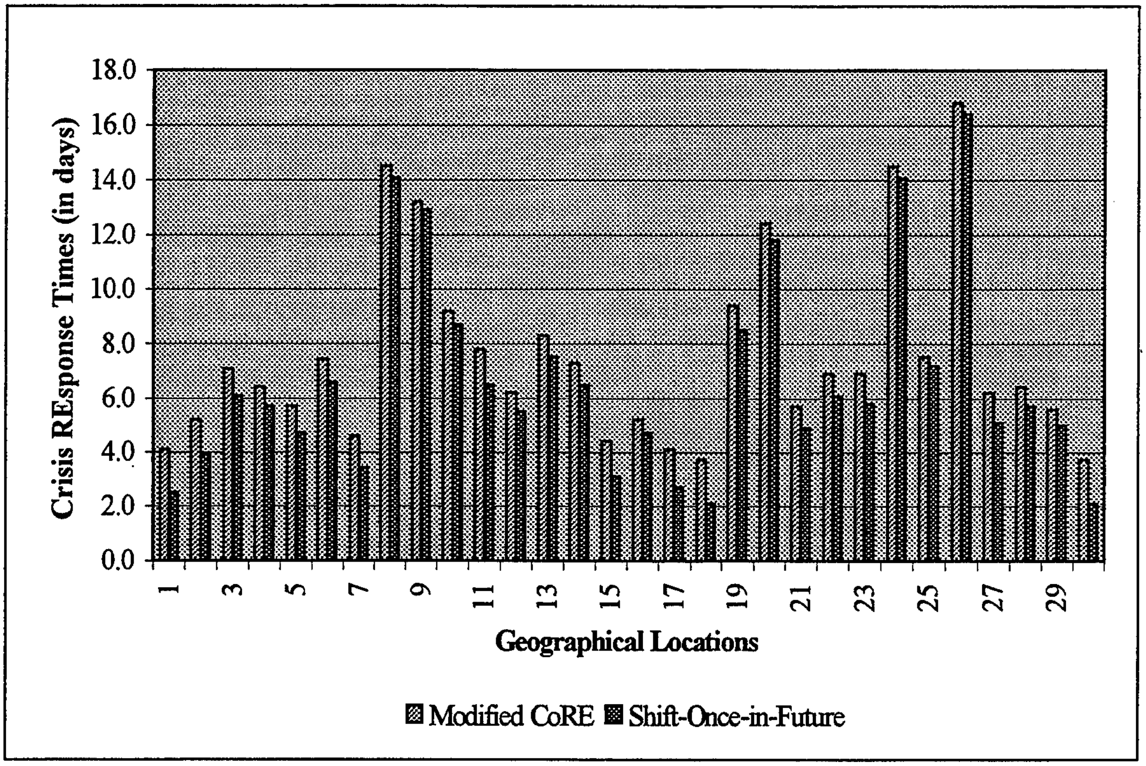

Figure 29. Comparison of the Average Crisis Response Times (in days) of a First Carrier Between Modified CoRE and Shift-Once-in-Future. For all geographical locations Shift-Once-in-Future yields faster crisis response.

Table 14 and Figure 30 show the average crisis response times of a second carrier, derived from Modified CoRE and Shift-Once-in-Future scenarios.

No.	Geographical Locations	Modified CoRE	Shift-Once-in-Future	Difference in the Response Times
1	Adriatic	12.5	9.5	3.0
2	Algiers	12.5	9.8	2.7
3	Baltic	13.9	10.1	3.8
4	Bugo, Philippines	12.4	11.3	1.1
5	Colombo	10.9	8.7	2.2
6	Dacca, Bangladesh	11.9	9.8	2.1
7	Djibouti	10.4	7.4	3.0
8	Ecuador	19.3	18.7	0.6
9	El Salvador	19.0	18.2	0.8
10	French Guyana	14.1	11.0	3.1
11	Haiti	15.4	11.7	3.7
12	Hong Kong	12.5	11.3	1.2
13	Iceland	14.2	11.0	3.2
14	Jakarta	11.4	9.7	1.7
15	Karachi	11.5	8.8	2.7
16	Korea	13.3	12.5	0.8
17	Kuwait	12.6	9.9	2.7
18	Lebanon	11.9	8.9	3.0
19	Liberia	15.0	12.6	2.4
20	Luanda	16.0	14.3	1.7
21	Madagascar	9.8	7.5	2.3
22	Malacca	10.8	9.1	1.7
23	Mombasa, Kenya	12.6	9.8	2.8
24	Montevideo, Uruguay	17.0	16.1	0.9
25	Sakhalin, Russia	16.0	15.2	0.8
26	Santiago, Chile	19.4	19.2	0.2
27	Somalia	11.9	9.1	2.8
28	Spratley Islands	11.5	10.0	1.5
29	Taiwan Strait	12.6	11.6	1.0
30	Tripoli	12.1	9.1	3.0
	Average	13.5	11.4	2.1

Table 14. Average Crisis Response Times (in days) of a Second Carrier to World-wide Locations. Shift-Once-in-Future yields an average decrease of 2.1 days in the crisis response times of the second carrier.

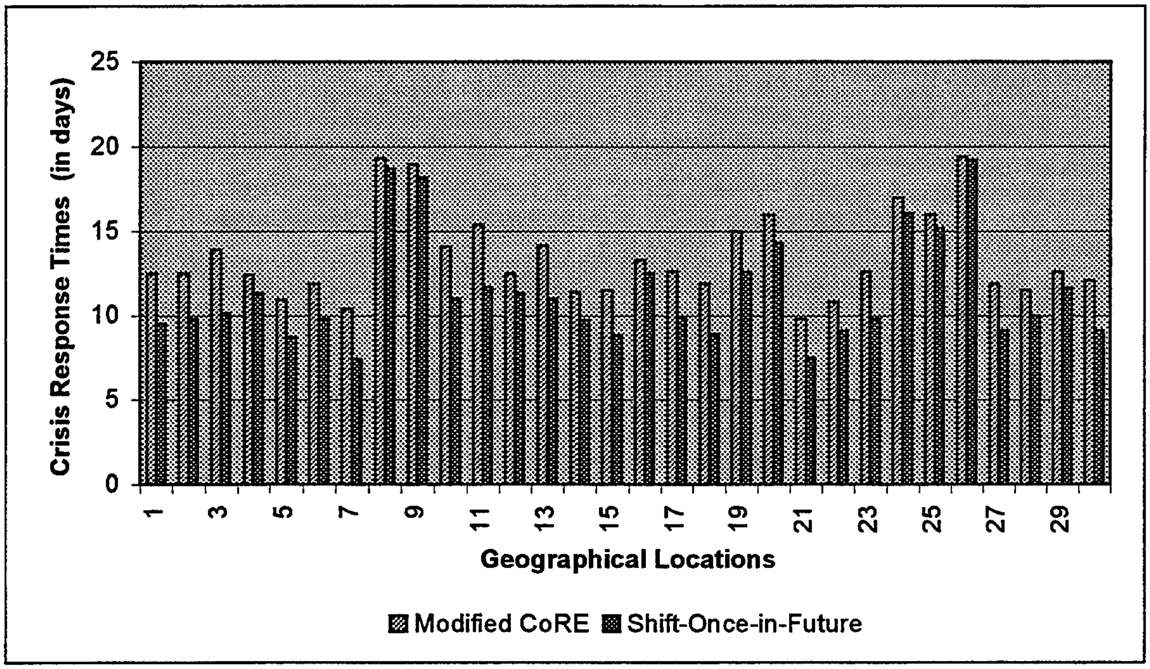

Figure 30. Comparison of the Average Crisis Response Times (in days) of the Second Carrier Between Modified CoRE and Shift-Once-in-Future. For all geographical locations Shift-Once-in-Future yields significantly faster crisis response.

When compared to Modified CoRE, the most conservative GENCoRE scenario, Shift-Once-in-Future yields an average decrease of nearly a full day in the crisis response time of a first carrier, and an average decrease of nearly two days for a second carrier.

VI. CONCLUSIONS AND RECOMMENDATIONS

This thesis shows that long-term aircraft carrier deployment planning can be synchronized with long-term maintenance availabilities and improved by shifting maintenance within limits allowed by CNO when necessary. As a result of improved long-range planning, AOR coverage achievable with existing force structure is significantly improved and average crisis response times by a first and second carrier are significantly shortened.

The synchronous planning of deployments and depot level maintenance yields at least 15% more AOR coverage than can be achieved with the current base case. Such an increase in coverage has heretofore been thought to require the availability of three additional aircraft carriers.

Moreover, this reasonable planning strategy decreases the estimated average worldwide crisis response time of a first carrier by an average of about one day and of a second carrier by about two days. Decreasing crisis response time has both strategic and economic significance. In the case of the Gulf War of 1990, a delay of two days in crisis response time by a second carrier has been estimated by Brown, et.al [1992, pg. 50] to increase the price of U.S. oil imports by an amount between \$0.73B and \$2.3B. The two-day delay could also result in a decrease of the U.S. Gross Domestic Product between \$13B and \$39B.

Synchronous long-term planning of deployments and depot level maintenance has been limited here to investigating improvement in coverage percentages and crisis response times by shifting the maintenance periods only one month. Clearly, more aggressive shifting may be of interest, although the limits allowed by CNO [OPNAV 1996c, pg. 3-4] may need further clarification before they are approved for automated planning use.

The previously mentioned differences in AOR coverage and response times achievable with the synchronous planning could certainly decrease over time as the baseline schedule is changed or updated to eliminate inefficiencies. Such potentially disruptive changes would be prevented through the use of synchronous scheduling as a long-term planning tool. Long-range maintenance and deployment schedules would be better defined, thus reducing volatility in both areas.

In an era in which the U.S. Navy must accomplish more with fewer resources, any planning tool that improves operational efficiency while simultaneously enabling better control of long-range maintenance requirements merits serious consideration.

Although not investigated in this thesis, there would seem to be potential savings available from improved long-range maintenance schedules. Material requirements and shipyard workloads could be forecast more reliably and better managed. In addition to improving efficiency at the maintenance and deployment scheduling levels, such a planning tool can offer valuable insight to budget analysts at the level of the Department of the Navy. Tradeoffs between costly maintenance requirements (such as RCOH) and the acquisition of additional force structures or improved readiness are constantly being considered. A planning tool that helps to quantify the impact of shifting carrier maintenance schedules necessitated by budgetary constraints would surely help senior Navy decision makers make more informed decisions and to prepare more persuasive requests for additional funding from the Office of the Secretary of Defense (OSD).

Allowing shifts of more than one month will increase the size of the resulting optimization models, as would a longer planning horizon. If these larger models cannot be solved directly, and if the effort is justified by the potential value of the results, more advanced solution methods may deserve attention.

GENCoRE can be embellished to consider posed crises --- future epochs of increased coverage demands on carriers. One can also explicitly evaluate changes in PERSTEMPO policies, and many other OPNAV policies that directly influence AOR coverage and crisis response times achievable by one of the planned carrier fleet.

Considering the strategic and economic significance of efficient planning of aircraft carrier fleet deployment, the decision-support optimization models introduced here have much to recommend then.

APPENDIX A. MAINTENANCE PERIODS FOR CARRIERS AS OF FEBRUARY 28, 1997

PACIFIC FLEET	Start	Finish	Maintenance
Independence (CV-62)	1-Jul-1996	1-Sep-1996	ISRA
Yokosuka	1-Sep-1997	1-Jun-1998	Inactivation
Kitty Hawk (CV-63)*	21-May-1997	21-Dec-1997	COH
San Diego	15-Jan-1998	15-Apr-1998	COH
Yokosuka (1 Sept 1998)	6-Mar-2000	2-Jun-2000	SRA
	22-Jan-2002	22-Apr-2002	SRA
	22-Oct-2003	22-Oct-2004	COH
	22-Oct-2005	22-Jan-2006	ISRA
	22-Oct-2006	22-Jan-2007	ISRA
Constellation (CV-64)*	15-Dec-1997	15-Apr-1998	DSRA
San Diego	1-May-1998	1-Aug-1998	DSRA
	1-Jan-1999	1-Apr-1999	ISRA
	1-Apr-2000	1-Jul-2000	ISRA
	1-Apr-2001	1-Jul-2001	ISRA
	1-Apr-2002	1-Jul-2002	ISRA
	1-Apr-2003	30-Sep-2003	Inactivation
Nimitz (CVN-68)	29-May-1998	30-Mar-2001	RCOH
Bremerton/Everett	18-Apr-2003	15-Oct-2003	PIA2
	15-Apr-2005	15-Oct-2005	PIA
	15-Apr-2007	15-Mar-2008	DPIA
Vinson (CVN-70)	10-Mar-1997	10-Sep-1997	PIA2
Bremerton/Everett	21-Jan-2000	6-Dec-2000	DPIA2
	13-Jan-2002	13-Jul-2002	PIA3
	13-Jan-2004	13-Jul-2004	PIA3
	13-Jan-2006	1-Dec-2006	DPIA3
	1-Jun-2008		PIA3
Lincoln (CVN-72)	1-May-1999	1-Nov-1999	PIA2
Bremerton/Everett	8-Jan-2001	6-Jul-2001	PIA2
	4-Jan-2003	15-Nov-2003	DPIA2
	15-May-2005	15-Nov-2005	PIA3
	15-May-2007		PIA3
Stennis (CVN-74)	12-Oct-1998	12-Apr-1999	PIA1
San Diego	1-Jun-2001	1-Dec-2001	PIA1
	1-Sep-2003	1-Aug-2004	DPIA1
	1-Jan-2006	1-Jul-2006	PIA2
	1-Jan-2008		PIA2

PACIFIC FLEET (Cont.)	Start	Finish	Maintenance
Reagan (CVN-76)	1-Jan-1997	1-Dec-2002	Construction
Bremerton/Everett	1-Jun-2003	1-Oct-2003	PSA/SRA
	1-Apr-2005	1-Oct-2005	PIA1
	1-Apr-2007	1-Oct-2007	PIA1
Phantom A (CVN 69.5)	1-Jan-1997	1-Aug-1999	RCOH
San Diego	1-Dec-1999	1-Feb-2000	PSA
Commission 1980	1-Sep-2001	1-Feb-2002	PIA
	1-Sep-2003	1-Feb-2004	PIA
	1-Sep-2005	1-Jul-2006	DPIA
	1-Feb-2008		PIA
Phantom C (CVN 71.5)	1-Apr-1996	1-Sep-1996	PIA
San Diego	1-Apr-1998	1-Feb-1999	DPIA
Commission 1988	1-Sep-2000	1-Feb-2001	PIA
	1-Sep-2002	1-Feb-2003	PIA
	1-Sep-2004	1-Nov-2006	RCOH
	1-Feb-2007	1-Apr-2007	PSA

Maintenance Activities

COH	Complex Overhaul
DPIA	Drydocking Planned Incremental Availability
DSRA	Drydocking Selected Restricted Availability
EDSRA	Extended Drydocking Selected Restricted Availability
ESRA	Extended Selected Restricted Availability
ISRA	Incremental Selected Restricted Availability
PIA	Planned Incremental Availability
PSA	Post Shakedown Availability
RCOH	Refueling Complex Overhaul
SRA	Selected Restricted Availability

*Note about Constellation and Kitty Hawk going to Yokosuka

ATLANTIC FLEET	Start	Finish	Maintenance
Enterprise (CVN-65)	13-Feb-1997	14-Aug-1997	ESRA
Norfolk	17-Jun-1999	27-Apr-2000	EDSRA1
	26-Jul-2001	24-Jan-2002	ESRA2
	7-Nov-2003	7-May-2004	ESRA2
	7-Nov-2005	20-Sep-2006	EDSRA2
	20-Mar-2008		SRA3
Kennedy (CV-67)	4-Dec-1997	1-Apr-1998	SRA
Mayport	4-Oct-1999	10-Feb-2000	DSRA
	26-Jan-2002	24-Jan-2003	COH
	24-Jul-2004	24-Oct-2004	SRA
	24-Apr-2006	24-Jul-2006	SRA
Eisenhower (CVN-69)	1-Jan-1997	28-Jan-1997	COH ends
Norfolk	14-Jan-1999	15-Jul-1999	PIA2
	19-Oct-2000	22-May-2003	RCOH
	22-Nov-2004	22-May-2005	PIA
	22-Oct-2006	22-Mar-2007	PIA
	22-Aug-2008		DPIA
Roosevelt (CVN-71)	20-Jun-1997	22-Jun-1998	EDSRA
Norfolk	13-Jan-2000	13-Jul-2000	PIA2
	12-Jul-2002	10-Jan-2003	PIA
	6-May-2004	17-Mar-2005	DPIA
	17-Sep-2006		PIA
Washington (CVN-73)	1-Jan-1997	1-Mar-1997	PIA1 ends
Norfolk	22-Apr-1998	4-Mar-1999	DPIA1
	20-Jun-2000	19-Dec-2000	PIA2
	9-Jan-2003	10-Jul-2003	PIA2
	27-Sep-2004	12-Aug-2005	DPIA2
	12-Jan-2007		PIA3
Truman (CVN-75)	1-Jan-1997	30-Jun-1998	Construction
Norfolk	5-Jan-1999	1-May-1999	PSA/SRA
	17-Mar-2001	15-Sep-2001	PIA1
	21-May-2003	21-Nov-2003	PIA1
	1-Sep-2005	21-Jul-2006	DPIA
	21-Jan-2008		PIA
Phantom B (CVN 70.5)	1-Jul-1998	1-Dec-1998	PIA
Norfolk	1-Jul-2000	1-Dec-2000	PIA
Commission 1984	1-Jul-2002	1-Feb-2005	RCOH
	1-May-2005	1-Jul-2005	PSA
	1-Feb-2007	1-Jul-2007	PIA

ATLANTIC FLEET (Cont.)	Start	Finish	Maintenance
Phantom D (CVN 72.5)	01-Apr-1997	01-Feb-1998	DPIA
Norfolk	01-Oct-1999	01-Mar-2000	PIA
Commisssion 1991	01-Oct-2001	01-Mar-2002	PIA
	01-Oct-2003	01-Aug-2004	DPIA
	01-Mar-2006	01-Aug-2006	PIA
Phantom E	1-Jan-1997	31-Dec-1997	DPIA
Norfolk	1-Jul-1999	30-Sep-1999	PIA
	1-Apr-2001		Inactivation

Maintenance Activities

COH	Complex Overhaul
DPIA	Drydocking Planned Incremental Availability
DSRA	Drydocking Selected Restricted Availability
EDSRA	Extended Drydocking Selected Restricted Availability
ESRA	Extended Selected Restricted Availability
ISRA	Incremental Selected Restricted Availability
PIA	Planned Incremental Availability
PSA	Post Shakedown Availability
RCOH	Refueling Complex Overhaul
SRA	Selected Restricted Availability

APPENDIX B. BASE CASE FLEET COMPOSITION

	Fleet Size									
	16	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**
PACIFIC FLEET										
Constellation/Stennis	Y	Y	Y	Y	Y	Y				
Kitty Hawk/Reagan	Y	Y	Y	Y	Y	Y	Y	Y		
Independence/Constellation/Kitty Hawk	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Nimitz	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Vinson	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lincoln	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Phantom A	Y	Y	Y	Y						
Phantom C	Y	Y								
ATLANTIC FLEET										
Enterprise	Y	Y	Y	Y	Y	Y	Y	Y	Y	
Kennedy	Y	Y	Y	Y	Y	Y	Y			
Eisenhower	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Roosevelt	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Washington	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Phantom E/Truman	Y	Y	Y	Y	Y					
Phantom B	Y	Y	Y							
Phantom D	Y									

APPENDIX C. THIRTY WORLDWIDE NOMINAL CRISIS LOCATIONS

Name	Lat	Long
Adriatic	40.34N	018.45E
Algiers	36.00N	001.30W
Baltic	59.30N	022.00E
Bugo, Philippines	05.45N	128.42E
Colombo	06.57N	079.49E
Dacca, Bangladesh	21.00N	090.00E
Djibouti	11.36N	043.09E
Ecuador	05.15S	082.00W
El Salvador	06.45N	084.19W
French Ghiana	05.00N	049.30W
Haiti	18.33N	072.24W
Hong Kong	22.18N	114.12E
Iceland	64.00N	022.33W
Jarkata	05.30S	106.30E
Karachi	24.49N	067.00E
Korea	34.45N	129.30E
Kuwait	28.45N	049.45E
Lebanon	32.49N	035.00E
Liberia	06.18N	010.49W
Luanda	08.45S	013.14E
Madagascar	18.09S	049.25E
Malacca	02.18N	101.18E
Mombasa, Kenya	04.04S	039.40E
Montevideo, Uruguay	34.54S	056.16W
Sakhalin, Russia	50.00N	143.00E
Santiago, Chile	34.45S	074.00W
Somalia	02.01N	045.19E
Spratley Islands	10.00N	111.30E
Taiwan Strait	25.45N	121.00E
Tripoli	32.49N	018.00E

APPENDIX D. ANALYSIS OF THE PLANNED TIMES BETWEEN THE END OF A MAINTENANCE AND THE START OF THE NEXT DEPLOYMENT

A. DOES OPTIMAL DEPLOYMENT CHANGE THE RESULTING DURATION OF WORK-UP PERIODS?

Although GENCoRE plans deployment cycles following all guidance for minimum work-up durations, there may be some concern that in pursuit of optimized long-term deployment plans, we tend to shave these work-ups to the minimum allowable duration.

In order to assess whether such suspicion is warranted, we treat the various models for prescribing planned deployments as a series of experimental treatments, with the resulting work-up durations pooled for each model as a statistically random sample.

B. A FIRST LOOK AT THE DATA

Table D.1 and Figures D.1 through D.5 provide a statistical summary of the resulting times between the end of a maintenance and the start of the next planned deployment (the resulting durations allowable for work-ups), derived from Modified CoRE and GENCoRE base case deployment plans.

Models	No. of Work-ups	Minimum Months Durations	First Quartile	Median Months Durations	Mean Months Durations	Third Quartile	Maximum Months Durations	Variance	Std. Dev.
Modified CoRE	34	8.4	10.3	11.0	11.8	13.6	20.1	6.5	2.5
Shift-Once	41	8.4	10.0	11.4	11.6	12.1	21.0	6.9	2.6
Shift-All	42	7.0	9.6	11.1	11.5	12.8	22.9	8.7	3.0
Shift-Once-in-Future	40	8.4	9.7	11.3	11.5	12.3	20.1	6.4	2.5
Shift-All-in-Future	40	7.0	9.1	11.3	11.5	12.8	20.1	7.4	2.7

Table D.1. Statistical Summary of Work-Up Period Durations Resulting from Modified CoRE and GENCoRE Base Case Deployment Plans. Observed time units are in months. 25% of the data lie below the first quartile, and 75% of the data lie above it. 25% of the data lie above third quartile, and 75% lie below it.

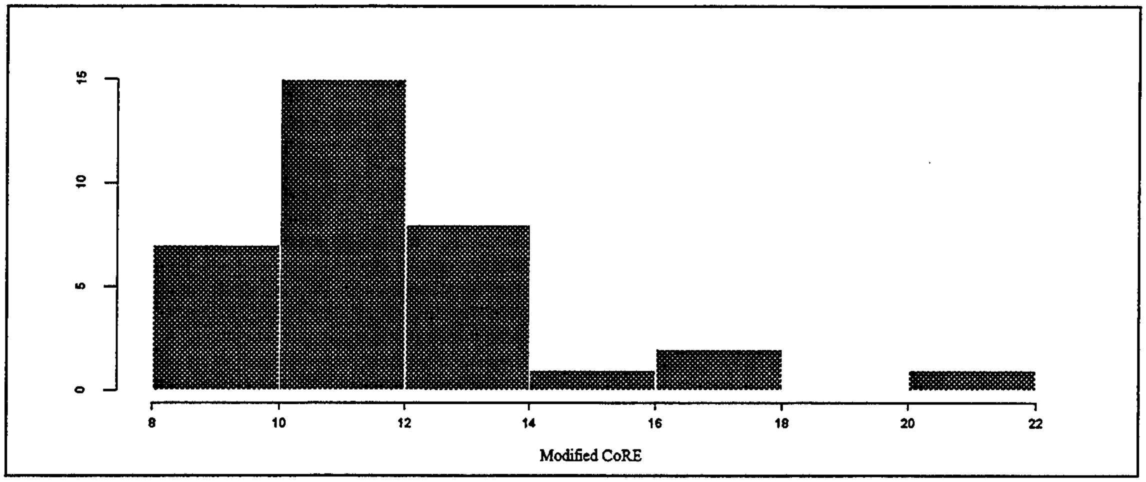

Figure D.1 Histogram of the Durations of Modified CoRE Work-Up Periods. The horizontal axis denotes the resulting times (in months) between the end of a maintenance and the start of the next planned deployment for the Modified CoRE. The vertical axis denotes the number of observations in each interval. For instance, the leftmost bar shows that there are seven work-up periods lasting from 8 to 10 months.

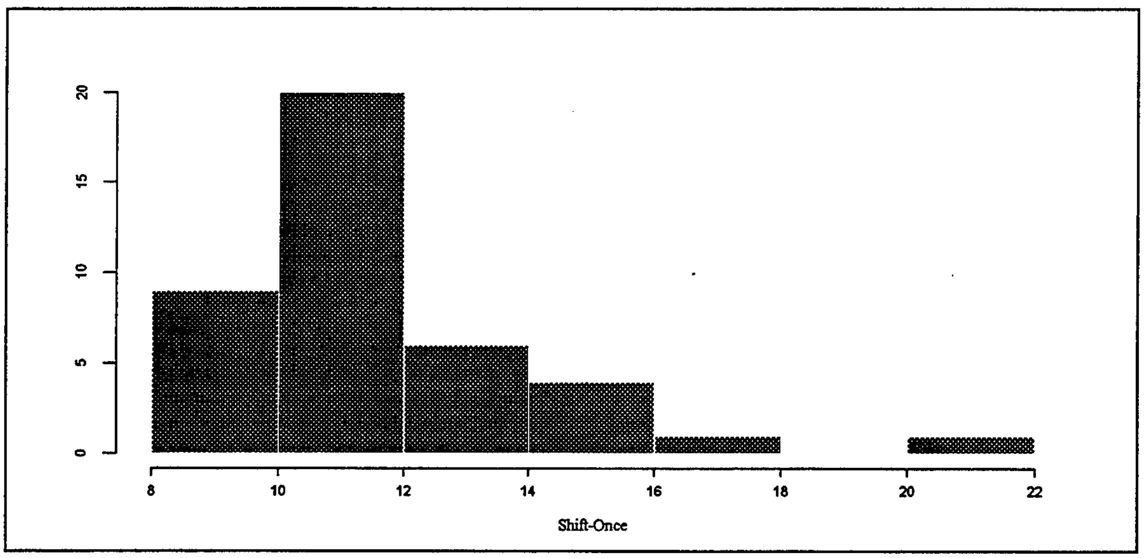

Figure D.2 Histogram of the Durations of Shift-Once Work-Up Periods. The horizontal axis denotes the resulting times (in months) between the end of a maintenance and the start of the next planned deployment for Shift-Once. The vertical axis denotes the number of observations in each interval. For instance, the leftmost bar shows that there are eight work-up periods lasting from 8 to 10 months.

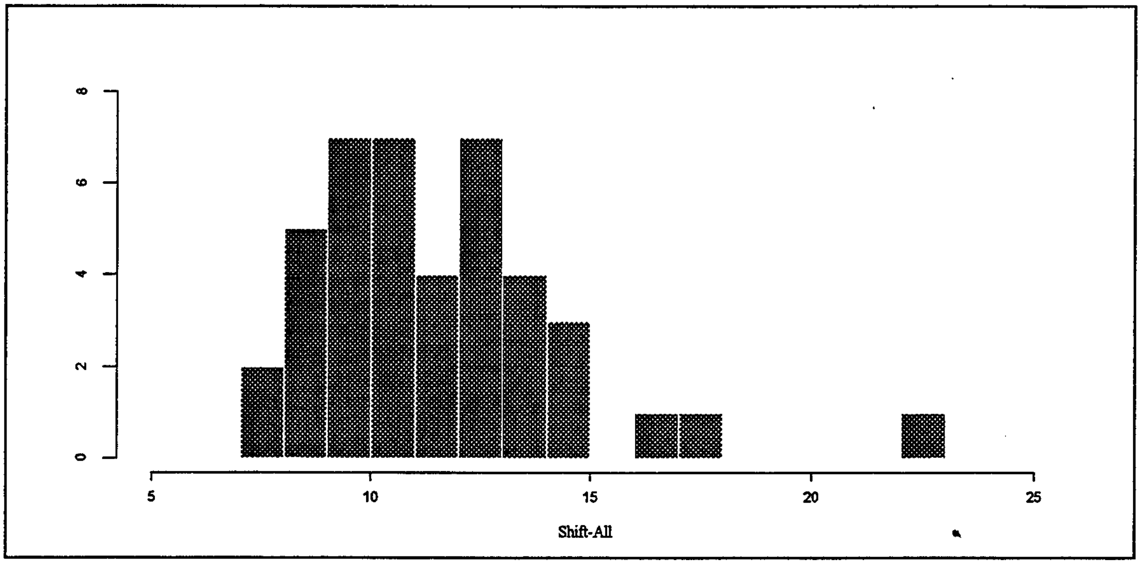

Figure D.3 Histogram of the Durations of Shift-All Work-Up Periods. The horizontal axis denotes the resulting times (in months) between the end of a maintenance and the start of the next planned deployment for Shift-All. The vertical axis denotes the number of observations in each interval. For instance, the leftmost bar shows that there are two work-up periods lasting from 7 to 8 months.

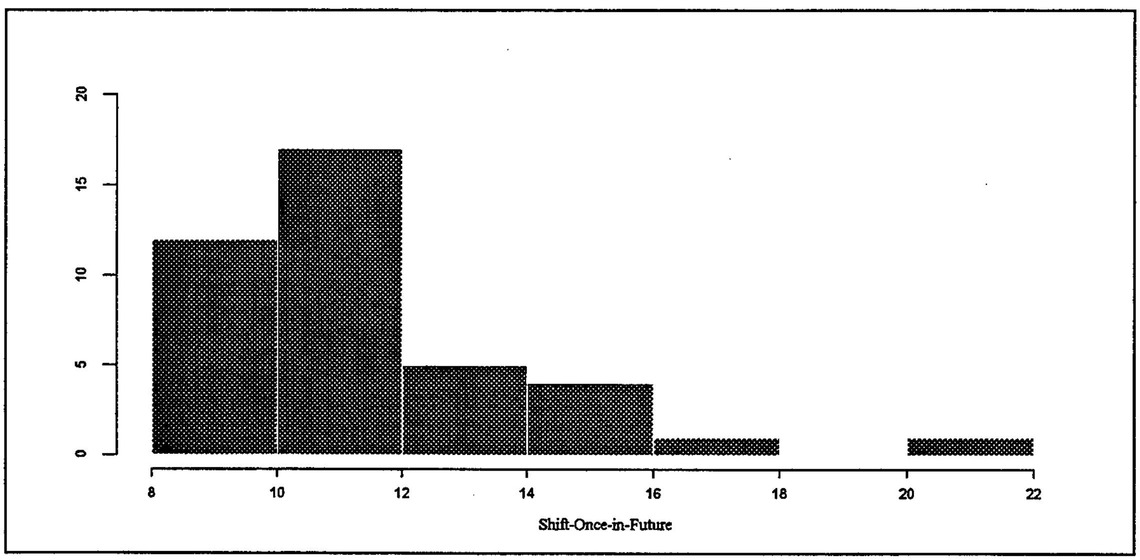

Figure D.4 Histogram of the Durations of Shift-Once-in-Future Work-Up Periods. The horizontal axis denotes the resulting times (in months) between the end of a maintenance and the start of the next planned deployment for Shift-Once-in-Future. The vertical axis denotes the number of observations in each interval. For instance, the leftmost bar shows that there are twelve work-up periods lasting from 8 to 10 months.

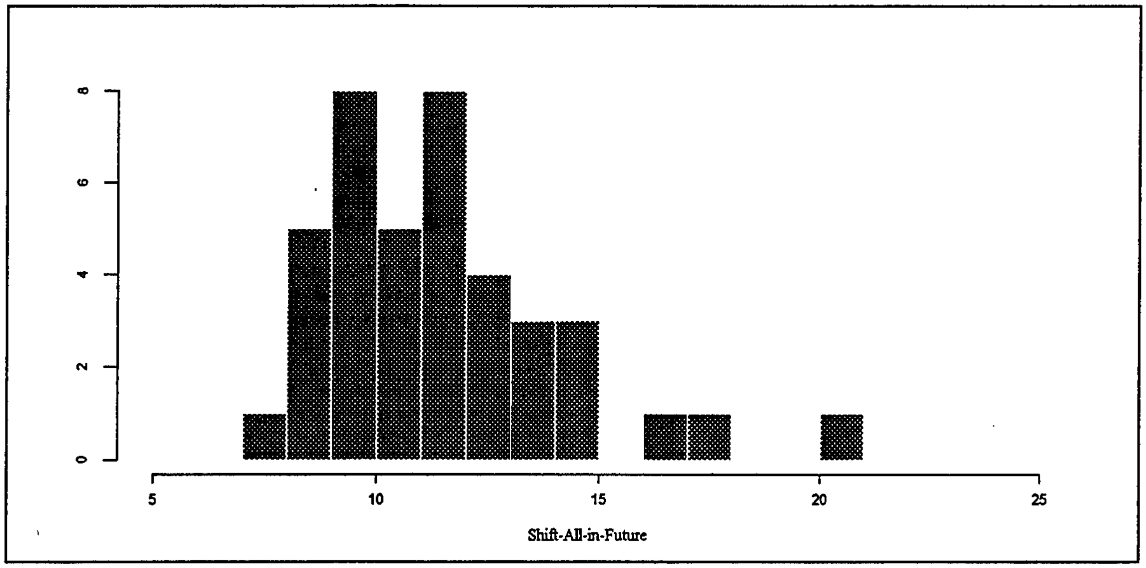

Figure D.5 Histogram of the Durations of Shift-All-in-Future Work-Up Periods. The horizontal axis denotes the resulting times (in months) between the end of a maintenance and the start of the next planned deployment for Shift-All-in-Future. The vertical axis denotes the number of observations in each interval. For instance, the leftmost bar shows that there is only one work-up period lasting from 7 to 8 months.

C. ONE-WAY ANALYSIS OF VARIANCE (ANOVA) TEST

1. Hypothesis

H_o : The models do not have an effect on the duration of resulting work-up periods.

H_1 : The models have an effect.

Or,

$Y_{i,j} = \mu + \alpha_i + \varepsilon_{i,j}$ $\quad j = 1,\ldots,J_i;$ $\quad i =$ Modified CoRE, Shift-Once, Shift-All, Shift-Once-in-Future, Shift-All-in-Future

$H_0 : \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 0$

H_1 : Not all $\alpha_i = 0$

Level of Significance: α =0.05.

2. Graphical Analysis

Figure D.6 provides the mean and median plot and Figure D.7 provides the box plot of the work-up period data for each model. According to the graphical analysis, there are no significant differences between the means, medians, and variances. Therefore, using precise statistical phrasing, we cannot reject the null hypothesis: "H_o: The models do not have an effect on the duration of resulting work-up periods."

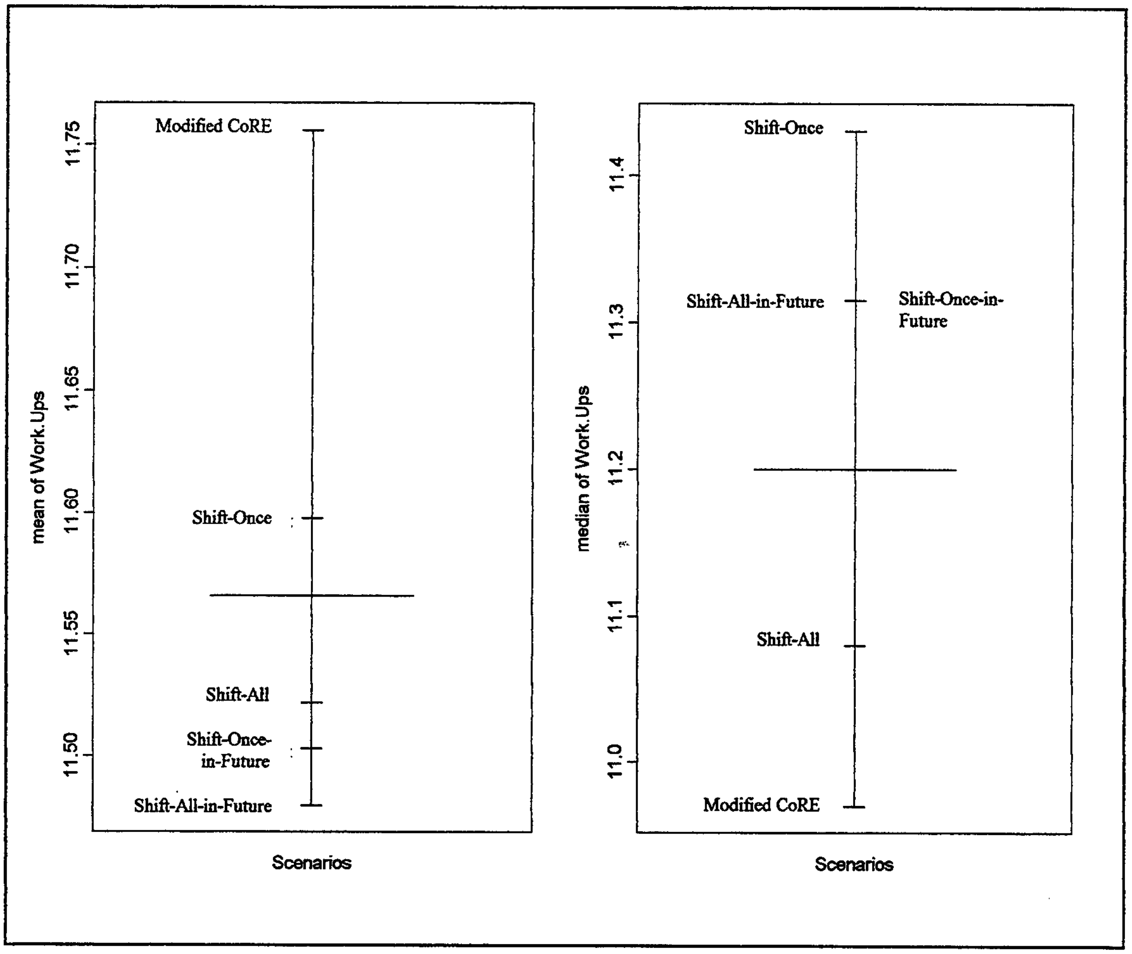

Figure D.6. Means and Medians of the Work-Up Period Durations for Base Case Scenarios Planned with Modified CoRE and GENCoRE. The graph in the left displays the means, and the other one displays the medians of the resulting the times (in months) between the end of a maintenance and the start of the next planned deployment. The graph is drawn with S-Plus [MathSoft 1997].

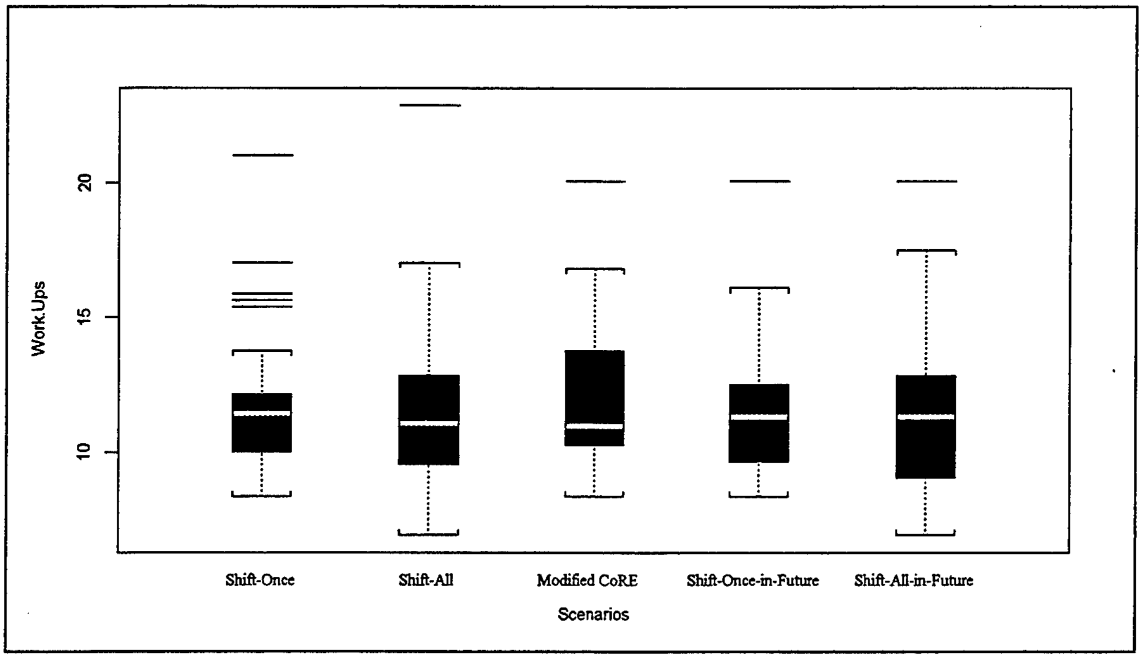

Figure D.7. Box Plots of the Work-Up Period Durations. The graph displays five box plots for each scenario. The vertical axis shows the resulting the times (in months) between the end of a maintenance and the start of the next planned deployment. A central box in the graph extends from the first quartile to the third quartile, so its height equals the interquartile range (IQR). A horizontal line within a box indicates the median. Vertical lines with close edges extend from each quartile to *adjacent values*, values of the last cases not more than 1.5 IQR beyond the quartiles. Farther-out values are called outliers and are graphed individually as vertical lines [Lawrance 1992]. The graph is drawn with S-Plus.

3. One-Way ANOVA Test

Anova Table:

	Df	Sum of Sq	Mean Sq	F Value	P-Value
V1	**4**	**1.808**	**0.451969**	**0.06258272**	**0.9927279**
Residuals	**192**	**1386.613**	**7.221941**		

Because the p-value (smallest value of level of significance that justifies rejection of the null hypothesis) in the ANOVA table is higher than the level of significance, we cannot reject our null hypothesis. Therefore, we cannot conclude that planned work-up periods are affected by our model alterations.

4. Checking The ANOVA Model Assumptions

ANOVA assumes that the residuals are independent and normally distributed with equal variance.

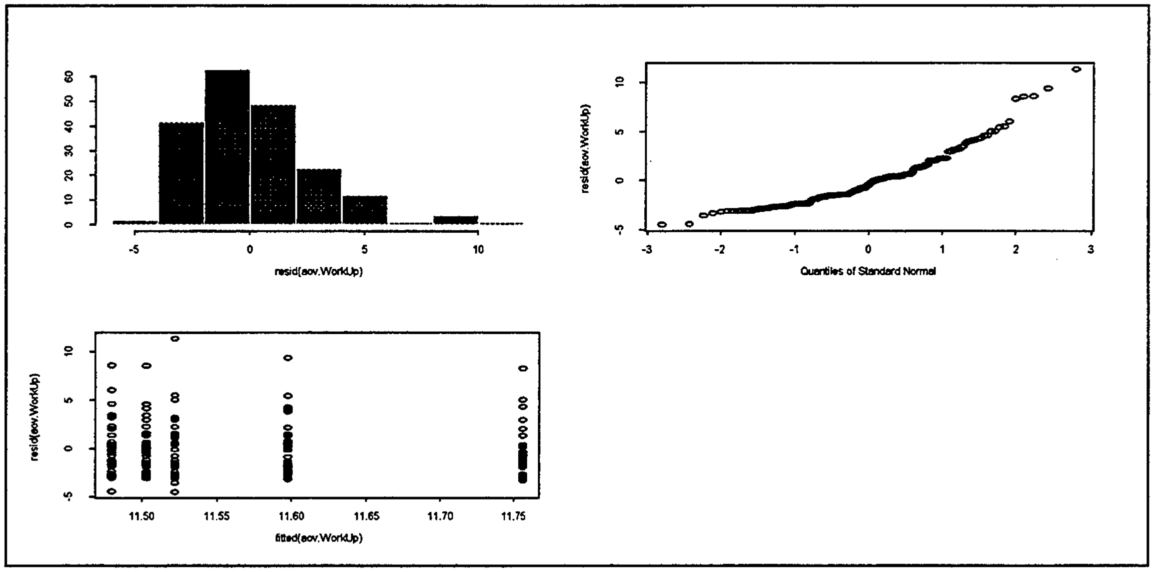

Figure D.8. Diagnostic Plots for the One-Way ANOVA Tests. The upper left graph is a histogram of the residuals, the upper right is a Quantile-Quantile (QQ) plot of the residuals, and the lower graph is a residuals-versus-fit plot.

The histogram and the QQ-plot do not strongly support the normal distribution assumption. However, according to the residuals versus fit plot, we can say that the equal variance assumption holds. The QQ-plot shows that the residuals are derived from a positively skewed distribution.

5. Conclusion of the Statistical Analysis

The normality assumption of the residuals is not strongly satisfied. Overlooking this parametric assumption of homoskedastic normality, we still suggest from the graphed data summaries that shifting maintenance schedules does not significantly affect the resulting times between the end of a maintenance and the start of the next deployment.

APPENDIX E. AN ALTERNATE SET PARTITIONING MODEL

Below is an alternate set partitioning formulation of CoRE. A similar approach can be used for GENCoRE.

Indices:

c	carriers
a	AORs (CENTCOM, EUCOM)
t	periods (in weeks)
$j \in J(c)$	set of *possible schedules* for each carrier c (i.e. schedules that satisfy the operations and maintenance constraints, and provide the period-by-period status of this carrier for the planning horizon)

Data:

A^a_{ctj}	equals 1 if schedule j of carrier c covers AOR a in period t, 0 otherwise
$WEIGHT^a$	weight of coverage in AOR a

Decision Variables (Binary)

y_j	equals 1 schedule j is selected, 0 otherwise
$uncovered^a_t$	equal 1 if AOR a is not covered in period t, 0 otherwise

Formulation

minimize $\sum_{a,j} WEIGHT^a * uncovered_j^a$

subject to

$$\sum_{j \in J(c)} y_j = 1 \qquad \forall\ c \qquad (1)$$

$$\sum_{c,j} A_{ctj}^a * y_j + uncovered_t^a \geq 1 \qquad \forall\ a, t \qquad (2)$$

In the above formulation, the objective is to minimize the uncovered periods in each AOR. Partition constraint (1) ensures that exactly one schedule is selected for each carrier. Constraint (2) expresses that each AOR should be covered in each period. Because this is not feasible for the current carrier force, this constraint is elasticized using a penalized elastic variable for each uncovered period.

Table E.1 shows the size of this set partition for a base case twelve-carrier force.

Number of Constraints		Number of Binary Variables	
Constraint (1)	Constraint (2)	y	Uncovered
14	1,046	222,293	1,046

Table E.1. Model Size for the Set Partitioning Formulation of CoRE with the Twelve-Carrier Force.

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