NAVAL POSTGRADUATE SCHOOL

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THESIS

OPTIMIZING GLOBAL COMBAT LOGISTICS FORCE SUPPORT FOR SEA BASE OPERATIONS

by

Walter C. DeGrange

March 2005

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Second Reader:	Gerald G. Brown

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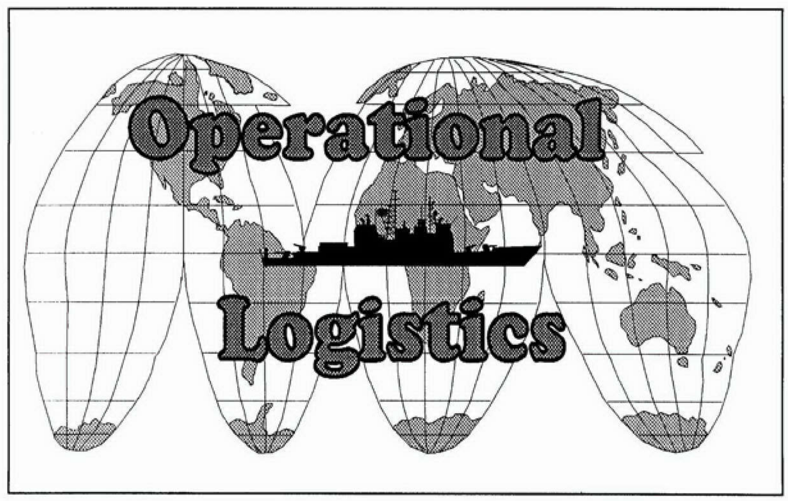
Amateurs discuss strategy,
Professionals study logistics



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The Navy has to choose the number of, and designs for, ships in the Combat Logistics Force (CLF), and then plan how to use them to provide logistical support to our Carrier Strike Groups, Expeditionary Strike Groups, and Seabasing platforms engaged in any variety of worldwide conflicts. CLF ships are very expensive to build and equip and our budget is limited --- we need to make sure the ships we buy and the way we integrate these with our CLF fleet can continue to provide the flexible support our Navy requires. We introduce a decision support tool using a global sea route and resupply base model, and a daily time resolution optimization of CLF ship activities to support any complete, worldwide scenario. Our result is an optimal, face-valid daily operational logistics plan – a schedule of evolutions for each available CLF ship. We discover exactly how to use CLF ships to support a notional, but particularly relevant, preemptive combat scenario with follow-on humanitarian assistance missions. Finally, we study how changing CLF ship numbers and missions can enhance operational effectiveness.

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OPTIMIZING GLOBAL COMBAT LOGISTICS FORCE SUPPORT FOR SEA BASE OPERATIONS

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ABSTRACT

The Navy has to choose the number of, and designs for, ships in the Combat Logistics Force (CLF), and then plan how to use them to provide logistical support to our Carrier Strike Groups, Expeditionary Strike Groups, and Seabasing platforms engaged in any variety of worldwide conflicts. CLF ships are very expensive to build and equip and our budget is limited --- we need to make sure the ships we buy and the way we integrate these with our CLF fleet can continue to provide the flexible support our Navy requires. We introduce a decision support tool using a global sea route and resupply base model, and a daily time resolution optimization of CLF ship activities to support any complete, worldwide scenario. Our result is an optimal, face-valid daily operational logistics plan – a schedule of evolutions for each available CLF ship. We discover exactly how to use CLF ships to support a notional, but particularly relevant, preemptive combat scenario with follow-on humanitarian assistance missions. Finally, we study how changing CLF ship numbers and missions can enhance operational effectiveness.

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LIST OF ACRONYMS AND ABBREVIATIONS

BBLS	Barrels
CFFC	Commander, U.S. Fleet Forces Command (formerly known as CINCLANTFLT)
CG	Guided-missile Cruiser
CLF	Combat Logistics Force
CINCLANTFLT	Commander in Chief, U.S. Atlantic Fleet
CNA	Center for Naval Analyses
CNO	Chief of Naval Operations
CONOPS	Concepts of Operation – Guidance for a particular situation
CONSOL	Consolidation Event – Resupply involving a CLF ship
CSG	Carrier Strike Group
CVN	Aircraft Carrier (Nuclear)
DDG	Guided-missile Destroyer
DD(X)	New Destroyer Class Ship
DFM	Distillate Fuel Marine (NATO F76)
DoD	Department of Defense
D-DAY	Operation's assault commences or hostilities begin
ESG	Expeditionary Strike Group
GAMS	General Algebraic Modeling System
JP5	Naval Aviation Fuel (NATO F44)
LHD	Amphibious Assault Ship
LPD	Amphibious Transport Dock Ship
LSD	Amphibious Dock Landing Ship
MPF(F)	Maritime Prepositioning Ship Future
MPG	Maritime Prepositioning Group
MSC	Military Sealift Command
NPS	Naval Postgraduate School
OPNAV	Office of the Chief of Naval Operations
OPNAV N42	CNO Navy Strategic Mobility and Combat Logistics
OPNAV N81	CNO Navy Assessments
STONS	Short Tons

T-AE	Ammunition Ship
T-AFS	Combat Stores Ship
T-AKE	Advanced Auxiliary Dry Cargo Ship
T-AO	Fleet Oiler
T-AOE	Fast Combat Stores Ship
T-AOE(X)	Fast Combat Stores Ship Future
UNREP	Underway Replenishment
VCNO	Vice Chief of Naval Operations

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EXECUTIVE SUMMARY

The U.S. Navy's ability to react to a multitude of missions in a short period of time is one of its great strengths. Logistically supporting this flexibility is expensive. Combat Logistics Force (CLF) ships, are tasked with the underway replenishment of combatant forces; this capability allows for the continuous and quick deployment of forces for a sustained period of time.

CLF assets are expensive to purchase and maintain. With a price tag of up to $1.2 billion for the new multi-commodity CLF ships determining an appropriate future CLF structure is critical for the execution of the various U.S. Navy missions.

There are many tools available to analyze the CLF. Most are either stochastic simulations or average consumption-rate models. Descriptive models, such as simulation, do not allow us to discover the full potential of the force, and steady-state analyses can easily miss critical details, such as constraints on scheduling, that can significantly impact performance. We use an optimization model, similar to one developed by Borden [2001] and further refined by Givens [2002] and Cardillo [2004] for their analyses of CLF levels that prescribe a near-optimal schedule for shuttle ship consolidations (CONSOLs) supporting a regional combat operation followed by a follow-on humanitarian aid effort.

Our model provides daily fidelity, prescribes CONSOL amounts of each of four commodities (aviation fuel, diesel fuel, ammunition, and stores) by shuttle ship, afloat group, and day. We develop an unclassified, 60-day notional scenario to establish the necessary amount of T-AKE auxiliary cargo-and-ammunition ships, T-AO fleet oilers, and T-AOE(X) multi-commodity ships that can sustain the force. Each of the six afloat groups in our scenario steams independently to an operating area and, on a given day, they combine to form a Sea Base. Each afloat group is also represented by a daily position during its respective transit, presence, and combat phases of deployment. We use logistic planning factors approved by OPNAV N42 for the burn, consumption and expenditure rates, and capacities of the individual naval ships. We track inventory levels each day for each commodity (i.e., ship and aviation fuels, stores, and ordnance). Each afloat group is located daily along with its consumptions for the 60-day excursion. Daily stock levels for four commodities are tracked with penalties for running below safety stock levels.

We formulate our model to maintain safety stock levels, and to encourage early delivery of as much of each commodity as possible. Since all commodity amounts vary from consolidation to consolidation, the best amount of each product to load and deliver is chosen to top off the station ship and its CSG combatants or afloat group, or to deliver as much as possible. The model endeavors to deliver exactly what each afloat group consumes during the entire 60-day hypothetical scenario.

The stationary Sea Base is formed from three Carrier Strike Groups (CSGs), two Expeditionary Strike Groups (ESGs), and one (MPG). We optimize the logistical support of forces transiting to the area of operations, as well as the actual Sea Base after its formation.

We conclude that 3 T-AKE and 4 T-AO ships will be required to support our notional 60-day scenario. We find that fuel drives the scenario during the deployment phase of the operation: All the ships expend fuel at a faster rate while transiting to the area of operations at best possible speed. We observe that stores (i.e., food and medical supplies) drives demand the last twenty days during the humanitarian aid effort. If we allow the reserve levels to increase to 60 percent, the number of required CLF ships increases to 3 T-AKE and 4 T-AO ships. If we use a single fuel to replace both aviation and diesel fuel, the CLF ship requirement drops to 3 T-AKE and 3 T-AO ships. If we use T-AOE(X) ships as shuttle ships instead of station ships our CLF ship requirement is 2 T-AKE, 2 T-AO, and 2 T-AOE(X) ships.

I. INTRODUCTION

Modern naval forces require logistical support at sea to remain effective for long periods of time. The Military Sealift Command (MSC) operates the Combat Logistics Force (CLF) to fulfill this role. CLF ships carry large inventories of fuel, ordnance, food and other supplies from ports to customer ships. The ability to transfer these stores while underway enables naval forces to operate at sea virtually indefinitely. MSC accomplishes this by using shuttle ships to transfer materiel from ports to ships at sea, while station ships resupply within the Carrier Strike Groups (CSGs). CLF ships are either single or multi-commodity ships, and each class of ship has different transit speeds. The CLF gives the U.S. naval forces additional sustainability by acting as an extension of the combatant ship's bunkers, magazines, and storerooms.

The CLF competes with many other Navy and DoD acquisition programs for funding. The new classes of CLF ships are not cheap. Each T-AOE(X) (the future multi-commodity ship) is estimated to cost $1.2 Billion and each T-AKE (two-commodity ship) costs approximately $420 Million in FY09 dollars. The ten-year outlook for acquisition funding is limited as DoD resources are directed toward retooling the military to become lighter and more responsive to the threats in the Global War on Terrorism.

Currently the Chief of Naval Operations (CNO) Navy Strategic Mobility and Combat Logistics (OPNAV N42) relies on many agencies using different tools to provide CLF analysis. Various products from other sources use either descriptive theater-level operating-area simulations or spreadsheet-based average cycle time resupply models. We become concerned when "average model" results are applied with confidence to combat scenarios that have highly-variable and geographically-dispersed demands for fuels, ordnance, and stores. These models are not capable of addressing a majority of OPNAV N42 questions, especially those concerned with feasible, efficient use of CLF assets in demanding scenarios.

We have developed an integer programming model of CLF sustainment of strike groups in almost any user-defined scenario. Given daily positions and consumption of each of four commodities (diesel fuel, aviation fuel, stores, and ammunition) for every afloat group in the scenario, our model prescribes the loading, movement, and replenishments of CLF shuttle ships with daily time resolution to maintain sufficient inventories of all four products for each afloat group in the model. See [Borden, 2001], [Givens 2002], [Cardillo, 2004] for the development and evolution of the model.

We analyze a demanding 60-day scenario involving an intense preemptive combat operation immediately followed by a humanitarian assistance support mission. Our results provide an optimal CLF configuration to meet these Navy future requirements and suggest important alternatives for effectively employing these ships.

We have used planning factors and concepts of operations (CONOPS) provided by experts at OPNAV N42, and they can use our results to gain a better understanding of the size and configuration of the CLF required for future logistical support.

A. BACKGROUND

1. The Current CLF Plan

The CLF is the foundation for naval operational logistic support of forces afloat. Recapitalizing the CLF fleet for meeting its future commitments is an important and difficult problem because funding is limited.

Tentatively scheduled for completion by FY15, this last phase of building CLF infrastructure is critical and will determine the future logistical capabilities for supporting the Navy of tomorrow as shown in Figure 1. The planned recapitalized CLF will consist of four classes of ships; T-AO 187 (fleet oilers), T-AOE 6 (fast multi-commodity support ships), T-AOE(X) (fast multi-commodity support ships future), and T-AKE (ammunition and stores). Their cargo capacities for the four basic commodities we consider and their speeds are summarized in Table 1.

CLF CLASS	DFM (BBLS)	JP-5 (BBLS)	STORES (STONS)	AMMUNITION (STONS)	SPEED (KNOTS)
T-AKE	0	0	3,971	1,916	17
T-AO	109,000	65,400	0	0	16
T-AOE or (X)	120,000	61,200	1,111	2,593	27

Table 1. CLF Ship Capacities and Speeds [Futcher, 2004]

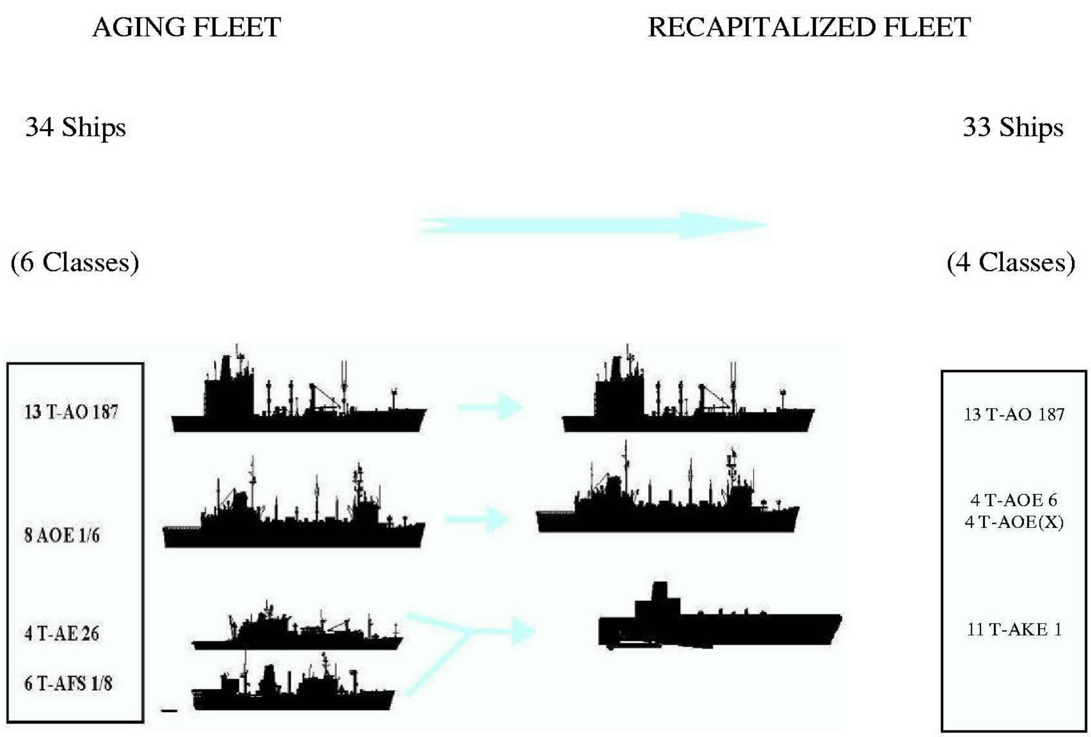

Figure 1. Current CLF Transition Plan.

The current vision of the future Combat Logistics Force Composition. Future CLF ship numbers provided by OPNAV N42. [derived from Lamboni, 2002]

Two questions that continue to be prominent in each budgeting cycle are: 1) how much CLF do we need, and 2) what design types are ideal and economical for meeting our future military requirements? These questions strike at the heart of planning. The CNO's surge plan stresses speed and the ability to reconfigure to the mission while closing to the objective. As an example, the former Amphibious Readiness Group (ARG) has been expanded into the Expeditionary Strike Group (ESG) with the addition of combatants, and now warrants further examination for CLF support. Lastly, the concept of operations for seabasing is under development and brings the question of logistical support for the multitude of ships and units making up the sea base into the foreground.

2. Concerns about Current Planning

A number of analysis of alternatives efforts and other CLF studies have produced this vision for the future CLF. The Center for Naval Analyses (CNA), the fleet, and the Naval Postgraduate School (NPS) are examining if the CLF is sized to meet wartime and peacetime presence requirements based on recent strategic planning guidance and Navy fleet response plans. The required number of T-AOE(X) and T-AKE ships continues to be the central issue. A CLF force of 32 ships by the year 2015 is considered by some to be excessive. Major studies in progress, such as the logistics concept of operations for seabasing, may not only justify this CLF fleet size, but possibly point out a need for more.

B. OBJECTIVES

The objective of this thesis is to size the CLF appropriately for any given scenario. The fictional scenario we provide determines the minimum number of CLF ships necessary to sustain multiple strike and maritime prepositioning groups (MPGs) deployed worldwide transitioning from a peacetime to wartime posture and then continuing to support follow-on humanitarian assistance operations. We are seeking to identify any redundancy in the CLF fleet or clearly indicate any shortfalls in logistical support.

II. A MODEL OF COMBAT LOGISTICS FORCE EMPLOYMENT

A. WHY CHOOSE AN OPTIMIZATION MODEL?

We prefer a prescriptive optimization model because we are interested in discovering the most effective, feasible way to employ CLF ships, which may not always be obvious when other analysis tools are used.

CNA used a steady-state analysis (or "average model") in its analysis of alternatives and statistical presence ratios for the time period between Operation Enduring Freedom and Operation Iraqi Freedom [CNA, 2003] to determine future CLF levels for the Navy's fleet response plan of six and eight CSGs. Their models ignore geographical and temporal operations and therefore overestimate the efficiency of the CLF in their scenarios.

Commander-in-Chief, Atlantic Fleet (CINCLANTFLT) used a simulation model for its recent CLF analysis [CINCLANTFLT, 2001]. Simulation is also an option, perhaps an overused one for CLF modeling, but descriptive simulation models require that we suggest alternatives to evaluate. Descriptive simulation models are often developed with specific operational plans or policies in mind, which can introduce certain biases and may distort the analysis in undesirable ways. While simulation is easier to implement, and admits stochastic variation of parameters, we see little to recommend introducing randomness until we ensure that our deterministic scenario and the planning factors used appear reasonable, determine what the core CLF fleet size should be, and specify where and how it should be used.

Our optimization model provides analyses independent from previous major CLF studies. No other organization is currently using optimization to look at future CLF fleet structure. No other organization is currently looking at the specific CLF support required for seabasing, from deploying from various ports and locations to forming the Sea Base and resupplying it. We seek insight, not complexity, and although mathematical optimization, by its nature, requires more mathematics than simulation, its power appeals here.

B. ASSUMPTIONS AND NOTATION

Throughout this document we refer to each Carrier Strike Group (CSG), Expeditionary Strike Group (ESG), and Maritime Prepositioned Group (MPG) as simply a group. A group is completely defined by the ships (both combatants and CLF station ships) that it comprises.

Our model is primarily influenced by the assumption that daily time resolution is adequate for a 60-day notional scenario and for all CLF movement and CONSOL scheduling. Finer resolution would add extra layers of complexity, straining our ability to generate credible consumption data, and coarser resolution would obscure too many essential details.

We assume deterministic, preplanned group movements, and deterministic CLF ship movements. All CLF movement is based on the standard formula: distance equals speed multiplied by time.

We assume each shuttle ship executes only one CONSOL before proceeding back to port to replenish. Although at first this assumption may appear unrealistic, we find the shuttle ship utilization to be above 80% for the majority of the CONSOL events in the time horizon of our scenario. This indicates the shuttle ships will not have enough stores to provide an adequate second CONSOL, and therefore will almost always return to port to prepare for a fully-loaded CONSOL event. The few cases where shuttle ship utilization is below 80% are all due to "topping off" CONSOLs en route to the theater. No other afloat group is in range for the CLF ship to perform a second CONSOL in each of these situations. This assumption is a restriction to our model, but it does not seem to make a difference. These operationally conservative *planning* assumptions reduce the theoretical CLF capability, but adhere to textbook practices for operating CLF station and shuttle ships. [Miller, 1992]

We assume that each ship in the afloat groups enters our scenario loaded with 100% of all commodities, and that each CLF shuttle ship can be optimally pre-positioned for its first consolidation visit to a strike group or MPG.

We assume that each aggregate commodity (e.g., "stores") in our model represents loads that fill demand exactly for all of the individual commodities (e.g., razors, food, toilet paper) it represents. This is especially important when considering different types of ammunition; the resolution of the model does not allow tracking of individual munitions types.

We assume that reloading a CLF shuttle ship requires two days, regardless of where or what we load. Borden [2001] and Givens [2002] use the very conservative estimate of three days. We consider two days a conservative estimate that accounts for potential backlog of commodities and ships at advance bases, "fog of war" delays, and a maximum reload event: a full ordnance load onto a T-AKE and a full resupply of stores. The current average reload time spent in port by a forward-deployed CLF shuttle ship supporting combat operations is between one and two days [Morgan, 2003]. We also assume that all in-port replenishment for the shuttle ships is 100%. All commodities required to replenish the shuttle ship completely are always present in the port.

We represent each group as single entity, viewed as an aggregate customer representing the individual ships that compose it. We assume that the groups in our scenario can aggregate smoothly into a larger single Sea Base entity. This preserves visibility of their logistic state, and ensures that our CONSOL visits deliver quantities that the afloat groups can receive.

The commodity capacity and consumption rates of each afloat group are based on the total capacities and consumption of all constituent platforms. Because of that, some fidelity is lost. But, the differences in the stock levels between individual platforms in a group tend to remain small. Although some additional fidelity is lost in assuming a single CONSOL visit to an individual group, we also assume that the shuttle ships will replenish the correct commodities with the appropriate ships of that group requiring resupply. These underway replenishments will occur on the same day, which implies in CLF language that "service station" (vice "delivery boy") ship UNREPs will be required for all of these underway replenishment events. [Miller, 1992]

The only groups that are represented without a station ship are those that will always be replenished directly by a shuttle ship, and never expend or require ordnance for our modeling purposes. This assumption is consistent with planning factor guidance provided by OPNAV N42. [Futcher, 2004]

Lastly, we assume that the CLF and combatant ships are virtually invincible during our hypothetical scenario. Our ships do not sink, take themselves out of service, or limit their combat or resupply capability because of enemy damage or engineering failures during the 60-day scenario. Our Navy's recent history on the high seas during combat has been that we seize and maintain naval superiority quickly, defend our naval forces quite well, and lose relatively little underway time during deployments due to maintenance failures. The expected capabilities of the opponent in this notional scenario to inflict damage directly on our naval forces are also assumed to be minimal.

C. MODEL MODIFICATION

We require the modeling of support for both transiting ship groups and the aggregated Sea Base. Our requirement leads us to modify model of Cardillo [2004] to include a mechanism that allows all ships from specified groups on a given day to merge to form the Sea Base. The Sea Base first appears on day 17 in our scenario, and represents the total capacities and the sum of current commodity levels of all groups of ships it comprises. We cannot treat every group individually at this point due to the reduction in utilization of the shuttle ships that would ensue. Aggregation of the Sea Base allows our model to effectively utilize CLF capacity and therefore properly optimize the amount of CLF support required.

SHIP CLASS	NUMBER
CVN	3
CG	5
DDG	5
DD(X)	2
LHD	2
LPD	2
LST	2
MPF(F)	8
Total	29

Table 2. Number of ships, by type, in the Sea Base

We modify the model to combine all capacity levels and current commodity levels from day 16 and assign the sums to the Sea Base on day 17. The Sea Base is made up of 3 CSGs, 2 ESGs and one MPG, with the breakdown by ship type shown in Table 2. Our aggregation of these ships' capacities and inventories allows more realistic utilization of CLF ships with the model assumption of only one CONSOL before resupply.

The models in Givens [2002] and Cardillo [2004] use an objective function (10) that penalizes inventory shortfalls and rewards CONSOLs. We modify the objective function to encourage the model to CONSOL the maximum amount of inventory to the forces earlier in the scenario. (See Appendix 1 for a full explanation of the model used Givens [2002] and Cardillo [2004, p. 27]) Our modified objective function is:

$$Max \sum_{s,ag,d,c|hitOK_{s,ag,d}} f(d) * penalty_c CONSOL_{s,ag,d,c}$$

$$- \sum_{ag,d,c} penalty_c SHORTAGE_{ag,d,c} - \sum_{ag,d,c} negpenNEGINV_{ag,d,c} , \qquad (10')$$

where $f(d)$ is defined for day d as:

$$f(d) \equiv \frac{|days| - d}{|days|}$$

and $|days|$ is defined as the number of days in the scenario. The new objective function (10') consists of three terms. The first rewards CONSOLs by volume and day, where the base reward on the first day of the scenario is equal to the penalty, by commodity, for falling below safety stock levels ($penalty_c$), and this reward decreases with each successive day until the reward for a CONSOL on the last day is zero, regardless of its volume. This is the key difference between our objective and (10), which did not place a premium on earlier deliveries. The second term captures the penalties for falling below safety stock levels, by volume. The final term is similar to the second, except that the unit volume penalty (*negpen*) for falling below zero inventory is much larger than any of the other penalties, to encourage the model to maintain feasible inventories.

D. MEASURES OF EFFECTIVENESS

We want to estimate the fewest number of shuttle ships that is able to sustain the deployed battle force with fuel, stores, and ordnance in our notional scenario. In our scenario, we want to minimize the amount of and the duration of shortfalls below afloat group safety stocks.

If we are able to keep all inventories above safety sock levels, then we prefer to maximize the volumes of commodities delivered to the CSG's station ship and the ESG and MPG entities, thereby "topping them off" whenever possible. We want to maximize the number of days separating CONSOLs. When we plan a consolidation visit by T-AKE and/or T-AO shuttle ships, we want the visit to be worthwhile. I.e., we want to make as few visits as possible, and make the most of each visit.

The stationary Sea Base in our scenario forces us to look for new methods of measuring optimality. Past theses using this model have considered feasibility the determining factor for calculating appropriate CLF level. Namely, whether the CLF ship can CONSOL with the group is determined by the relative speed of both entities. This was an appropriate measure since the scenarios were supporting only transiting CSGs or ESGs. These models struggle to find feasible sequences of CONSOLs due to these limitations. In contrast, the Sea Base is stationary. Feasibility is not an issue, but efficiency and safety stock levels are.

For this seabasing scenario, we measure the utilization of each CONSOL by taking the volume of each commodity transferred and dividing it by the total capacity for that commodity on the CLF ship delivering it. We would like to keep this ratio as high as possible because each CLF ship can only CONSOL once before returning to port to resupply. A CONSOL of zero to fifty percent is considered poor utilization, and we color-code this event red (dark in grayscale) in our tabular displays. Likewise, fifty one to seventy five percent is considered marginal and colored yellow (gray in grayscale), and seventy six to one hundred percent is considered good utilization and is color-coded green (light in grayscale).

As an example, Table 3 presents the utilization data for all shuttle ships in our base scenario. We see each CONSOL represented as a line in the table, where, reading across, we see the shuttle ship, the day on which the CONSOL occurrs, the location (latitude and longitude) of the CONSOL, and the percent of total commodity capacity transferred to the customer ship. Clearly, as we add CLF ships, the utilization numbers will drop for each individual CLF ship.

Shuttle Ship	Day	Lat	Long	DFM	JP5	Class I	Class V
take01	d03	35.75	23	0%	0%	0%	100%
take02	d02	1.27	103.83	0%	0%	0%	100%
tao02	d01	1.27	103	58%	0%	0%	0%
take04	d16	0.6	56.5	0%	0%	23%	0%
tao07	d16	0.6	56.5	61%	84%	0%	0%
tao01	d16	-1.5	44.1	61%	84%	0%	0%
take02	d16	-3.7	41.4	0%	0%	12%	0%
tao02	d16	-3.7	41.4	100%	3%	0%	0%
tao06	d15	-3.17	42.21	100%	3%	0%	0%
take03	d07	-6.1	63.95	0%	0%	6%	0%
take03	d16	-3.7	40	0%	0%	27%	0%
tao03	d07	-6.1	63.95	22%	1%	0%	0%
tao04	d16	-3.7	40	100%	8%	0%	0%
take05	d16	-3.7	40	0%	0%	23%	0%
tao03	d16	-3.7	40	0%	84%	0%	0%
tao05	d16	-3.7	40	45%	0%	0%	0%
take03	d28	-3.7	40	0%	0%	100%	100%
take03	d50	-3.7	40	0%	0%	100%	0%
take04	d31	-3.7	40.8	0%	0%	31%	79%
take04	d47	-3.7	40.8	0%	0%	100%	100%
take04	d59	-3.7	40.8	0%	0%	100%	0%
take05	d28	-3.7	40	0%	0%	11%	35%
take05	d40	-3.7	40	0%	0%	100%	32%
take05	d53	-3.7	40.8	0%	0%	100%	0%
tao03	d29	-3.7	40.8	100%	100%	0%	0%
tao03	d42	-3.7	40	100%	72%	0%	0%
tao03	d60	-3.7	40	100%	100%	0%	0%
tao04	d29	-3.7	40.8	100%	100%	0%	0%
tao04	d47	-3.7	40.8	100%	100%	0%	0%
tao04	d60	-3.7	40	100%	6%	0%	0%
tao05	d29	-3.7	40.8	32%	100%	0%	0%
tao05	d42	-3.7	40	33%	0%	0%	0%
tao05	d58	-3.7	40	100%	0%	0%	0%
tao06	d28	-3.7	40	100%	38%	0%	0%
tao06	d41	-3.7	40.8	100%	100%	0%	0%
tao06	d54	-3.7	40	0%	100%	0%	0%
tao07	d32	-3.7	40	67%	100%	0%	0%
tao07	d52	-3.7	40	100%	100%	0%	0%

Table 3. Example of Shuttle Ship Utilization Data

For instance, the ship labeled 'take03' makes three CONSOLs, one on day 07, one on day 16, and one on day 28. On day 07, it is at latitude -06.10, longitude +063.95, and transfers 22% of its DFM and 1% of its JP5. This is a very low utilization CONSOL. Red (dark) cells represent CONSOLs of no more than 50 percent shuttle ship capacity. Yellow (gray) cells represent larger CONSOLs no more than 75 percent. Green (light) cells show CONSOLs larger than 75 percent.

Next we look at the commodity inventory levels for the customer ships. Our goal here is to keep inventory levels above reserve levels. The most desirable situation is when all inventories remain above reserve levels, and exhibit no long-term downward trends. We refer to this as an "even trend". Figure 2 illustrates even trend inventories for the Sea Base. Reducing the number of CLF ships will negatively impact inventory levels, and, at some point, will render an even trend infeasible.

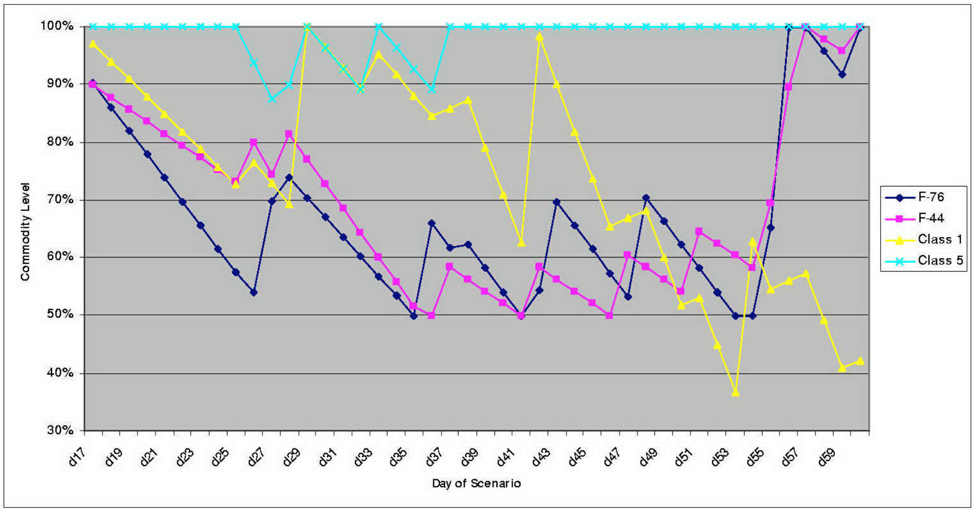

Figure 2. Example of "even trend" Commodity Levels for the Sea Base

For instance, we observe an "even trend" for F-76 (DFM), F-44 (JP-5), and Class 5 (Ammunition). We observe a "decreasing trend" for Class 1 (Stores)

The final step is to consider both indicators together, as summarized in Figure 3. If the utilization is high (green) and the commodity levels exhibit an even trend, then the number of CLF ships is nearly optimal, in the sense that adding CLF ships would just lower the utilization of all CLF ships, and removing CLF ships would introduce a decreasing trend in some inventory levels. If the utilization is red and the commodity level trend is even then the number of CLF ships is too high. If the utilization is green and the commodity level trend is decreasing then the number of CLF ships is insufficient to maintain commodity levels above the reserve amount. This last option is not a real possibility. In this case, the "wasted" capacity could be re-tasked to produce higher inventories. Even if the utilization started out red, it would become green as the CLF ships deliver large quantities of material to make up the shortages.

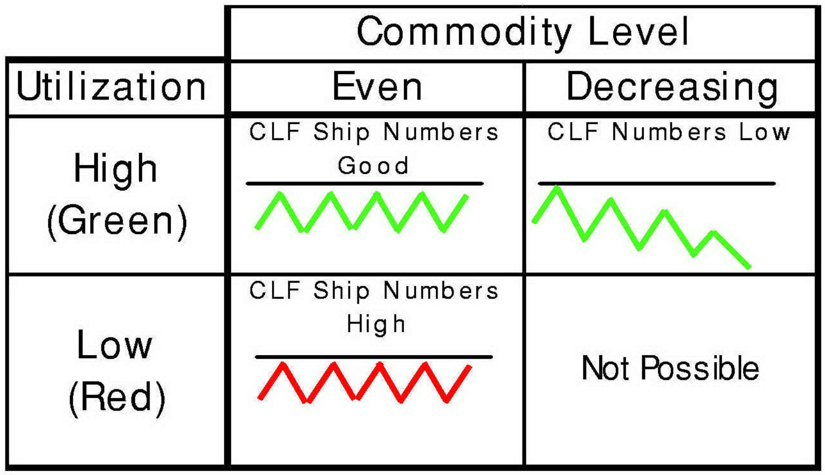

Figure 3. CLF performance matrix used to determine desirable CLF ship levels

E. NAVIGABLE SEA-ROUTE NETWORK

Our CLF shuttle ships (T-AKEs and T-AOs) can navigate in the tracks of the afloat groups. They can also part company with a customer group at any time, sail to a port, reload, and depart for the next required CONSOL or multiple- underway replenishment event. Because each CONSOL's day and location are outputs of our model, rather than inputs, we require a model of all navigable world sea routes, to support the possible CLF movements. Figure 4 is a display of the node locations and regional node-to-node arcs that represent our simple world sea-routes network. This is a navigable, connected network model that allows shuttle ships to sail on all the major sea routes in the world. The model can easily be adapted for operations concentrated in other parts of the world, and is easily extended to allow for higher resolution. This model has been refined and improved throughout the evolution of our optimization research.

We define a set of nodes worldwide; each node is either an at-sea waypoint or a port at which we can reload our shuttle ships. Waypoints include the Strait of Gibraltar, Indian Ocean, etc., and ports include San Diego, Augusta Bay, Sasebo, etc. (see Figure 4). Our sea-route model includes, by implication, a node for each daily position of each group track in our scenario. We identify adjacent node pairs in order to navigate between them on great-circle routes.

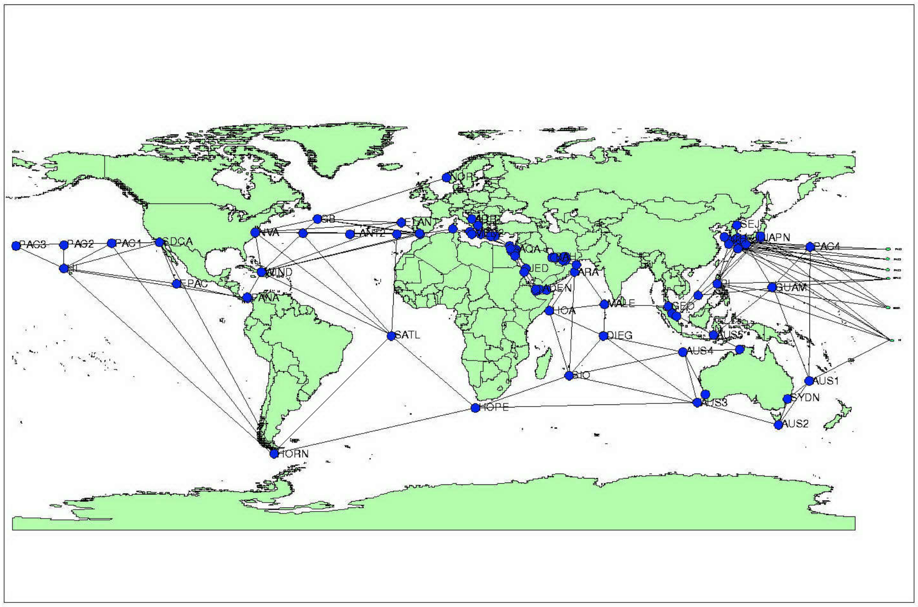

Figure 4. World Sea Routes Nodes and Arcs

A simple world network depicts minimum node locations required for transit in the open sea (waypoints), reloading at ports, and establishing operational areas in major world regions of interest. The network is composed of 83 nodes, 156 fast arcs, 10 slow arcs, and 24 ports; details are provided in Appendixes B and C. The network is constructed in three phases. First, a node is defined at each port and at a number of at-sea waypoints frequently used by ships navigating worldwide. A "fast arc" connects each pair of these nodes between which full-speed transit is feasible. A "slow arc" connects some node pairs (e.g., canal entrances) with a fixed transit time. Next, any group's daily position not collocated with one already in the network is added, with an arc connecting each of these successive daily positions. Finally, wherever a fast arc and/or group's track arc intersect some other such arc, we induce a waypoint, and add neighboring arcs. The result is a worldwide network that our shuttle ships use while moving between advance bases and the scenario's afloat groups.

The time required to transit between any adjacent pair of nodes is mathematically determined by speed and great-circle distance, except for a few distinguished "slow arcs" for which a fixed transit time is provided manually. Slow arcs include, for instance, the Suez Canal and the Malaccan Strait. (See Appendix C, Table 2 for a complete list of slow transit arcs.)

Given this network of nodes and adjacent arcs, with transit times for each, we solve for the shortest paths between all pairs of nodes using the Floyd-Warshall algorithm. (see Ahuja, et. al. [1993], p.144). Surprisingly, we require relatively few nodes to represent the transit from Norfolk, via the Mediterranean and Red Seas, to the North Arabian Sea. If needed, our sea route model also expresses operational restrictions at each node. For example, CONSOLs are precluded in canals and other restricted passages, such as in the Malaccan Strait or Suez Canal.

The result is a navigable, connected (i.e., we can navigate, eventually, from any node to any other node worldwide) world sea-route model. A workable model with decent fidelity in the Indian, Northern Atlantic, and Pacific Oceans, (where we can expect to operate) can be prepared in about one hour. A much higher-resolution model of all the world's navigable waters can be finished in several hours. Only the former is necessary here.

The movement of all ships in our model is deterministic. The movement of each group is confined to planned routes similar to those prepared by a ship's navigation team (see Figure 5). Shuttle ships are free to move anywhere along a navigable world sea route that we create by combining our base network with the afloat group tracks. If a node is not connected to another node by an arc, then a shuttle ship cannot travel directly between the two nodes. Even though this requires us to build dense networks in key areas of operation, it prevents the shuttle ships from planning to travel over land. The core model we implement is basically the same one used by Borden [2001], Givens [2002], and Cardillo [2004] but includes the necessary refinements for our scenario and specific questions.

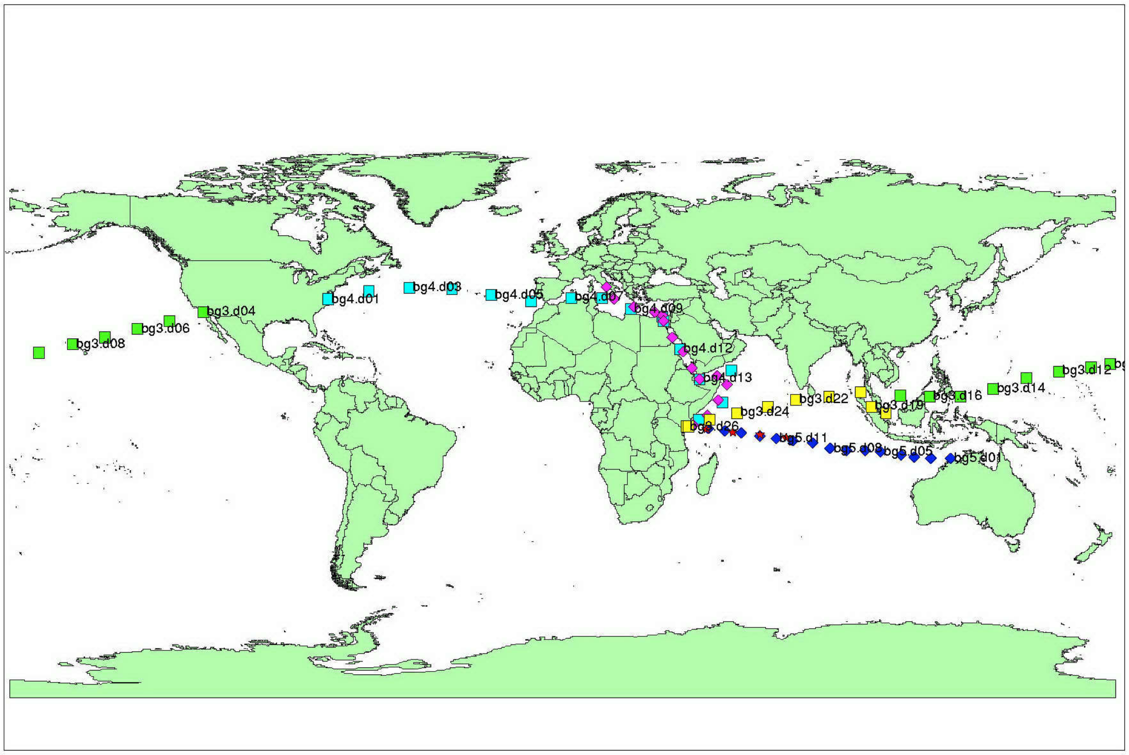

Figure 5. CSG, ESG, and MPG Scenario Tracks

This is an illustration of our tracks of three CSGs, two ESGs, and one MPG to the area of operations off East Africa. CSG 1 departs San Diego and transits the Pacific and Indian Oceans. CSG 2 departs Norfolk and transits the Atlantic Ocean, Mediterranean Sea, and Indian Ocean. CSG departs Singapore and transits the Indian Ocean. ESG 1 departs Darwin, Australia and transits the Indian Ocean. ESG 2 departs Naples, Italy and transits the Mediterranean and Indian Oceans. MPG 1 departs Diego Garcia and transits the Indian Ocean. Afloat group latitude and longitude track data is in Appendix D.

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III. SCENARIO DEVELOPMENT

We extend the decision support tool provided by Borden [2001], Givens [2002], and Cardillo [2004] embellishing the associated global sea-route network and resupply base model. We also develop an unclassified, realistic scenario involving the number and types of CLF ships required to sustain a foreseeable amount of deployed battle forces for that situation at sea.

We also use OPNAV N42 official logistics planning factors [Futcher, 2004]. Using these planning factors permits comparison with results from other CLF studies. Each group component of our scenario is given a daily position during transit, presence, and combat phases of deployment.

By assuming that each ship in each group starts its deployment fully loaded, and then by deducting, for every group, on every day, a date-specific consumption of stores, ordnance, and fuel, we forecast daily commodity inventory levels and calculate any shortages when these levels fall below desired minimum percentages of total group capacities. Based on these forecasted inventories, we know when a group requires a consolidation of cargo from the T-AKE and T-AO shuttle ships, and how much cargo it can receive.

A. COMBAT LOGISTICS FORCE

Operationally, the CLF employs its ships in two ways. For functional simplicity and most of our purposes in modeling the CLF, a CLF ship is categorized as either a station ship or shuttle ship. Station ships are T-AOEs, and are part of a CSG. Station ships receive fuel, stores, and ordnance from shuttle ships, and redistribute those commodities to the carrier and her escorts using both connected replenishment via standard Navy underway replenishment equipment and vertical replenishment from embarked helicopters that are used to transport stores to the decks of the customer ships. Shuttle ships have historically been single-product ships that transport supplies from forward logistics sites and deliver them to a station ship in the operational theater. In textbook situations, the shuttle ship delivers as much (or all) of its cargo capacity as the station ship can receive, which in turn stores and delivers its cargo to its combatant customers.

Following OPNAV N42's CLF transition plan, a relatively young T-AO 187 class of fleet oilers, and an even younger class of T-AOE 6 triple-product ships will be retained. We use the data provided by Table 1 to assign CLF class characteristics to each of the CLF ships in our model.

B. SEA BASING

The Sea Base allows operations including the staging and rapid movement of land forces ashore.

> *Sea Base*: an inherently maneuverable, scalable aggregation of distributed, networked platforms and organizations – capable of receiving deploying forces and supporting deployment of those forces. [Clark, 2002]
>
> *Seabasing:* the rapid deployment, assembly, command, projection, reconstitution, and re-employment of joint combat power from the sea, while providing continuous support, sustainment, and force protection to select expeditionary joint forces without reliance on land bases within the Joint Operating Area (JOA). These capabilities expand operational maneuver options and facilitate assured access and entry from the sea. [Department of Defense, 2004]

From the definitions, we deduce the importance of two items: access to bases, and the platforms of the sea base. Access can be limited by political decisions by states, such as the decision of Turkey to deny use of their seaports during Operation Iraqi Freedom. Access can also be limited by to employment of enemy weapons, including weapons of mass destruction. The ability to respond rapidly and in areas of limited access provides the genesis of expanded seabasing. The sea base can project and support forces ashore in addition to its inherent strike capability.

We concentrate our efforts on the assets to maintain the required fuel, ordnance, and dry cargo flow to the sea base in support of the forces operating from and within the sea base. The sustainment of sea base-to-shore movement has been examined by other organizations such as OPNAV N70 (Warfare Integration And Assessment) and the Marine Corps Combat Development Command [Stewart, Futcher, Macht, 2005].

C. LOGISTICS PLANNING FACTORS

In his seminal work on naval logistics, Eccles [1950, pg. 37] states: "All logistics planning is based on usage factors which are average figures computed in many various ways." Eccles' factors have come to be called "logistic planning factors." These factors are tabulations that yield consumption rates as simple functions of platform type, number of personnel, and/or individual ship activity. All planning factors are based on experience or usage data.

Naval ships are designed and constructed with self-sufficiency at sea in mind. Commodities such as dry provisions will last for quite some time, and their usage rate does not change much from combat to peacetime operations. It is practical to express the reciprocal of fuel and dry stores usage rates in terms of "days of supply," rather than hours. This offers a time fidelity that is easier for logistic planners to work with, and mimics the time-phased force deployment data for an entire operation plan. Propulsion fuel must be replenished every few days, and its usage is a function of how a particular combatant ship is maneuvered. Both fuel and ammunition are replenished as frequently as practical during combat. Usage rates for aviation fuel and ordnance are difficult to determine because they are driven by the operational tempo, rather than just calendar days.

Dry stores replenishment is usually considered the least demanding of the three major commodities, as long as a consistent source of supply is available. Dry stores or DOD Class I (i.e., subsistence items) are of particular importance to us in our scenario. The humanitarian aid effort executed from day 37 until day 60 assumes the use of dry stores such as food and medical supplies. We calculate usage rates for the humanitarian relief by multiplying the consumption numbers needed to support combat ashore from the Sea Base by four. Historical information in this area is very difficult to find and depends greatly on the situation and the amount of U.S. Navy involvement. Our numbers estimate supporting approximately 200,000 people (consuming 5.5 lbs. of food per day) for twenty four days. [Futcher, 2004]

OPNAV N42 solicited much of the current and past data and studies available on fuel burn rates to arrive at reasonable figures for surge and sustainment phases of an operation for each ship type in Table 4.

Consumption - Peacetime

		CLASS III	CLASS III	CLASS III
		POL Petroleum, Oil, Lubricants	POL Petroleum, Oil, Lubricants	POL Petroleum, Oil, Lubricants
Hull Type	Hull Name	DFM Diesel Fuel Marine Barrels (Bbls) Capacity	DFM Diesel Fuel Marine Barrels (Bbls) Consumption	DFM Diesel Fuel Marine Barrels (Bbls) Days of Supply (DOS)
CG	Cruiser - Guided Missile	15,032	757	19.86
CVN	Carrier - Nuclear	0	0	NA
DDG	Destroyer - Guided Missile	10,518	646	16.28
DDX	Destroyer - Next Generation	15,777	723	21.82
FFG	Frigate - Guided Missiles	4,286	304	14.10
LCS	Littoral Combat Ship	3,428	232	14.78
LHD	Amphibious Assault Ship (Multi-Purpose)	42,976	1,070	40.16
LPD	Amphibious Transport Dock	23,750	528	44.98
LSD	Dock Landing Ship	19,150	446	42.94
MPF	Maritime Preposition Fleet	29,000	1,200	24.17
SSN	Submarine - Nuclear	0	0	NA
T-AKE	Dry Cargo/Ammunition Ship	28,039	407	68.89
T-AO	Oiler	109,059	343	317.96
T-AOE (X)	Fast Combat Support Ship - Next Generation	120,000	960	125.00
TSV	Theater Support Vessel	2,100	233	9.01

Table 4. Example of Logistics Planning Factors for Daily Usage [Futcher, 2004]

As of July 2004, OPNAV N42's collaborative work with many different agencies resulted in approval of a complete set of these planning factors. See Cardillo [2004] for a discussion of the planning factors used here. This important development allows decision makers to compare the results of very different planning efforts much more easily.

D. CAPACITIES BY SHIP TYPE

We treat each strike group and MPG as a single entity consisting of the capacities of all of its ships requiring support. Each shuttle ship is also a single entity and the amount it can transfer is limited to the available station ship capacity within a CSG, and the cumulative capacities of the ships within an ESG or MPG. The ship capacities used in our notional scenario are not the published capacities normally found in design specifications. OPNAV N42's transferable capacities for CLF ships and available combatant capacities were determined after reviewing multiple sources for modeling purposes and are standards for all CLF related models for the Navy (see Table 5). The chosen transferable capacities consider many factors, such as ship stability, customer demand for specific products, damage and/or spoilage, safety from fuel spillage, and weapon retrograde, all which limit the total cargo amount that can be delivered regardless of the gross capacities of the individual ships.

		CLASS III	CLASS III	CLASS I, VI, IX	CLASS V
		POL Petroleum, Oil, Lubricants	POL Petroleum, Oil, Lubricants	Subsistence Personal Demand Items Repair Parts	Ammunition
Hull Type	Hull Name	DFM Diesel Fuel Marine Barrels (Bbls)	JP5 Jet Propulsion 5 Barrels (Bbls)	Stores Short Tons (Stons)	Ordnance Short Tons (Stons)
CG	Cruiser - Guided Missile	15,032	475	68	94
CVN	Carrier - Nuclear	0	74,642	1,710	1,765
DDG	Destroyer - Guided Missile	10,518	475	55	48
DDX	Destroyer - Next Generation	15,777	713	23	225
LHD	Amphibious Assault Ship (Multi-Purpose)	42,976	9,952	520	391
LPD	Amphibious Transport Dock	23,750	6,700	195	88
LSD	Dock Landing Ship	19,150	1,144	140	38
MPF	Maritime Preposition Fleet	29,000	28,000	500	750
T-AKE	Dry Cargo/Ammunition Ship	28,039	23,450	3,971	1,915
T-AO	Oiler	109,059	64,880	0	0
T-AOE (X)	Fast Combat Support Ship - Next Generation	120,000	61,230	1,111	2,593

Table 5. CLF Ship Transferable and Combatant Ship Available Capacities

These capacities have been determined from multiple sources and represent reasonable estimates for planning. [Futcher, 2004]

Even though the T-AKE has some fuel storage capacity and the T-AO has some stores capacity for emergencies, we do not feel these should be included in our *planning* model. The T-AKE shuttle ship capacities we use for stores and ordnance are significantly skewed. The capacities for these commodities on each T-AKE are potentially adjustable. Our fixed amount favors the stores transfer capacity over ordnance by just over a two-to-one weight ratio. We use these values because of the humanitarian aid modeled in the scenario.

E. SCENARIOS

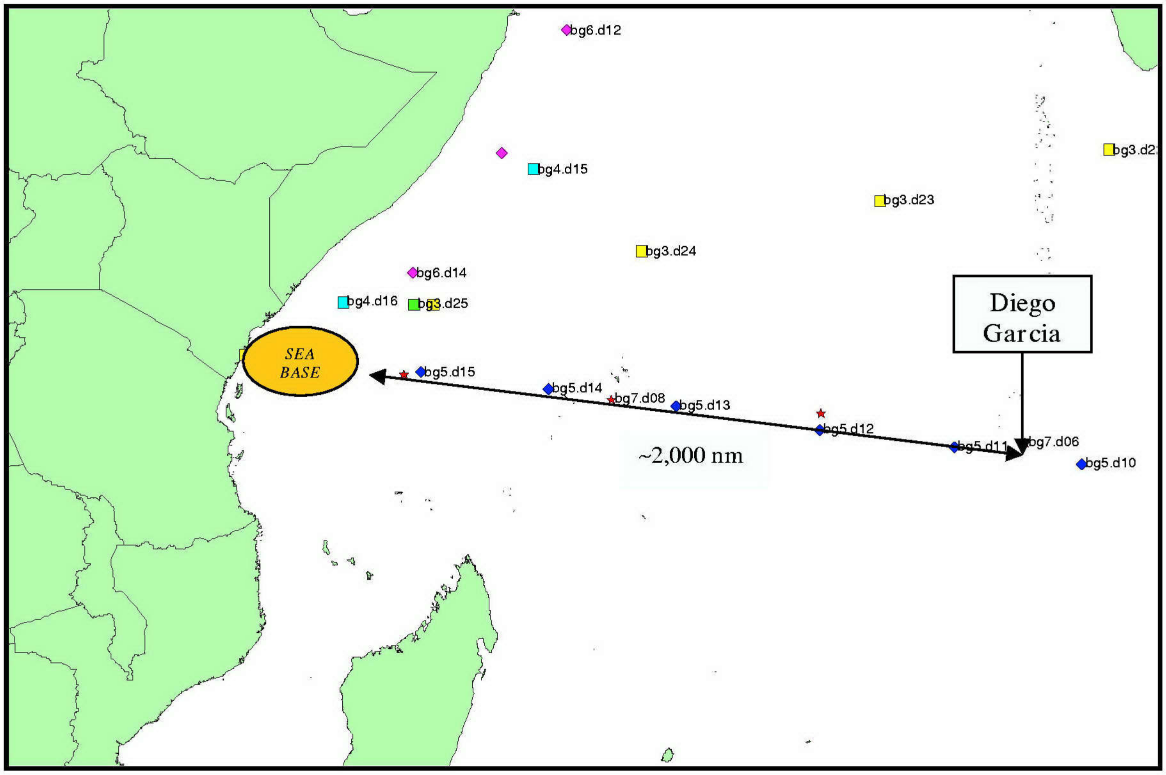

Figure 6. Area of Operations for Scenario

We develop a base scenario and three modified scenarios for evaluating different CONOPs for CLF support of the Sea Base. All of our scenarios are based on a 60-day fictional event that starts with the alerting of forces to contend with a possible conflict situation in the eastern coast area of Central Africa. The events escalate into a medium intensity conflict followed by a humanitarian aid effort. This situation is illustrative, rather than predictive.

The Naval force responding to the crisis consists of three CSGs, two ESGs and one MPF(F) squadron. One CSG is deployed outside the Mediterranean Sea at the start. The additional two CSGs surge from Norfolk, Virginia, and San Diego, California, respectively. One ESG is deployed in the Mediterranean near Naples, Italy and the second ESG is located near Darwin, Australia. The MPF(F) squadron departs from Diego Garcia on day four. Upon arrival the MPF(F) and other Naval assets begin assembling a Sea Base.

All ship groups steam at best possible speed towards the crisis area of operations and are assigned the "surge consumption factor". The surge consumption factor takes into consideration the high fuel usage for maintaining increased speed. The forces use the "peacetime consumption factor" after arrival to the operating area and before hostilities commence, representing the consolation of forces and preparation for combat operations. Combat operations are high intensity for three days and then shift to combat sustainment levels for the next seven days. Forces shift back to peacetime usage rates with elevated stores consumption representing the follow-on humanitarian operations.

Our base scenario examines the number of CLF ships required to support forces that have a 50-percent reserve level. The second scenario changes the reserve level to 60 percent. Our third scenario explores the use of a single fuel instead of using both DFM and JP-5. We investigate changing the role of T-AOE CLF ships from station ships to shuttle ships in the forth scenario.

1. Scenario 1: Base Scenario

We assemble ships into CSGs, ESGs, MPG, and finally a Sea Base and then apply OPNAV N42 certified logistics planning factors over the duration of each operational phase. Reserve levels for all commodities are set to 50 percent of total capacity (afloat group plus station ship capacities).

A typical (CSGs 1 through 3) CSG in this study consists of a nuclear aircraft carrier (CVN), a T-AOE 6 or T-AOE(X) class station ship, one CG 47 *Ticonderoga* class cruiser, and two DDG 51 *Arleigh Burke* class destroyers. Nuclear fast attack submarines that are a part of any type of strike group are considered self-sufficient and not modeled to receive CLF support.

An ESG in our model is comprised of one LHD 1 *Wasp* class amphibious assault ship, a LPD 17 *San Antonio* class transport dock ship, one LSD 41 *Whidbey Island* class dock landing ship, a CG, one DDG, and one DD(X) class destroyer ship.

A notional MPG consists of eight potentially different maritime prepositioning future ships and one supply ship serving as an afloat sustainment base for the group.

"Best speed" is defined as the fastest speed of the slowest ship in the strike group; in this case, it is 26 knots as limited by the station ship for the CSG, and 20 knots as limited by the amphibious ships for the ESG. For the MPG ships, 12 knots is used as the transit speed from Diego Garcia to theater to allow for the fly-on assembly of MPG components prior to arrival. In our scenario, a surge speed of 20 knots is used for the MPG. We assume that an ESG and MPG will patrol their theaters at 12 knots for presence phase operations. During major combat, the consumption rates of aviation fuel and ordnance are much higher as the aircraft fly a maximum number of sorties each day, and the CVN steams at 16 knots in the operating area, while the remaining CSG ships operate at their respective surge speeds. For sustained combat, the CSG will patrol its area at 14 knots and expend ordnance and aviation fuel at sustainment rates.

2. Scenario 2: 60 Percent Reserve Level

This excursion explores the same phasing of ships as the base scenario while increasing the reserve levels of all customer ships to 60 percent. We seek the number of CLF ships required to support the force here.

3. Scenario 3: Single Fuel

We examine the use of a single fuel taking the place of both DFM (NATO designator F-76) and JP-5 (NATO designator F-44). The Navy is currently developing a single fuel for all its ships and aircraft, to reduce additional workload for carrying separate fuels. Additionally this increases the operational flexibility. The tankers (T-AOs, T-AOEs, T-AOE(x)s) will no longer have to determine two fuel requirements for each customer. This will allow for optimal use of a fuel load and avoid issues such as running out of JP-5 before DFM. Consumption rates for fuel are increased 2% to represent a richer fuel mixture and higher burn rates for most conventionally-powered surface ships.

4. Scenario 4: T-AOE Shuttle Ships

This excursion examines using T-AOEs in a shuttle ship role instead of their normal role as a station ship. The T-AOE class enjoys a ten-knot speed advantage over both the T-AKE and T-AO. This means it can cover approximately 240 more nautical miles a day. T-AOE fuel capacity is equivalent to the T-AO but the stores and ammunition capacity are 40% and 50%, respectively of those of the T-AKE.

In practice, a station ship can function as a shuttle ship only while its CSG customer is transiting to the operational theater. U.S. Central Command is a good example of a combatant command that has a relatively small and easily-congested ocean theater. Commander, Task Force 53 is often directed to assume operational control of an incoming station ship by ordering it to detach from its CSG. The station ship then replenishes not only its former CSG customers, but also other U.S. Navy and North Atlantic Treaty Organization ships present. It may also function as a shuttle ship at times. This is a common occurrence. Immediately before Operation Iraqi Freedom began, the USS CAMDEN (AOE 2) was nearly eight months into a deployment, but was authorized to remain empty of commodities and function solely as a shuttle ship to service the five carrier battle groups in U.S. Central Command's theater for Operation Iraqi Freedom's 30-day campaign. [Morgan, 2003]

This scenario removes the T-AOEs from the CSGs resulting in lower commodity capacities. The T-AOEs are then used in the role of shuttle ships. Our removal of the station ships results in the forces arriving to the operational area with decreased commodity levels. We compensate for this by prepositioning CLF assets in the Mediterranean Sea and in Singapore. The T-AKE and T-AO pair in both locations can top off the ships in transit. Our additional support of the units in transit allow for the ships to arrive at approximately the same levels at the other three scenarios and allows us to compare the scenarios more thoroughly.

F. SCENARIO ANALYSIS

In each of our scenarios, we attempt to find the most appropriate CLF level by choosing initial number of CLF ships, running the model with those CLF ships, and observe the utilizations and inventory levels that result. If we find an "even trend" with low utilization we remove a CLF ship (red utilization). If we find a "decreasing trend" with high utilization then we add a ship (declining inventory). If we find an "even trend" with high utilization we have the "optimal" mix of CLF.

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IV. RESULTS, AND INSIGHTS AND CONCLUSIONS

A. RESULTS

SCENARIO	T-AKE	T-AO	T-AOE(X)	TOTAL CLF
1. 50% Reserve	3	4	-	7
2. 60% Reserve	3	6	-	9
3. Single Fuel	3	3	-	6
4. T-AOE Shuttle Ships	2	2	2	6

Table 6. Optimized CLF Shuttle Ship Numbers for each Scenario

We discover interesting results with each scenario (see Table 6). Scenario 1, is our base scenario, and establishes the number of CLF ships required to maintain support throughout.

Scenario 2 explores the same factors as the base scenario with a 60 percent reserve levels instead of 50 percent.

Scenario 3 looks at the effect of Navy using a single fuel instead of the two separate fuels it currently uses. We combine the capacities of DFM and JP5 into one commodity for all ships.

Scenario 4 examines changing the role of T-AOEs from station to shuttle ships. T-AOEs' speed is approximately ten knots faster than either the T-AKE or the T-AO. This means it can support ships over a greater distance. The T-AOE can use its speed advantage to cover the four thousand nautical mile round trip to Diego Garcia in 37% less time (8.1 days compared to 11.8 days, including two loading days).

1. Base Scenario

The optimization model for Scenario 1 has 32,305 constraints and 10,527 variables, and solves in less than two minutes on a 2-MHz personal computer using

GAMS [Brooke, Kendrick, Meeraus, Raman, 1998] with CPLEX solver [ILOG, 2003]. We find that three T-AKE and four T-AO shuttle ships conducting 27 CONSOLs are required to support the force.

					Amounts				Utilization Rates per CONSOL			
CLF Ship	Day	Lat	Long	Customer	DFM (kbbls)	JP-5 (kbbls)	Class I (Stons)	Class V (Stons)	DFM	JP5	Class I	Class V
tao04	d12	-6.8	63.9	ESG 1	91.7	1.3	0.0	0.0	84%	2%	0%	0%
tao02	d15	-3.17	42.21	ESG 2	109.0	1.6	0.0	0.0	100%	2%	0%	0%
take01	d15	-3.7	40.8	CSG 3	0.0	0.0	870.6	0.0	0%	0%	22%	0%
take02	d16	0.6	56.5	CSG 1	0.0	0.0	928.6	0.0	0%	0%	23%	0%
tao03	d16	0.6	56.5	CSG 1	83.2	48.3	0.0	0.0	76%	74%	0%	0%
take03	d16	-1.5	44.1	CSG 2	0.0	0.0	928.6	0.0	0%	0%	23%	0%
tao01	d16	-1.5	44.1	CSG 2	83.2	48.3	0.0	0.0	76%	74%	0%	0%
take01	d27	-3.7	40.8	Sea Base	0.0	0.0	3971.4	1728.0	0%	0%	100%	90%
tao02	d28	-3.7	40	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
tao04	d28	-3.7	40	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
take03	d29	-3.7	40.8	Sea Base	0.0	0.0	3186.6	1370.0	0%	0%	80%	72%
tao01	d29	-3.7	40.8	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
take02	d31	-3.7	40.8	Sea Base	0.0	0.0	835.8	1012.0	0%	0%	21%	53%
tao03	d31	-3.7	40.8	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
take01	d40	-3.7	40	Sea Base	0.0	0.0	3971.4	1915.6	0%	0%	100%	100%
tao02	d41	-3.7	40.8	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
tao04	d41	-3.7	40.8	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
tao01	d42	-3.7	40	Sea Base	109.0	64.8	0.0	0.0	100%	99%	0%	0%
take02	d43	-3.7	40.8	Sea Base	0.0	0.0	3971.4	614.4	0%	0%	100%	32%
tao03	d44	-3.7	40	Sea Base	99.5	20.5	0.0	0.0	91%	31%	0%	0%
take03	d49	-3.7	40.8	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
take01	d52	-3.7	40	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao02	d54	-3.7	40	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
tao04	d54	-3.7	40	Sea Base	109.0	37.1	0.0	0.0	100%	57%	0%	0%
take02	d55	-3.7	40.8	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao01	d55	-3.7	40.8	Sea Base	57.3	10.3	0.0	0.0	53%	16%	0%	0%
tao03	d59	-3.7	40.8	Sea Base	100.1	41.0	0.0	0.0	92%	63%	0%	0%

Table 7. Scenario 1 CLF CONSOL Amounts and Utilization Data

For example, tao03 CONSOLs with CSG 1 on day 16. The utilization is 76 percent for DFM and 74 percent for JP-5 indicating a green utilization for DFM and yellow for JP-5.

Both ESGs are replenished for fuel en route as shown in Table 7. We expect this since ESGs do not have the additional inventory provided by a station ship. On day 12 ESG 1 is topped off with 91.7 kbbls of DFM and on day 15 ESG 2 is topped off with 109 kbbls of DFM. These en route replenishments are important and allow both ESGs to arrive to form the Sea Base at 76 and 92 percent inventory level for DFM.

The MPG does not receive any fuel replenishment and arrives at the Sea Base with a 55-percent DFM inventory level. The CSG 1 and 2 forces are topped off with fuel on day 16. We observe in Figure 7 that the Sea Base begins with a 75-percent level for DFM. The DFM level does decrease until it drops below the 50 percent reserve level on day 28. After one day below the reserve level CONSOLs from tao2 and tao4 begin to increase DFM inventory. The other Sea Base commodity inventory levels never approach the 50-percent reserve level and are support with the CLF ship types and numbers.

We observe the utilization of all CLF ships replenishing the Sea Base remains high throughout the scenario. Together with the even trend indicated in Figure 7 from day 38 to the end, we can use our measures of effectiveness to support this as an optimal number of CLF ships.

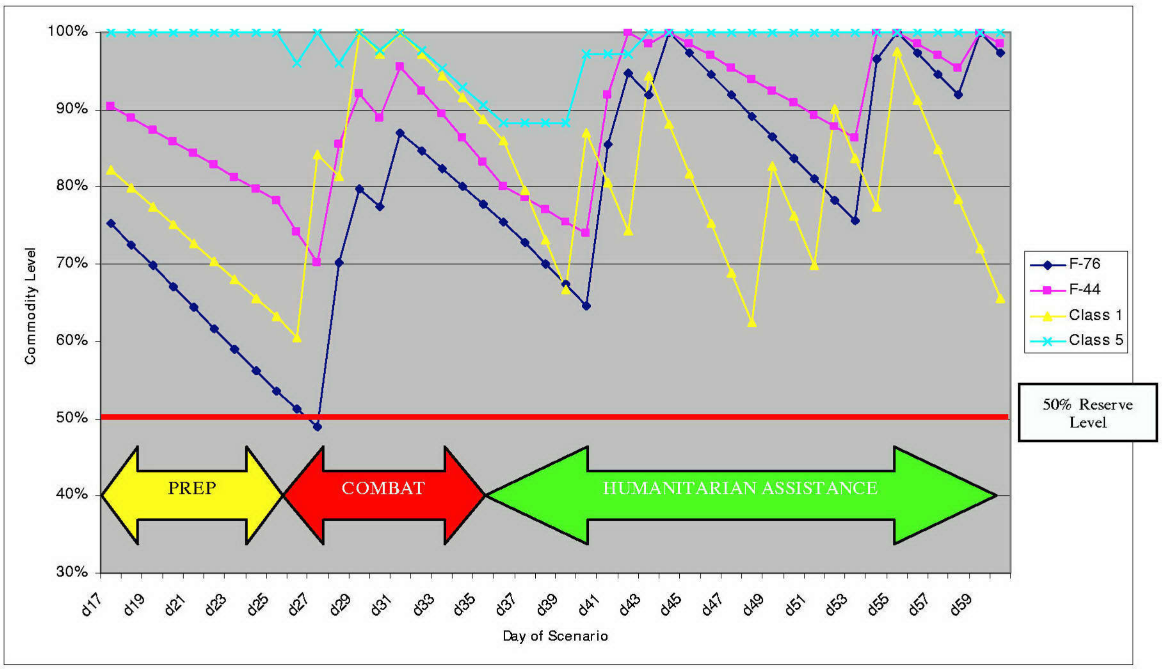

Figure 7. Scenario 1 Sea Base Commodity Usage and Resupply Levels

2. 60 Percent Reserve Scenario

The optimization model for Scenario 2 has 39,853 constraints and 12,143 variables, and solves in just over 2 minutes on a 2-MHz personal computer. Three T-AKE and six T-AO shuttle ships conducting 33 CONSOLs are required to support and sustain the force at 60-percent reserve levels.

We observe Scenario 3 exhibits more CONSOLs and requires more ships than the other scenarios. The increase of the reserve level to 60 percent stresses our ability to deliver fuel more than our stores or ammunition replenishing capacity. We again use three T-AKEs and observe that neither the stores nor ammunition inventory levels approach the 60-percent reserve level during the entire scenario.

Utilization for T-AOs supporting the Sea Base is very low (See Table 8). Five out of the last six T-AO fuel CONSOLs are under 50-percent utilization. The challenging task of keeping the forces above 60 percent at the beginning of the scenario sets the number of T-AOs high, resulting in extra capacity during the final week.

					Amounts				Utilization Rates per CONSOL			
CLF Ship	Day	Lat	Long	Customer	DFM (kbbls)	JP-5 (kbbls)	Class I (Stons)	Class V (Stons)	DFM	JP5	Class I	Class V
take03	d09	33.65	21.95	CSG 1	0.0	0.0	522.4	0.0	0%	0%	13%	0%
tao04	d09	-8.9	81.2	CSG 1	68.8	1.0	0.0	0.0	63%	1%	0%	0%
tao05	d12	20.9	37.95	CSG 2	62.4	36.2	0.0	0.0	57%	55%	0%	0%
take02	d15	-3.7	40.8	CSG 2	0.0	0.0	870.6	0.0	0%	0%	22%	0%
tao02	d15	-4.4	47.3	ESG 1	45.9	0.6	0.0	0.0	42%	1%	0%	0%
tao06	d15	-3.17	42.21	ESG 1	109.0	1.6	0.0	0.0	100%	2%	0%	0%
take01	d16	0.6	56.5	ESG 2	0.0	0.0	928.6	0.0	0%	0%	23%	0%
tao01	d16	-3.7	40	CSG 3	57.7	48.6	0.0	0.0	53%	74%	0%	0%
tao03	d16	0.6	56.5	CSG 3	83.2	48.3	0.0	0.0	76%	74%	0%	0%
take03	d24	-3.7	40	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
take02	d27	-3.7	40.8	Sea Base	0.0	0.0	2757.1	1728.0	0%	0%	69%	90%
tao05	d27	-3.7	40.8	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
tao04	d28	-3.7	40	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
tao06	d28	-3.7	40	Sea Base	109.0	60.8	0.0	0.0	100%	93%	0%	0%
tao02	d29	-3.7	40.8	Sea Base	109.0	20.9	0.0	0.0	100%	32%	0%	0%
take01	d30	-3.7	40	Sea Base	0.0	0.0	1253.7	1876.0	0%	0%	32%	98%
tao03	d31	-3.7	40.8	Sea Base	60.6	41.8	0.0	0.0	56%	64%	0%	0%
tao01	d33	-3.7	40.8	Sea Base	42.3	41.8	0.0	0.0	39%	64%	0%	0%
take03	d36	-3.7	40	Sea Base	0.0	0.0	2507.4	1915.6	0%	0%	63%	100%
tao05	d40	-3.7	40	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
take01	d42	-3.7	40	Sea Base	0.0	0.0	3971.4	1120.4	0%	0%	100%	59%
tao06	d42	-3.7	40	Sea Base	104.6	58.8	0.0	0.0	96%	90%	0%	0%
tao04	d44	-3.7	40	Sea Base	50.1	20.5	0.0	0.0	46%	31%	0%	0%
take02	d46	-3.7	40	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao01	d48	-3.7	40	Sea Base	100.1	41.0	0.0	0.0	92%	63%	0%	0%
take03	d50	-3.7	40	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao03	d50	-3.7	40	Sea Base	50.1	20.5	0.0	0.0	46%	31%	0%	0%
tao02	d51	-3.7	40.8	Sea Base	25.0	10.3	0.0	0.0	23%	16%	0%	0%
tao05	d53	-3.7	40.8	Sea Base	50.1	20.5	0.0	0.0	46%	31%	0%	0%
take01	d55	-3.7	40.8	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao06	d55	-3.7	40.8	Sea Base	50.1	20.5	0.0	0.0	46%	31%	0%	0%
tao04	d57	-3.7	40.8	Sea Base	50.1	20.5	0.0	0.0	46%	31%	0%	0%
take02	d58	-3.7	40	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%

Table 8. Scenario 2 CLF CONSOL Amounts and Utilization Data

Our inventory levels in stores and ammunition show increased fluctuation compared to maintaining the level at 50-percent reserve. The three T-AKEs are able to maintain the inventory levels above the 60-percent reserve level.

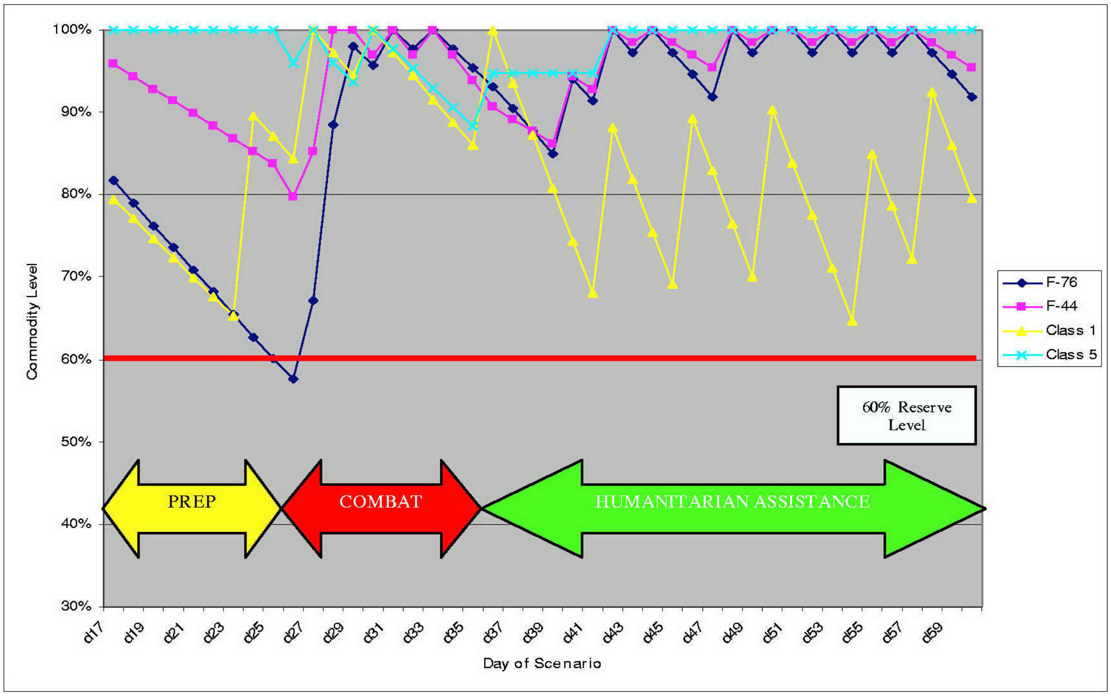

Figure 8. Scenario 2 Sea Base Commodity Usage and Resupply Levels

3. Single-Fuel Scenario

The optimization model for Scenario 3 has 40,612 constraints and 11,886 variables, and solves in just under 2 minutes. Three T-AKE and three T-AO shuttle ships are required to conduct 24 CONSOLs.

All CONSOLs prior to the formation of the Sea Base occur on day 15 and 16 (see Table 9). This is the latest date of a first CONSOL among all our scenarios. Three groups are topped off with DFM before day 17.

					Amounts			Utilization Rates per CONSOL		
CLF Ship	Day	Lat	Long	Customer	Single Fuel (kbbls)	Class I (Stons)	Class V (Stons)	SF	Class I	Class V
take02	d15	-3.7	40.8	CSG 1	0.0	881.1	0.0	0%	22%	0%
tao03	d15	-3.17	42.21	CSG 2	118.6	0.0	0.0	68%	0%	0%
take01	d16	0.6	56.5	CSG 2	0.0	939.8	0.0	0%	24%	0%
take03	d16	-1.5	44.1	ESG 1	0.0	939.8	0.0	0%	24%	0%
tao01	d16	-3.7	41.4	ESG 2	126.5	0.0	0.0	73%	0%	0%
tao02	d16	-1.5	44.1	CSG 3	134.1	0.0	0.0	77%	0%	0%
take02	d27	-3.7	40.8	Sea Base	0.0	3971.4	1728.0	0%	100%	90%
tao03	d28	-3.7	40	Sea Base	174.4	0.0	0.0	100%	0%	0%
take03	d29	-3.7	40.8	Sea Base	0.0	3160.0	1370.0	0%	80%	72%
tao01	d29	-3.7	40.8	Sea Base	174.4	0.0	0.0	100%	0%	0%
tao02	d29	-3.7	40.8	Sea Base	174.4	0.0	0.0	100%	0%	0%
take01	d30	-3.7	40	Sea Base	0.0	415.8	506.0	0%	10%	26%
take02	d39	-3.7	40.8	Sea Base	0.0	3971.4	1915.6	0%	100%	100%
tao03	d41	-3.7	40.8	Sea Base	174.4	0.0	0.0	100%	0%	0%
tao01	d42	-3.7	40	Sea Base	174.4	0.0	0.0	100%	0%	0%
tao02	d42	-3.7	40	Sea Base	174.4	0.0	0.0	100%	0%	0%
take01	d44	-3.7	40	Sea Base	0.0	3971.4	1120.4	0%	100%	59%
take03	d45	-3.7	40.8	Sea Base	0.0	3118.3	0.0	0%	79%	0%
take02	d51	-3.7	40.8	Sea Base	0.0	3971.4	0.0	0%	100%	0%
tao03	d54	-3.7	40	Sea Base	174.4	0.0	0.0	100%	0%	0%
tao01	d55	-3.7	40.8	Sea Base	174.4	0.0	0.0	100%	0%	0%
tao02	d55	-3.7	40.8	Sea Base	174.4	0.0	0.0	100%	0%	0%
take01	d56	-3.7	40	Sea Base	0.0	3971.4	0.0	0%	100%	0%
take03	d57	-3.7	40.8	Sea Base	0.0	3478.9	0.0	0%	88%	0%

Table 9. Scenario 3 CLF CONSOL Amounts and Utilization Data

The Sea Base begins with a 75-percent DFM level, as seen in Figure 9, that decreases to the 50-percent reserve level by day 27. Starting at day 28 the DFM commodity level is maintained at an even trend by the available T-AO force.

The stores and ammunition levels maintain the same level as Scenario 1. We conclude that this is due to our using the same number of T-AKEs to support identical requirements.

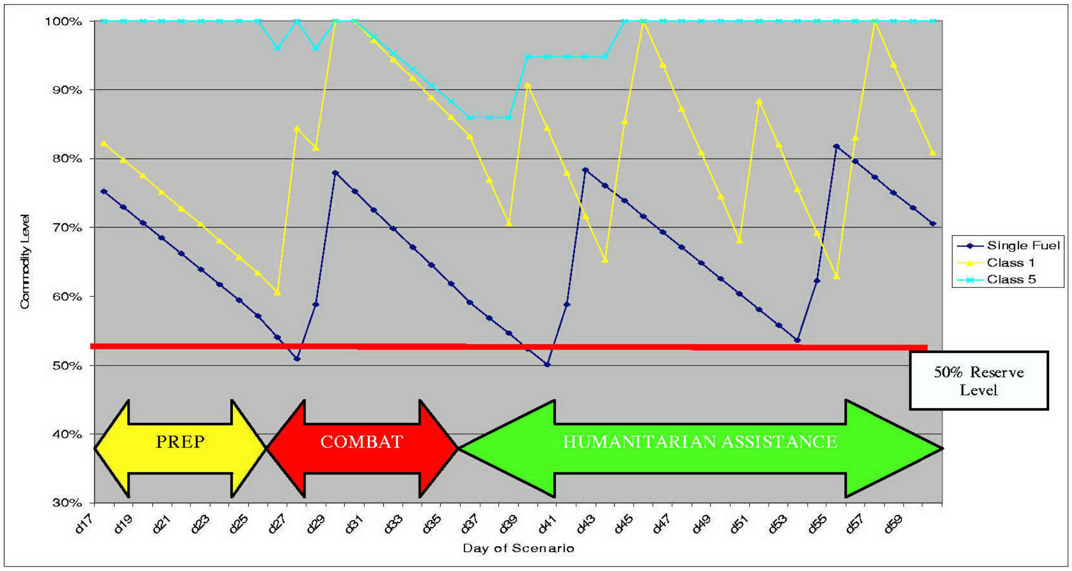

Figure 9. Scenario 3 Sea Base Commodity Usage and Resupply Levels

4. T-AOE Shuttle Ship Scenario

The integer linear program for Scenario 4 has 27,443 constraints and 9,713 variables, and solves in just over 5 minutes. Two T-AKE, two T-AO, and two T-AOE shuttle ships conduct 26 CONSOLs to support and sustain the forces.

We observe (see Table 10) the earliest CONSOLs among any of our scenarios on day 8. The model uses the speed advantage of the T-AOE to CONSOL with CSG 1 and top off all commodities.

					Amounts				Utilization Rates per CONSOL			
CLF Ship	Day	Lat	Long	Customer	DFM (kbbls)	JP-5 (kbbls)	Class I (Stons)	Class V (Stons)	DFM	JP5	Class I	Class V
taoe01	d08	37.22	12.75	CSG 1	21.0	24.1	460.3	0.0	18%	39%	41%	0%
tao01	d09	6.2	109.7	CSG 1	23.7	27.1	0.0	0.0	22%	41%	0%	0%
taoe02	d12	-3.7	40	CSG 1	25.4	36.3	690.5	0.0	21%	59%	62%	0%
tao02	d15	-4.4	47.3	CSG 2	109.0	1.6	0.0	0.0	100%	2%	0%	0%
take01	d16	0.6	56.5	ESG 1	0.0	0.0	920.6	0.0	0%	0%	23%	0%
take02	d16	0.6	56.5	CSG 3	0.0	0.0	0.0	0.0	0%	0%	0%	0%
taoe01	d18	-3.7	40	Sea Base	120.0	61.2	1111.0	0.0	100%	100%	100%	0%
taoe02	d21	-3.7	40.8	Sea Base	120.0	54.2	1111.0	0.0	100%	89%	100%	0%
taoe01	d27	-3.7	40.8	Sea Base	120.0	61.2	1111.0	1728.0	100%	100%	100%	67%
tao02	d29	-3.7	40.8	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
taoe02	d30	-3.7	40	Sea Base	118.5	38.2	1111.0	1876.0	99%	62%	100%	72%
take02	d33	-3.7	40.8	Sea Base	0.0	0.0	3971.4	1518.0	0%	0%	100%	79%
tao01	d34	-3.7	40	Sea Base	77.0	65.4	0.0	0.0	71%	100%	0%	0%
taoe01	d37	-3.7	40.8	Sea Base	61.6	61.2	1111.0	1518.0	51%	100%	100%	59%
taoe02	d39	-3.7	40.8	Sea Base	46.2	29.5	1111.0	0.0	39%	48%	100%	0%
take01	d41	-3.7	40.8	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
take02	d45	-3.7	40.8	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao02	d46	-3.7	40	Sea Base	109.0	65.4	0.0	0.0	100%	100%	0%	0%
taoe01	d46	-3.7	40	Sea Base	52.8	6.3	1111.0	0.0	44%	10%	100%	0%
taoe02	d48	-3.7	40	Sea Base	46.2	20.5	1111.0	0.0	39%	33%	100%	0%
take01	d53	-3.7	40.8	Sea Base	0.0	0.0	3971.4	0.0	0%	0%	100%	0%
tao01	d54	-3.7	40	Sea Base	109.0	61.5	0.0	0.0	100%	94%	0%	0%
taoe01	d55	-3.7	40.8	Sea Base	52.8	10.3	1111.0	0.0	44%	17%	100%	0%
take02	d57	-3.7	40.8	Sea Base	0.0	0.0	3653.7	0.0	0%	0%	92%	0%
taoe02	d57	-3.7	40.8	Sea Base	46.2	20.5	1111.0	0.0	39%	33%	100%	0%
tao02	d59	-3.7	40.8	Sea Base	46.2	20.5	0.0	0.0	42%	31%	0%	0%

Table 10. Scenario 4 CLF CONSOL Amounts and Utilization Data

We find that without the additional capacity of the station ships, the Sea Base is formed with 47 percent (which is below the 50-percent reserve level). This is a temporary situation, and by day 31 the Sea Base is replenished to the 100-percent level for DFM. The ability to carry all four commodities is utilized three times by T-AOEs on day 27, day 30, and day 37. The utilization for the commodities transferred during these CONSOLs is very high. We see one-hundred percent utilization of stores for all ten CONSOLs between T-AOEs and the Sea Base.

The reduced stores capacity in the T-AOE class causes a larger drop in the stores inventory on day 53 than is observed in the other scenarios.

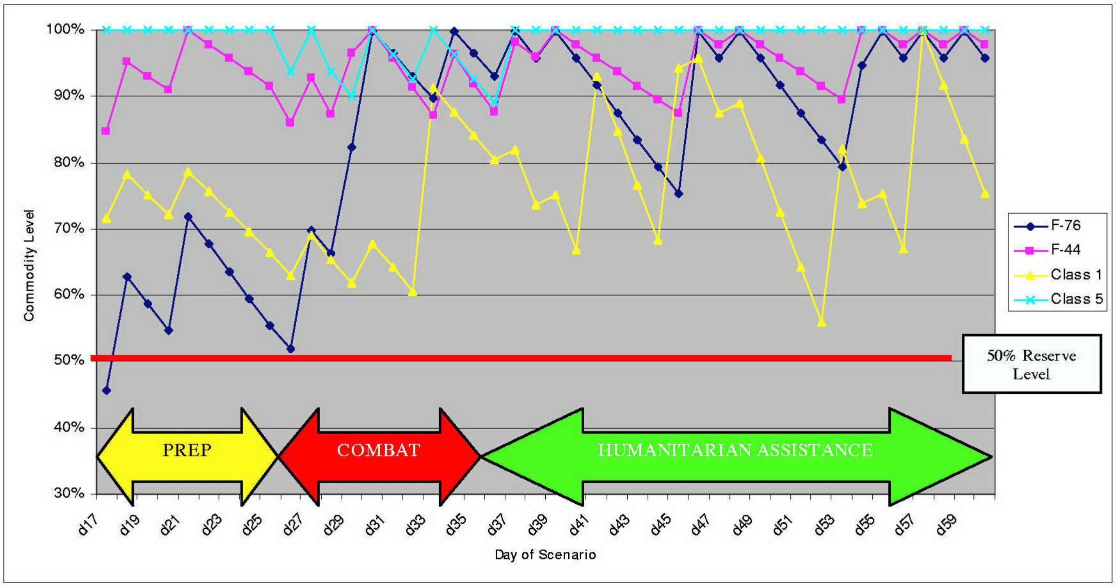

Figure 10. Scenario 4 Sea Base Commodity Usage and Resupply Levels

B. INSIGHTS

Configuration of the T-AKE to carry more stores than ammunition is key to support the follow-on humanitarian aid effort in our scenario. The ammunition inventory of the station ship and that provided by the T-AKEs is sufficient considering our scenario with ten days of total combat. The humanitarian aid effort is much more logistically challenging to support at the range of the forward logistics site in this scenario.

The implementation of a Navy single fuel reduces both the number of total T-AOs and CONSOLs needed to support forces in that scenario.

Changing the role of T-AOEs from station to shuttle ship can reduce the required number of total ships to support forces in our scenario. The cost for the change is providing continuous support to the forces during the transit to the area of operations. Assigning T-AOEs as station ships and then reassigning them to the shuttle ship role upon arrival in a area of operations is a concept warranting further research.

C. CONCLUSIONS

We have demonstrated the use of a prescriptive optimization model for sizing the CLF. This model can be used to analyze almost any conceivable scenario involving naval assets, under a variety of proposed CONOPS.

We have illustrated our model with a 60-day seabasing scenario involving a ramp-up to combat, Sea Base formation, and transition to a logistically demanding humanitarian assistance mission.

D. FUTURE DEVELOPMENT

As new classes of ships become available to MSC, each can be added to the model to determine its viability as a CLF shuttle ship or station ship. The new high speed logistics ships are an obvious class to incorporate, once their planning factors become more specifically defined.

The addition of the ability to perform multiple CONSOLs on one trip would allow a more accurate assessment of utilization, but we conjecture that this will become a concern only with future fast, high capacity ships, as we achieve very good utilization numbers with our current CLF ships.

APPENDIX

A. CLF MODEL FORMULATION

1. Indices

s	Shuttle ship (~21)
$v(s)$	Shuttle ship class (e.g., T-AKE, T-AO)
p	Port available to load shuttle ships (~18)
ag	Afloat group (~10) (alias ag’)
$d=1,\ldots,D$	Day (D ~ 70) (alias d’)
c	Commodity (DFM, JP5, STOR, ORDN)

2. Given Data

$speed_v$	Speed of shuttle ship class v (nm/day)
$portok4v_{p,v}$	=1 if port p can accommodate shuttle ship class v, 0 otherwise
$inptTAT$	Time in port to resupply and turn around a shuttle ship (days)
$legdays_{v,ag,d,p}$	Shuttle ship class v transit time from afloat group ag position on day d to port p following given sea routes and/or afloat group tracks (days)
$useAG_{ag,d,c}$	Consumption by afloat group ag during day d of commodity c (c-units)
$mxload_{ag,c}$	Maximum capacity of afloat group ag to carry commodity c (c-units)
$safety_{c,ag}$	Minimum desired fraction of $mxload_{ag,c}$ to be held at all times
$canhitag_{ag,d}$	Logical indicator if afloat group ag can CONSOL on day d
$scanhitag_{s,ag}$	Logical indicator if shuttle ship s can HIT ag
$capacity_{s,c}$	Shuttle ship s capacity to deliver commodity c (c-units)
$penalty_c$	Penalty per deficit unit of desired storage held by afloat group (penalty per c-unit)
$negpen_c$	Penalty per negative unit of storage held (penalty per c-unit)

3. Derived Data

$hitOK_{s,ag,d}$ Binary indicator enabling shuttle ship s to CONSOL ag on day d, defined as $canhitag_{ag,d} \wedge scanhitag_{s,ag}$.

$canhitag_{ag,d}$ argument derives from maneuvering and/or operating restrictions on *ag* during day *d*, (e.g., canal passage precludes a CONSOL) while $scanhitag_{s,ag}$ can restrict shuttle ships to CONSOL only a subset of afloat groups, and in the extreme case even assigning *s* exclusively to a single *ag*.

$cycledays_{v,ag,d,ag',d'}$ If a shuttle ship of class *v* departs afloat group *ag* on day *d* to reload at some port *p*, the minimum number of days before a CONSOL with afloat group *ag'* on day *d'* is

$$\min\left\{\infty, \min_{p|portok4v_{p,v}=1}\left[\min_{d'\geq legdays_{ag,d,p}+inptTAT+legdays_{ag',d',p}}(legdays_{v,ag,d,p}+inptTAT+legdays_{v,ag',d',p}\right]\right\}$$

Note that this admits a cycle with slack time (or, "shuttle ship waiting time") $d'-d-cycledays_{v,ag,d,ag',d}\geq 0$, and that, because of the relative motion of a shuttle ship and an Afloat Group over navigable sea routes, and their daily proximity to ports and to each other, there will be cases in which planning for a shuttle ship to wait for this amount of time is more efficient and realistic than restricting plans to have no such slack.

4. Decision Variables

$HIT_{s,ag,d}$	Binary indicator of shuttle ship *s* CONSOL visit to afloat group *ag* on day *d*
$CONSOL_{s,ag,d,c}$	Shuttle ship *s* delivery to afloat group *ag* on day *d* of commodity *c* (*c*-units)
$SHORTAGE_{ag,d,c}$	afloat group *ag*, at end of day *d*, has this deficiency below $safety_c$ (*c*-units)
$NEGINV_{ag,d,c}$	Afloat group *ag*, at end of day *d*, has this deficiency below zero (*c*- units)

5. Formulation

s.t.

$$mxload_{ag,c} + \sum_{dp\leq d|hitOK_{s,ag,dp}} CONSOL_{s,ag,dp,c} - \sum_{dp\leq d} useAG_{ag,dp,c} \leq mxload_{ag,c} \qquad \forall ag,d,c \qquad (1)$$

$$mxload_{ag,c} + \sum_{dp \le d | hitOK_{s,ag,dp}} CONSOL_{s,ag,dp,c} - \sum_{dp \le d} useAG_{ag,dp,c} + SHORTAGE_{ag,d,c} + NEGINV_{ag,d,c} \ge safety_c mxload_{ag,c} \quad \forall ag,d,c \tag{2}$$

$$CONSOL_{s,ag,d,c} \le mxconsol_{s,ag,d,c} * HIT_{s,ag,d} \quad \forall s,ag,d,c \mid hitOK_{s,ag,d} \tag{3}$$

$$HIT_{s,ag,d} + HIT_{s,ag',d'} \le 1 \quad \forall s,ag,d,ag',d' \mid \left[(d' > d \wedge cycledays_{v|s(v),ag,d,ag',d'} = \infty) \vee (ag' \ne ag \wedge d' = d)\right] \wedge hitOK_{s,ag,d} \tag{4}$$

$$HIT_{s,ag,d} \in \{0,1\} \quad \forall s,ag,d \tag{5}$$

$$0 \le CONSOL_{s,ag,d,c} \le mxconsol_{s,ag,d,c} \quad \forall s,ag,d,c \tag{6}$$

$$0 \le STORES_{ag,d,c} \le mxload_{ag,c} \quad \forall ag,d,c \tag{7}$$

$$0 \le SHORTAGE_{ag,d,c} \le safety_c mxload_{ag,c} \quad \forall ag,d,c \tag{8}$$

$$0 \le NEGINV_{ag,d,c} \le \sum_{dp \le d} useAG_{ag,dp,c} \quad \forall ag,d,c \tag{9}$$

$$Max \sum_{s,ag,d,c | hitOK_{s,ag,d}} 2 * penalty_c CONSOL_{s,ag,d,c} - \sum_{ag,d,c} penalty_c SHORTAGE_{ag,d,c} - \sum_{ag,d,c} negpenNEGINV_{ag,d,c} \tag{10}$$

6. Discussion

Inequalities (1) limit daily, afloat group commodity levels to their available capacities. We assume at the beginning of our notional scenario, each afloat group is full to capacity with every commodity. Thereafter, the stores state is computed as the initial load plus all CONSOL quantities, less all consumption quantities, for a particular day. Inequalities (2) similarly limit minimum commodity levels to a desired safety stock margin, account for any shortages below this safety stock, and optionally, will account for negative commodity levels while waiting for a CONSOL event to occur. Inequalities (3) limit underway replenishment quantities to be zero unless a CONSOL event occurs, in which case the transferred quantities cannot exceed the maximum conveyable capacity of either the shuttle or customer ships. Constraints (4) restrict successive shuttle ship

CONSOLs with more than one afloat group from occurring, until sufficient time is allowed for the CLF ship to cycle through a port for resupply. Constraints (5) stipulate that shuttle ship consolidation visits are binary. Simple bounds (6)-(9) restrict commodity volumes to be non-negative and finite. The objective function (10) rewards maximum shuttle ship CONSOL volumes, penalizes any deficiencies below desired safety stocks, and heavily penalizes any shortages below zero inventories, in an effort to encourage the most efficient scheduling of all shuttle ship CONSOL events [Cardillo, 2004].

B. SEA ROUTES MODEL NODE LIST

Node ID	LAT	LONG	Name	Node ID	LAT	LONG	Name	Node ID	LAT	LONG	Name
ADEN	12.8	45.0	Aden	GUAM	13.5	144.6	Guam	PAC4	30.8	160.8	mid-Pacific waypt4
ADR	42.5	16.0	Adriatic Sea	HANM	34.0	131.0	Hanmon Straits	PANA	8.9	-79.6	Panama, Atlantic
AQA	29.5	35.0	Aqaba Jordan	HI	21.4	-158.2	Hawaii	PANP	9.4	-79.9	Panama, Pacific
ARA	20.0	60.0	Arabian Sea	HOA	3.5	49.2	Horn of Africa	PER	-32.0	115.8	Perth, Australia
AUG	37.2	15.2	Augusta Bay IT	HOPE	-37.8	17.7	Cape of Good Hope	PG1	26.5	55.5	Per Gulf waypt1
AUS1	-26.5	160.5	Australia 1	HOR	26.6	56.3	Strait of Hormuz	PG2	26.3	51.5	Per Gulf waypt2
AUS2	-45.1	147.2	Australia 2	HORN	-57.4	-68.5	Cape Horn	PI	15.0	121.0	Philippines
AUS3	-35.7	112.6	Australia 3	IWA	33.9	132.1	Iwakuni JP	REDN	28.3	34.5	Red Sea north
AUS4	-14.0	106.5	Australia 4	JAPN	34.5	139.7	Japan North	RED1	27.0	34.5	Red Sea 1
AUS5	-6.8	119.5	Australia 5	JAPS	31.8	133.4	Japan South	REDM	20.0	38.5	Red Sea middle
BAH	26.2	50.6	Bahrain	JEB	25.0	55.1	Jebel Ali	ROTA	36.6	-6.4	Rota SP
CHEJ	34.0	125.5	Cheju Strait	JED	21.5	39.1	Jeddah	SAS	33.2	129.7	Sasebo JP
DARW	-12.9	130.5	Darwin, Australia	KORS	34.0	129.0	Korean Strait	SATL	-7.0	-18.2	South Atlantic
DIEG	-7.3	72.4	Diego Garcia	LANT1	36.6	-56.1	mid-Atl waypt1	SCHI	10.0	113.0	South China Sea
EAF	-3.7	40.3	East African Coast	LANT2	36.3	-36.0	mid-Atl waypt2	SDCA	32.7	-117.2	San Diego CA
ECHS	32.0	126.0	E China Sea	LANT3	36.1	-15.8	mid-Atl waypt3	SING	1.3	103.8	Singapore
ELANT	41.0	-14.0	East Atlantic	MAL	2.5	101.7	Str of Malacca	SIO	-24.1	57.9	South IO
EPAC	15.0	-110.0	East Pacific	MALE	6.3	73.0	Male Maldives	SEJ	40.0	129.5	Japan, Sea
FUJ	25.2	56.4	Al Fujayrah UAE	MAN	12.7	43.3	Bab el Mandeb	SOJ	34.5	130.0	Sea of Japan
GA1	12.0	43.5	Aden, Gulf waypt1	MED1	38.3	8.0	Med waypt1	SOO	40.0	19.0	Strait of Otranto
GA2	12.5	48.0	Aden, Gulf waypt2	MED2	36.2	16.0	Med waypt2	SOU	35.5	24.2	Souda Bay, Crete
GB	42.5	-50.0	Grand Banks	MED3	36.0	20.0	Med waypt3	SYDN	-33.9	151.2	Sydney, Australia
GEO	5.4	100.3	G'town Malaysia	MED4	35.5	26.0	Med waypt4	SUEZN	31.3	32.3	Suez Canal, North
GIB	36.0	-5.8	Str of Gibraltar	NOR	60.3	5.2	Norway fjiord	SUEZS	29.9	32.6	Suez Canal, South
GOA	29.0	34.8	Gulf of Aqaba	NVA	36.9	-76.3	Norfolk VA	WIND	20.0	-73.8	Windward Passage
GOO	23.0	61.0	Gulf of Oman	PAC1	32.2	-137.7	mid-Pacific waypt1	OKIN	30.0	130.0	Okinawa, Japan
GOS	28.8	33.0	Gulf of Suez	PAC2	31.7	-158.2	mid-Pacific waypt2	YELL	35.0	124.0	Yellow Sea
				PAC3	31.2	-178.7	mid-Pacific waypt3	YOK	35.3	139.7	Yokosuka JP

C. SEA ROUTES MODEL ARC LIST

1. Fast Arc List

Aden	Aden, Gulf waypt2
Aden	Aden, Gulf waypt1
Aqaba Jordan	Red Sea north
Augusta Bay IT	Med waypt2
Augusta Bay IT	Strait of Otranto
Augusta Bay IT	Souda Bay, Crete
Augusta Bay IT	Suez Canal, North
Australia 1	mid-Pacific waypt4
Australia 1	Hawaii
Australia 1	Okinawa, Japan
Australia 2	Australia 1
Australia 2	Okinawa, Japan
Australia 2	Australia 3
Australia 3	Perth, Australia
Australia 3	Australia 4
Australia 4	Perth, Australia
Australia 4	Darwin, Australia
Australia 4	Australia 5
Australia 5	Darwin, Australia
Cheju Strait	Yellow Sea
Diego Garcia	Male Maldives
Diego Garcia	Australia 3
Diego Garcia	Australia 4
East African Coast	Horn of Africa
East African Coast	Diego Garcia
E China Sea	Cheju Strait
E China Sea	Yellow Sea
E China Sea	Sasebo JP
E China Sea	Korean Strait
East Atlantic	Str of Gibraltar
East Atlantic	Grand Banks
East Atlantic	Norfolk VA
East Atlantic	Rota SP
East Atlantic	Okinawa, Japan
East Pacific	Japan South
East Pacific	Hawaii
East Pacific	Guam
East Pacific	Philippines
East Pacific	San Diego CA
East Pacific	Sasebo JP
East Pacific	Norfolk VA
East Pacific	Adriatic Sea
Aden, Gulf waypt1	Aden, Gulf waypt2
Aden, Gulf waypt2	Arabian Sea
Grand Banks	Str of Gibraltar
Grand Banks	Norfolk VA
Grand Banks	Rota SP
Grand Banks	Okinawa, Japan
Grand Banks	Norway fjiord
G'town Malaysia	Male Maldives
G'town Malaysia	Adriatic Sea
Str of Gibraltar	Norfolk VA
Str of Gibraltar	Rota SP
Str of Gibraltar	Okinawa, Japan
Gulf of Aqaba	Red Sea north
Gulf of Oman	Male Maldives
Gulf of Oman	Arabian Sea
Gulf of Oman	Strait of Hormuz
Gulf of Suez	Philippines
Gulf of Suez	Okinawa, Japan
Guam	mid-Pacific waypt4
Guam	Hawaii
Guam	Japan South
Guam	East Pacific
Guam	South China Sea
Guam	Australia 1
Guam	Australia 5
Hanmon Straits	Iwakuni JP
Hanmon Straits	Korean Strait
Hanmon Straits	Sea of Japan
Hawaii	mid-Pacific waypt1
Hawaii	mid-Pacific waypt2
Hawaii	mid-Pacific waypt3
Hawaii	mid-Pacific waypt4
Hawaii	Panama, Pacific
Hawaii	Philippines
Hawaii	Sasebo JP
Hawaii	San Diego CA
Hawaii	Norfolk VA
Horn of Africa	Arabian Sea
Horn of Africa	Diego Garcia
Horn of Africa	Male Maldives
Cape of Good Hope	South Atlantic
Cape of Good Hope	Japan, Sea
Cape of Good Hope	Australia 3
Cape Horn	Hawaii
Cape Horn	mid-Pacific waypt1
Cape Horn	San Diego CA
Cape Horn	South Atlantic
Cape Horn	Cape of Good Hope
Iwakuni JP	Japan South
Japan North	Hawaii
Japan North	Philippines
Japan North	Japan South
Japan North	South China Sea
Japan North	San Diego CA
Japan North	Norfolk VA
Jebel Ali	Per Gulf waypt1
Korean Strait	Sea of Japan
Med waypt1	Med waypt2
Med waypt1	Str of Gibraltar
Med waypt2	Suez Canal, North
Med waypt3	Suez Canal, North
Med waypt3	Souda Bay, Crete
Norfolk VA	Rota SP
Norfolk VA	Okinawa, Japan
Norfolk VA	Yellow Sea
mid-Pacific waypt1	Sasebo JP
mid-Pacific waypt1	San Diego CA
mid-Pacific waypt1	Norfolk VA
mid-Pacific waypt2	Sasebo JP
mid-Pacific waypt2	San Diego CA
mid-Pacific waypt2	Norfolk VA
mid-Pacific waypt3	Sasebo JP
mid-Pacific waypt3	San Diego CA
mid-Pacific waypt3	Norfolk VA
mid-Pacific waypt4	Sasebo JP
mid-Pacific waypt4	San Diego CA
mid-Pacific waypt4	Norfolk VA
Panama, Atlantic	Okinawa, Japan
Per Gulf waypt1	Per Gulf waypt2
Per Gulf waypt2	Bahrain
Philippines	E China Sea
Philippines	Sasebo JP
Philippines	San Diego CA
Philippines	Japan, Sea
Philippines	Norfolk VA
Philippines	Philippines
Philippines	Jebel Ali
Philippines	Bab el Mandeb
Red Sea north	Philippines
Rota SP	Okinawa, Japan
Sasebo JP	Cheju Strait
Sasebo JP	Korean Strait
Sasebo JP	Japan, Sea
Sasebo JP	Norfolk VA
South Atlantic	Okinawa, Japan
South Atlantic	mid-Atl waypt1
South Atlantic	mid-Atl waypt3
South Atlantic	Norfolk VA
San Diego CA	Norfolk VA
Japan, Sea	South China Sea
Japan, Sea	Australia 5
Japan, Sea	Horn of Africa
Japan, Sea	Diego Garcia
Japan, Sea	Australia 4
Japan, Sea	Australia 3
Japan, Sea	Arabian Sea
Sea of Japan	Japan, Sea
Strait of Otranto	Adriatic Sea
Strait of Otranto	Med waypt2
Strait of Otranto	Med waypt3
Souda Bay, Crete	Strait of Otranto
Souda Bay, Crete	Med waypt2
Souda Bay, Crete	Med waypt3
Yokosuka JP	Japan North

2. Slow Arcs

From	To	Delay
Aqaba Jordan	Gulf of Aqaba	0.25
Al Fujayrah UAE	Strait of Hormuz	0.25
Aden, Gulf waypt1	Bab el Mandeb	0.25
Gulf of Oman	Strait of Hormuz	0.25
Gulf of Suez	Okinawa, Japan	0.25
Strait of Hormuz	Jebel Ali	0.25
Strait of Hormuz	Per Gulf waypt1	0.25
Str of Malacca	Japan, Sea	0.25
Panama, Atlantic	Panama, Pacific	1.00
Suez Canal, North	Okinawa, Japan	1.00

Delay in days

D. CSG, ESG, AND MPG ROUTES

	CSG 1		CSG 2		CSG 3		ESG 1		ESG 2		MPG 1	
	LAT	LONG	LAT	LONG	LAT	LONG	LAT	LONG	LAT	LONG	LAT	LONG
Day 01	19.9	-170.6	36.9	-76.3	-13.9	126.2	40.7	14.0	-7.3	72.4	0.6	105.1
Day 02	16.1	178.2	39.3	-63.2	-13.9	119.5	36.8	16.6	-6.1	64.0	2.7	100.5
Day 03	15.3	171.7	40.5	-50.1	-13.5	114.3	34.5	23.0	-5.5	55.2	7.2	96.7
Day 04	13.9	161.2	39.9	-36.2	-12.8	109.9	32.6	29.6	-4.5	46.6	5.8	86.4
Day 05	11.6	150.5	38.1	-23.4	-11.8	103.3	31.8	32.4	-3.7	40.0	4.8	75.9
Day 06	8.3	140.0	36.0	-10.4	-11.4	98.1	29.9	32.6	-3.7	40.8	2.7	66.4
Day 07	5.8	129.4	37.2	2.7	-11.4	92.1	24.7	35.6	-3.7	40.0	0.6	56.5
Day 08	5.8	119.2	37.2	12.8	-10.7	86.8	20.0	39.1	-3.7	40.8	-1.6	47.8
Day 09	6.2	109.7	33.7	22.0	-8.9	81.2	15.0	42.1	-3.7	40.0	-3.7	40.0
Day 10	0.6	105.1	31.3	32.3	-8.2	74.8	11.3	44.4	-3.7	40.8	-3.7	40.8
Day 11	2.7	100.5	29.9	32.6	-7.5	69.5	12.5	50.2	-3.7	40.0	-3.7	40.0
Day 12	7.2	96.7	20.9	38.0	-6.8	63.9	9.8	53.4	-3.7	40.8	-3.7	40.8
Day 13	5.8	86.4	11.4	44.5	-5.8	57.9	4.7	50.7	-3.7	40.0	-3.7	40.0
Day 14	4.8	75.9	14.1	54.9	-5.1	52.6	-0.3	47.0	-3.7	40.8	-3.7	40.8
Day 15	2.7	66.4	4.0	52.0	-4.4	47.3	-3.2	42.2	-3.7	40.0	-3.7	40.0
Day 16	0.6	56.5	-1.5	44.1	-3.7	41.4	-3.7	40.2	-3.7	40.8	-3.7	40.8

The Sea Base is formed on Day 17 and is located at latitude -003.7 and longitude 040.3.

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