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An optimization model for Sea-Based Logistics Supply System for the Navy and Marine Corps

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

AN OPTIMIZATION MODEL FOR SEA-BASED LOGISTICS SUPPLY SYSTEM FOR THE NAVY AND MARINE CORPS

by

Donato S. Powell

September 2004

Thesis Advisor:	Javier Salmeron
Second Reader:	David A. Schrady

Approved for public release; distribution is unlimited

Amateurs discuss strategy, Professionals study logistics

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13. ABSTRACT (maximum 200 words)

The United States is moving into a new era in which the enemy no longer provides symmetric opposition. The Navy and Marine Corps will face new challenges in the way they deploy and conduct future operations. One important way that these challenges will be met involves sea-based operations, which provide the sustainment necessary for prolonged operations and prevent unwanted operational pauses.

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This thesis analyzes the problem of finding an optimal mix of Combat Logistics Force shuttle ships required to sustain the sea-base. This is accomplished through two optimization models: The first one determines a shuttle mix ensuring required inventory levels at the sea-base are maintained at all times. Since this requirement may cause some shuttles to be loaded partially, in the second model we manually assign the shuttle mix and then minimize unmet demand. This model yields a mix of shuttles that strikes a balance between shuttle cost and meeting sea-base demand. This thesis uses varying distances for conducting analyses over several scenarios.

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**AN OPTIMIZATION MODEL FOR SEA-BASE LOGISTICS SUPPLY SYSTEM
FOR THE NAVY AND MARINE CORPS**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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TABLE OF CONTENTS

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

ALSS	Advance Logistic Support Site
ARG	Amphibious Ready Group
BLT	Battalion Landing Team
CE	Command Element
CLF	Combat Logistics Force
CNA	Center of Naval Analysis
CSG	Carrier Strike Group
CSS	Combat Service Support
CSSE	Combat Service Support Element
DOS	Days of Supply
ESG	Expeditionary Strike Group
GCE	Ground Combat Element
LCAC	Landing Craft Air Cushion
MEB	Marine Expeditionary Brigade
MEU	Marine Expeditionary Unit
MPF(F)	Maritime Prepositioning Force (Future)
MPS	Maritime Prepositioning Ships
nm	Nautical Miles
OMFTS	Operational Maneuver from the Sea
RO/RO	Roll On Roll Off
SBL	Sea-Based Logistics
SDS	Supply Distribution System

SOC	Special Operations Capable
SSC	Small Scale Contingency
USMC	United States Marine Corps
USN	United States Navy

LIST OF FIGURES

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LIST OF TABLES

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

The United States is moving into a new era in which the enemy no longer provides symmetric opposition. The Navy and Marine Corps will face new challenges in the way they deploy and conduct future operations. One important way that these challenges will be met involves sea-based operations, which provide the sustainment necessary for prolonged operations and prevent unwanted operational pauses.

This thesis provides a tool that optimizes a mix of Combat Logistics Force shuttle ships required to sustain the sea-base in a small-scale contingency war at varying distances (1,600nm, 2,500nm, 3,500nm). The supported unit is a Marine Expeditionary Brigade.

We develop two formulations and the associated optimization models. Both the first and second formulations are represented through a time-space transportation network from an Advance Logistics Support Site directly to the sea-base, over a pre-specified planning horizon of 45 days.

The first formulation determines the (weighed) number and type of shuttles required to guarantee minimum levels of supply at the sea-base. This requirement, however, may cause some shuttles (required to meet the demand) to be used inefficiently. For example, shuttles may end up loaded well-below their capacity.

The second formulation minimizes (weighed) unmet demand, if any, for a pre-specified mix of shuttles. For the second formulation, we manually remove and/or exchange shuttles from the solution to the first formulation, and then minimize unmet demand. This yields a mix of shuttles that is "best" for a specified scenario. "Best" in this context, means that we have found a reasonable compromise between the first and second goals.

This thesis may provide insight into the adaptability needed for conducting "network centric" sea-based operations that are developed by either crisis or deliberate planning criteria.

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I.   INTRODUCTION

A.   OPERATIONAL MANUEVER FROM THE SEA AND SEA-BASED LOGISTICS

The concept of Operational Maneuver from the Sea (OMFTS) is a momentous shift from over seventy-five years of United States Marine Corps (USMC) doctrine. In place of using the traditional beachhead as a supply point, OMFTS creates movement directly from the sea to the objective. By eliminating a cumbersome, costly, and oftentimes dangerous concentration of supplies and personnel on the beach, with OMFTS the Marine Corps can maximize the use of assets and personnel, which in turn contributes to the safety and efficacy of a maneuver. Naturally, OMFTS' rapid movement from the sea requires precise logistical support and planning.

To pursue this shift in doctrine, the Marine Corps has defined the following fundamental principles of OMFTS to achieve an operational objective [United States Marine Corps (1997)]:

- Using the sea as a maneuver space,

- Generating overwhelming tempo and momentum,

- Pitting strength against weakness, and

- Emphasizing intelligence, deceptions, and flexibility, integrating all organic, joint, and combined assets.

The concept of Sea-Based Logistics (SBL) is to provide sustainment for Naval forces to project power around the world and offer the joint force commander complementary war fighting capabilities from the sea. The United States Navy (USN) and USMC plan to implement sea-based logistics by adhering to the following tenets [United States Marine Corps (1998)]:

- Primacy of the Sea-base,

- Reduced demand,

- In-stride sustainment (i.e. network-based, automated logistics system),

- Adaptive response and joint operations, and

- Force closure and reconstitution at sea.

This thesis analyzes a sea Supply Distribution System (SDS) for the USMC as part of the effort to plan for possible scenarios where OMFTS and SBL become a reality. The primary question is "What is the best mix of Combat Logistic Force (CLF) shuttle ships needed for a specified operation (scenario)?"

B.   SUSTAINMENT AT SEA

Sustainment at sea is a key element for the concept OMFTS. The USN and USMC team must be able to remain at sea for prolonged periods in order to prevent interruptions or operational pauses. Also, the Navy and Marine Corps require access in areas around the world where ammunition handling restrictions are imposed at ports. Having the ability to sustain from the sea provides the decision maker with the confidence of planning combat operations without the need of imposing multiple courses of action for replenishment. Sustainment at sea also provides the Ground Combat Element (GCE) with the necessary supplies needed to ensure a successful mission. The USMC will receive its supplies from the Maritime Preposition Ships (MPS) squadron, which is periodically replenished.

C.   MARITIME PREPOSITIONING FORCE (FUTURE)

The Maritime Prepositioning Force (Future) MPF(F) provides the Marine Corps with warehouse storage space for all commodities entering and leaving the sea-base. Currently, this is done with the assurance of a secure area that allows the offload of all needed equipment. [United States Marine Corps (1997)]. The MPF(F) will incorporate at-sea arrival and assembly of units, direct support of the landing force, and at-sea reconstitution and redeployment of the force. The Navy and Marine Corps are currently evaluating ship configurations for MPF(F). The initial design efforts have been identified in the Mission Need Statement and the MPF(F) Analysis of Alternative was prepared by the Center of Naval Analysis (CNA). [CNA, 2004].

The following designs developed are shown below:

- Ships that could serve as a mobile warehouse with no sea-base capability.

- Ships that could support a portion of the sea-base requirements across all functional areas, called distributed capability squadrons.

- Families of specialized ships that support a portion of the sea-base requirements in specific subsets of areas, including [CNA, 2004]:

1. Aviation operations,
2. Marine Expeditionary Brigade (MEB) command and control,
3. Logistics support,
4. Ground force deployment and support,
5. Special purpose missions like Special Operations Capable (SOC).

This thesis uses the unconstrained full Aviation Combat Element (ACE) design (six MPF(F) ships) to analyze three scenarios with a Marine Expeditionary Brigade (MEB) size force. If the ship designs are small enough to be built at any of the ship building companies, the squadron is said to be constrained. If the design is too large, the squadron is considered unconstrained, which typically consists of six MPS. The MPS will support a MEB, which is the middle size force of the three Marine Air-Ground Task Force (MAGTF).

D.   THESIS GOALS

As stated in Section A, our main goal is to optimize the mix of CLF shuttle ships required to sustain the sea-base in a small-scale contingency war. This goal is accomplished through two optimization models that complement each other. Accordingly, we have two formulations. Both formulations are represented through a time-space transportation network from an Advance Logistics Support Site (ALSS) directly to the sea-base, over a pre-specified planning horizon (typically 45 days). In the first formulation, network resources (i.e., available shuttles of different types) are

optimized in order to satisfy the sea-base demand in full. In the second formulation, resources are given as an input, and unmet demand is assessed.

Our first formulation determines the minimum (weighed) number of shuttles required to guarantee minimum reserve levels of supply at the sea-base. Weights (also called penalties) imposed on shuttle types capture approximate acquisition and operating costs. The smaller the number assigned as a penalty implies the more economical the shuttle type is. In addition, we subjectively incorporate shuttle characteristics in each assigned penalty: The lesser the penalty implies a slower shuttle and the smaller number of commodity type(s) that can be stowed (i.e., a single-commodity shuttle is "cheaper" than a double-commodity shuttle). The resultant mix of shuttles from the first formulation ensures that the reserve levels are never violated.

Our second formulation minimizes (weighed) unmet demand, if any, for a pre-specified mix of shuttles. The second formulation attempts to minimize the reserve level violations. Those commodities that are deemed more important than others are assigned a higher penalty. We subjectively choose each assigned penalty based on how important the commodity is in comparison with the other commodities. The shuttle mix input for the second formulation is typically based on the result of the first formulation (where unmet demand is not allowed), from which, for example, we may have removed a particular shuttle.

We develop three scenarios in order to explore shuttle capabilities for meeting the sea-based demand (divided into provisions, ammunition, and fuel) over time

F.   STATE OF THE ART

A number of thesis projects developed at the Naval Postgraduate School document efforts to assess the feasibility of sea-based operations in support of OMFTS. In this section we briefly describe those theses that possess an Operations Research background.

USN Lt. Mark Beddoes (1997) uses a deterministic approach to calculate the maximum distance from the beach that sea-based Combat Service Support (CSS) assets

would be able to maintain, while still supporting operations that OMFTS envisions. Lt. Beddoes assumes a one-for-one replacement of the CH-46E helicopter with the MV-22 helicopter, while maintaining the current assignment of four CH-53 aircraft. This work concludes that the ships of the Amphibious Ready Group (ARG) could not remain more than 100nm from shore and still satisfy the logistical requirements.

USMC Major Robert Hagan's thesis (1998) models the sea-based sustainment of a MEU. By creating and analyzing five typical Marine Expeditionary Unit (MEU) scenarios and determining sustainment requirements and available transportation capacities for each, Major Hagan deduces that a competition between resupply sorties and tactical mobility sorties will exist in the OMFTS environment. His analysis reveals that, in many cases, sustainment sorties alone require more sorties than are actually available. He also identifies that a requirement exists to manage the aerial transportation of liquid products (water and fuel) more efficiently than is currently done. By making such improvements the number of sustainment sorties could be substantially decreased.

USN Lt. Harold Viado (1999) proposes a network optimization model to plan an optimal deliver schedule. His Sea-Based Logistics Optimization Model is a mixed-integer program that determines the minimum initial level of fuel required at the Landing Zones and for the Marines of the MEU's Battalion Landing Team.

USMC Captain Norman Reitter's thesis (1999) focuses on sustainment and distribution in a sea-based environment. His Sea-Based Logistics Decision Support System is developed to assist sustainment planners in this environment to predict inventory levels of forces ashore and to assist in managing transportation assets. A utilization schedule is constructed to determine if a feasible distribution plan exists.

USMC Captain Christopher Frey (2000) models the sea-based sustainment of MEB forces deployed from amphibious shipping. Frey's optimization model analyzes twenty-seven cases (per day, over 15 days) comprising different ship-to-shore distances,

different levels of aircraft attrition, and different footprints of mobile logistics forces deployed ashore. His model optimizes the number of aircraft sorties carrying only a specific cargo. It also attempts to use all available CH-53E sorties, with the MV-22 aircraft delivering the remaining supplies. Finally, the Landing Craft Air Cushions are incorporated to deliver all the remaining supplies that cannot be delivered by air.

USMC Captain William Lambert's thesis (2001) developed an Air Plan Construction Heuristic to expedite the planning and scheduling of the aviation portion of STOM. This heuristic attempts to minimize the time required to deliver all serials ashore, subject to aircraft availability, but without modeling deck spots explicitly and the capacity of Landing Zones ashore. This thesis is currently restricted for distribution.

USN CDR. Steven L. Kennedy's thesis (2002) compares alternatives for resupplying the sea-base. Different scenarios are analyzed for how well each resupply alternative maintains the required levels of food, fuel, and ordnance at the sea-base with varying distances from an ALSS. The scenarios differ by distances between the sea-base and the ALSS, consumption rates at the sea-base, and shuttle ship alternatives. Sustainment requirements and safety stock levels are determined and compared for twelve different cases. This analysis provides insight into the type and number of resupply ships needed to maintain sustainment requirements at the sea-base. There are no current plans to incorporate the use of MPS as CLF shuttle capable.

USMC Major Michael J. Powell's thesis (2002) uses the previous work on Ship to Objective Maneuver and Sea-Based Logistics to form a more comprehensive model that considers the intricate details associated with ship-board flight operations, flight operations in general, and the inherent constraints and problems of factors such as attack aircraft and attack helicopter sorties. This thesis acknowledges the ability to plan using discrete analysis. Constraints such as deck cycle times, limited crew day (both aircrew and flight deck crew), limited deck spots, refueling considerations, and other similar needs create a very dynamic environment that is best suited to optimization modeling.

We are able to leverage from the prior sea-based studies mentioned above. Kennedy's thesis uses a MPS variant as a shuttle ship for his analysis. As mentioned above, there are no current plans to incorporate the use of MPS as CLF shuttle capable. This known fact is considered in this thesis. Hagan's thesis uses a MEU size force deployed from an ARG to conduct analysis of sea-based sustainment. This is also taken into consideration with the use of a 2015 MEB. The 2015 MEB is partially formed from an Expeditionary Strike Group (modified ARG). The scope of this thesis includes CLF ships and MPS, which provide the essential background for establishing and referencing key issues that directly or indirectly impact sea-based logistics.

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II.   MODEL DEVELOPMENT

A.   APPROACH
1.   Model Overview

We have two formulations. The first formulation (introduced in Section I.D) is built to ensure inventory levels at the sea-base are within upper and lower limits at all times.   This requirement, however, may cause some shuttles (required to meet the demand) to be used inefficiently. For example, shuttles may end up loaded well-below their capacity. In these cases, the second formulation is implemented. In this model, we manually remove one or more shuttles from the solution to the first formulation, and then minimize unmet demand. Using the first formulation gives us an ideal starting point for choosing a mix of shuttle types. This resultant mix of shuttles from the first formulation ensures that the reserve levels are never violated. This final mix is implemented in the second formulation. The second formulation attempts to fully load all shuttles while minimizing the reserve level violations which ultimately yield a particular mix of shuttles that is "best" for a specified scenario. "Best" in this context, means that we have found a reasonable compromise between the optimal solution to the first and second formulations.

In general, the second formulation results will not meet the demand for all periods, unless we maintain all shuttles from the first formulation solution, or exchange some of these shuttles by others that can meet all the demand as well. However, the planners may deem it acceptable to allow the demand to fall below the reserve level of ten days of supply (DOS) occasionally, if in turn operational costs are substantially reduced.

Our model is built with 45 one-day periods. We track each period and report type and number of vessels that are waiting at an ALSS or the sea-base, or returning to an ALSS. We also track the amount of supplies loaded and unloaded, and the sea-base percent of inventory level by commodity type. Our model incorporates a ten-day delay or travel time for a T-AKE type vessel to arrive at an ALSS after the commencement of an operation. Also, owing to the obvious hazard, incompatibility of fuel and ammunition loaded simultaneously in a T-AKE type vessel is enforced.

2. Scenario Development

The analysis in this thesis involves three Marine Corps Combat Development Command (MCCDC) provided scenarios. The scenarios (see Table 1) differ by distances from the closest ALSS to the sea-base. Each scenario emulates a small-scale contingency (SSC) war and the supported unit is tailored to a 2015 MEB. The operation lasts 45 days in all tested scenarios.

Scenario Geography	Closest ALSS	Distance (nm)
Iran (Gulf of Oman)	ALSS-1, Diego Garcia	2,500
Lagos, Nigeria	ALSS-2, Rota, Spain	3,500
North Korea	ALSS-3, U.S. Naval Base Guam	1,600

Table 1.   Geographic Scenarios and Distances from Sea-base

B.   SEA-BASE CHARACTERISICS AND SUSTAINMENT REQUIREMENTS

A MPS squadron design consists of six identical unconstrained distributed capability ships (Figure 1). The squadron provides a warehouse stowage space for the sea-base.
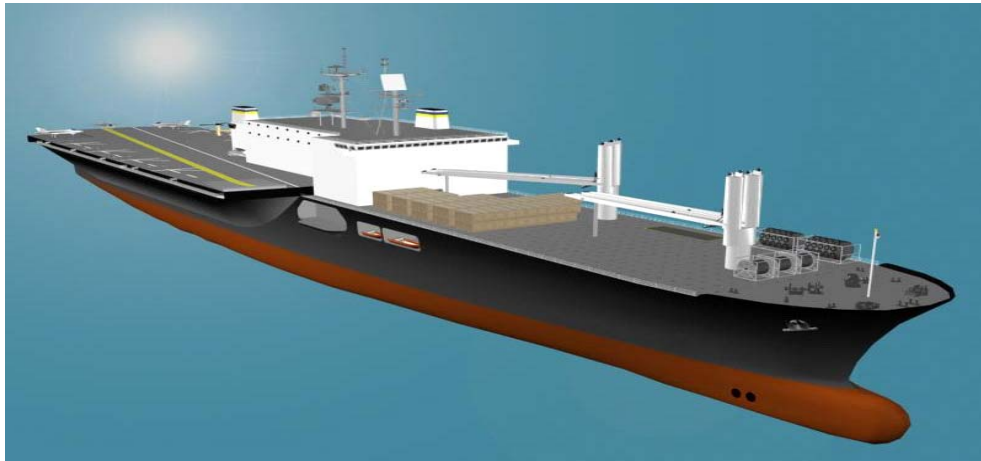

Figure 1.   MPF(F) Unconstrained Size, Distributed Capability Ship Characteristic

Table 2 shows the capacity for each commodity, each ship, and the total capacity for all six ships combined. The capacity is broken down by each ship and each commodity type. We identify all six ships together which include the entire sea-base. [CNA (2004)].

Commodity	Per Ship (short tons)	Sea-Base Total: Six Ships (short tons)
Fuel	5,247	31,482
Provisions	988	5,928
Ordnance	6,150	36,900

Table 2.   Sea-Base Capacity (short tons)

The sea-based sustainment requirements are calculated using the baseline MPF 2015 MEB Table of Organization. [United States Marine Corps (2003)]. The commodities used are fuel, provisions, and ordnance. Demand is initially consumed at a five-day surge rate and the remaining forty days of the operation are consumed at a sustain rate. Consumption rates are provided in Table 3 [CNA (2002)]. Consumption rates can be changed to accommodate a variety of cases.

Commodity	Surge Rate (short tons/day)	Sustain (short tons/day)
Fuel	1,842	1,228
Provisions	70	70
Ordnance	619	495

Table 3.   Sea-Base Consumption Rate (short tons/day)

Typically the minimum reserve level is set to fifty percent of the sea-base capacity, which should be approximately the reserve level for ten DOS at sustain rate of consumption. Initially the MPS squadron will arrive to the sea-base with 20 DOS of provisions, ordnance, and fuel.

C. SHUTTLE CHARACTERISTICS

The type of vessels used as shuttles and their associated capacities are listed in Table 4. A conservative estimate of the load and unload times for each vessel type at an ALSS and sea-base is shown in Table 5 (Kennedy 2002), assuming the shuttle is loaded in full. For example, since our scenarios use one-day time periods and it takes a T-AO 30 hours to load at an ALSS, this load time is conservatively identified as two periods. Table 6 represents speed and travel times, which are determined by distance traveled and speed of each vessel type. Travel times must also be reported by an integer number of periods.

We assume penalties for every shuttle used (first formulation) and unmet demand (second formulation) as follows:

$$\text{First formulation} \begin{cases} \text{T-AO: } 5 \\ \text{T-AOE: } 7 \\ \text{T-AKE: } 6 \end{cases} \qquad \text{Second formulation} \begin{cases} \text{Fuel: } \quad 4 \\ \text{Ammunition: } 5 \\ \text{Provision: } \quad 3 \end{cases}$$

As described in Section I.D, these penalties are subjective and after expert opinion they can be modified within the model.

Commodity	T-AO	T-AOE	T-AKE
Fuel	26,166	21,282	2,646
Provisions	N/A	650	830
Ordnance	N/A	1,800	5,080

Table 4. Shuttle Ship Capacities (short tons)

Vessel Type	Load Time (hours)	Unload Time (hours)
T-AO	30	14
T-AOE	59	24
T-AKE	74	24

Table 5. Load and Unload Time for Each Vessel Type at an ALSS and Sea-Base

Vessel Type	Speed (knots)	Distance Traveled (nm)	Travel Time (hours)
T-AO	20	1,600	80
		2,500	125
		3,500	175
T-AOE	24	1,600	67
		2,500	104
		3,500	146
T-AKE	20	1,600	80
		2,500	125
		3,500	175

Table 6.   Vessel Speed and Travel Times for Each Vessel Type

D.   PROBLEM SPECIFICATION

In this section we provide a list of problem specifications that have been used to build our mathematical models (described later in this chapter). These specifications and the model formulation capture more features than our scenarios (for example, more than one ALSS are allowed although our test cases consider one ALSS only).

1. Time:

a. Planning horizon is divided into same-length periods (45 one-day periods).

b. All time-related magnitudes such as travel times, loading and unloading times, etc. (see below) are measured in exact (integer) period units. We round all time-related data to the closest integer greater than or equal to the data.

2. ALSS:

Each scenario may have one or more ALSSs.

3. Sea-base:

The sea-base has a maximum storage capacity at any time period and also a capacity for each commodity. See below.

4. Shuttles:

a. There are several shuttle types (e.g., T-AO, T-AKE, and T-AOE).

b. We allow multiple shuttles of each type to be available for the first formulation. (Some scenarios may restrict the maximum number of selected shuttle types.) No shuttles will be in route to and from the sea-base. Some shuttles will not be available at the beginning of the operation (e.g., T-AKE will arrive at an ALSS ten days after the operation starts).

c. Shuttles may be multi-product or single product.

d. Each vessel has a maximum storage capacity at any time period, and also a capacity for each commodity.

5. Traveling between the ALSS and the sea-base:

a. Travel times are shuttle dependent.

b. A shuttle that is assigned to a route from an ALSS to the sea-base may return to the same ALSS or to a different ALSS (if any).

c. The number of trips that a given shuttle can make is limited by its speed, the distance traveled and loading and unloading times. Shuttle attrition and maintenance needs are disregarded.

6. Commodities:

a. There are multiple commodity types to be considered. (e.g., ammunition, provisions, and fuel).

b. For each type of commodity, there is a minimum inventory (supply reserve level) required at the sea-base.

c. Consumption rates for each commodity at the sea-base are known by period.

d. Some shuttle types may have commodity incompatibility, e.g., fuel and ammunition cannot be loaded at the same time (i.e., two commodity shuttle types).

e. Each ALSS has a limited commodity of each type via the Continental United States to the ALSS.

f. All commodity units are converted to short tons.

g. Commodity loading and unloading times must be considered.

E. MODEL FORMULATION

1. First Formulation

The first formulation attempts to find the best shuttle mix that can sustain the sea-base at or above ten DOS at all times. The formulation is as follows:

1. Sets

T Set of time periods (e.g., day), for $t \in T = \{0,1,2,...,45\}$.

V Type of shuttles, for $v \in V = \{$T-AKE, T-AO, T-AOE$\}$.

S Set of potential shuttles, for $s \in S$. (We allow a sufficiently large number of each type, so there is virtually no restriction in the number of shuttles that can be selected for the mix.)

I Set of Advance Logistic Support Sites, for $i \in I$.

C Set of commodity types, for $c \in C = \{$Fuel, Ammo, Provisions$\}$.

H Set of period types regarding demand for $h \in H = \{$Sustain, Surge$\}$.

$N^V \subset C \times C \times V$, Subset of triplets (c,c',v) where shuttle type v cannot carry commodity c and commodity c' at the same time.

$N^S \subset C \times C \times$ S, Subset of triplets (c,c',s) where shuttle s cannot carry commodity c and commodity c' at the same time. Calculated as follows: $(c,c',s) \in N^S$ if $(c,c',v_s) \in N^V$.

$M^S \subset S \times C$, Subset of pairs (s,c) where $(s,c,c') \in N^S$ for any $c' \in C$.

2. Data (and units)

v_s — Shuttle type for each shuttle s.

n_{iv}^{V} — Travel time for shuttle type v from ALSS i to the sea-base and vice versa (periods).

n_{si}^{S} — Travel time for shuttle s from ALSS i to the sea-base and vice versa (periods). Calculated as $n_{si}^{S} = n_{iv_s}^{V}$.

$resup_{cit}$ — Resupply of commodity c at ALSS i in period t (tons).

Bd_c — Baseline demand for commodity c (tons).

$Dc_{c,h}$ — Demand coefficient for commodity c in any period type h (tons).

t_v^{V0} — Time when shuttle type v becomes available (period index).

t_s^{S0} — Time when shuttle s becomes available. Calculated as $t_s^{S0} = t_v^{V0}$ (period index).

h_t — Period type for period t.

dem_{ct} — Demand of commodity c at sea-base in period t (tons). Calculated as $dem_{ct} = Bd_c\, Dc_{c,h_t}$.

q_{cv}^{V} — Capacity of commodity c on shuttle type v (tons).

q_{cs}^{S} — Capacity of commodity c on shuttle s (tons). Calculated as $q_{cs}^{S} = q_{cv_s}^{V}$.

q_v^{TV} — Total combined capacities of shuttle type v (tons).

q_s^{TS} — Total combined capacities of shuttle s (tons). Calculated as $q_s^{TS} = q_{v_s}^{TV}$.

n_v^{VL}, n_v^{VU} — Loading and unloading time, respectively, for shuttle type v (periods).

n_s^{SL}, n_s^{SU} — Loading and unloading time, respectively, for shuttle s (periods). Calculated as $n_s^{SL} = n_{v_s}^{VL}$, $n_s^{SU} = n_{v_s}^{VU}$.

b_c^{O} — Initial inventory of commodity c at the sea-base (tons).

$\underline{B}_c$ — Lower bound (reserve level) for commodity c (tons).

$\bar{B}_c$ Upper bound (capacity of sea-base) for commodity c (tons)

p_v^V Penalty for using a ship of type v

(penalty units/shuttle).

p_s^S Penalty for using shuttle s. Calculated as $p_s^S = p_{v_s}^V$ (penalty units/shuttle).

ε Small penalty to discourage unnecessary trips and waiting at the sea-base. We

use $\varepsilon = 0.01$.

3. Decision Variables

Binary:

X_{cst} 1 if shuttle s is carrying any commodity type c in period t, 0 otherwise.

D_{sit} 1 if shuttle s departs from ALSS i to sea-base in period t, 0 otherwise.

W_{sit}^I 1 if shuttle s waits at ALSS i in period t, 0 otherwise.

W_{st}^B 1 if shuttle s waits at sea-base in period t, 0 otherwise.

R_{sit} 1 if shuttle s returns from sea-base to ALSS i in period t, 0 otherwise.

E_s 1 if shuttle s is used, 0 otherwise.

Continuous:

K_{cst} Amount of commodity c on shuttle s in period t (tons).

L_{csit} Amount of commodity c loaded on shuttle s at ALSS i in period t (tons).

U_{cst} Amount of commodity c unloaded from shuttle s to the sea-base in period

t (tons).

A_{cit} Inventory of commodity c at ALSS in period t (tons).

B_{ct} Inventory of commodity c at the sea-base in period t (tons).

4. Formulation

Initial conditions:

$$\sum_i W^I_{si0} = 1, \quad \forall s \tag{2.1}$$

$$W^B_{s0} = 0, \quad \forall s \tag{2.2}$$

$$D_{si0} = 0, \quad \forall s,i \tag{2.3}$$

$$R_{si0} = 0, \quad \forall s,i \tag{2.4}$$

$$B_{c0} = b^0_c, \quad \forall c \tag{2.5}$$

$$K_{cs0} = 0, \quad \forall c,s \tag{2.6}$$

$$L_{csit} = 0, \quad \forall csit \mid t < t^{S0}_s \tag{2.7}$$

Inventory at ALSS i:

$$A_{ci0} = r_{ci0}, \quad \forall c,i \tag{2.8}$$

$$A_{cit} = A_{ci,t-1} - \sum_s L_{csit} + r_{cit}, \quad \forall c,i,t \mid t \geq 1 \tag{2.9}$$

Loading, unloading and carrying cargo:

$$K_{cs0} = 0, \quad \forall c,s \tag{2.10}$$

$$K_{cst} = K_{cs,t-1} - \sum_i L_{csit} + U_{cst}, \quad \forall c,s,t \mid t \geq 1 \tag{2.11}$$

$$\sum_c K_{cst} \leq q^{TS}_s, \quad \forall s,t \tag{2.12}$$

$$K_{cst} \leq q^S_{cs} \quad \forall c,s,t \tag{2.13}$$

$$L_{csit} \leq \frac{q^S_{cs}}{n^{SL}_s} \cdot W^I_{csit}, \quad \forall c,s,i,t \tag{2.14}$$

$$U_{cst} \leq \frac{q^S_{cs}}{n^{SU}_s} \cdot W^B_{cst}, \quad \forall c,s,t \tag{2.15}$$

$$E_s \geq D_{sit}, \quad \forall s,i,t \tag{2.16}$$

Commodity Incompatibility:

$$X_{cst} + X_{c'st} \leq 1, \quad \forall t, \forall (c,c',s) \in N^S \tag{2.17}$$

$$q^S_{cs} X_{cst} \geq K_{cst}, \quad \forall t, \forall (c,s) \in M^S \tag{2.18}$$

Inventory at the sea-base:

$$B_{ct} = B_{c,t-1} + \sum_s U_{cst} - dem_{ct}, \quad \forall c,t \,|t \geq 1 \tag{2.19}$$

$$D_{sit} \leq W^I_{si,\,t-1}, \qquad\qquad \forall s,i,t \,|t \geq 1 \tag{2.20}$$

$$W^B_{st} \leq \sum_{i\,|\,t \geq n^S_{si}} D_{si,\,t-n^S_{si}} + W^B_{s,t-1}, \qquad \forall s,t|t \geq 1 \tag{2.21}$$

$$W^B_{st} \geq \sum_{i\,|\,t \geq n^S_{si}} D_{si,\,t-n^S_{si}}, \qquad\qquad \forall s,t|t \geq 1 \tag{2.22}$$

$$W^I_{sit} \leq R_{si,t-n^S_{si}} + W^I_{si,t-1}, \qquad \forall s,i,t|t \geq 1 \tag{2.23}$$

$$W^I_{sit} \geq R_{si,t-n^S_{si}}, \qquad\qquad \forall s,i,t|t \geq 1 \tag{2.24}$$

$$R_{sit} \leq W^B_{s,\,t-1}, \qquad\qquad \forall s,i,t \,|t \geq 1 \tag{2.25}$$

$$B_{ct} \geq \underline{B}_c, \qquad\qquad \forall c,t \tag{2.26}$$

$$B_{ct} \leq \overline{B}_c, \qquad\qquad \forall c,t \tag{2.27}$$

Logical constraints:

$$\sum_i D_{sit} + \sum_i W^I_{sit} + \sum_i R_{sit} + W^B_{st} \leq 1, \qquad \forall s,t \,|t \geq 1 \tag{2.28}$$

$$X,D,W^I,R,E \in \{0,1\} \tag{2.29}$$

$$K,L,U,A,B \geq 0 \tag{2.30}$$

Objective Function:

$$\text{Min} \sum_s p^S_s E_s + \sum_s \sum_i \sum_t \varepsilon D_{sit} + \sum_s \sum_t \varepsilon W^B_{st} \tag{2.31}$$

Overall, the first formulation can be stated as follows:

(First formulation): Min (2.31)

s.t. (2.1) – (2.30)

2.   Second Formulation

In the second formulation, we specify a given mix of shuttles. That is, the number of shuttles of each type is limited, typically by the solution provided by the first

formulation from which we may have removed or exchanged select shuttles. Additional formulation for this problem is as follows:

 a. Sets

Replace S from the first formulation by S given by the analyst. (see Section II.A.1)

 b. Data (and units)

pen_c Penalty per unit of unmet demand c (penalty units/ton).

 3. Decision Variable

Continuous:

Y_{ct} Unmet demand of commodity c in time period t (tons).

 4. Formulation

Objective Function:

Replace $\text{Min} \sum_s p_s^S E_s + \sum_s \sum_i \sum_t \varepsilon D_{sit} + \sum_s \sum_t \varepsilon W_{st}^B$, from the first formulation by:

$$\text{Min} \sum_s pen_c Y_{ct} + \sum_s \sum_i \sum_t \varepsilon D_{sit} + \sum_s \sum_t \varepsilon W_{st}^B \qquad (2.32)$$

 Inventory at the sea-base:

Replace (2.26): $B_{ct} \geq \underline{B}_c, \forall c,t$ by:

$$B_{ct} + Y_{ct} \geq \underline{B}_c, \qquad\qquad \forall c,t \qquad\qquad (2.33)$$

$$Y \geq 0 \qquad\qquad (2.34)$$

 The second formulation can be shortly stated as follows:

(Second formulation): Min (2.32)

$$\text{s.t.} \begin{cases} (2.1) - (2.25) \\ (2.27) - (2.30) \\ (2.33) - (2.34) \end{cases}$$

3. Formulation Description

Equations (2.1) to (2.6) establish rules at the start of the operation. The shuttles are forced to be at an ALSS, and the amount of each commodity type loaded is zero tons. Equation (2.7) forces some shuttles to be idle until a pre-specified time. This captures the fact that some shuttles, such as T-AKE, may not be available for the first ten days of the operation.

The inventory balance at an ALSS is represented by Equations (2.8) and (2.9).

Loading, unloading, and carrying a commodity aboard a shuttle is represented by Equations (2.10) to (2.17). The amount of commodity on a shuttle at the start of the operation is zero. Thereafter, the amount of commodity on a shuttle is balanced by commodity loaded and unloaded from the shuttle. The amount loaded cannot exceed the loading capacity per time period, and it requires the shuttle to be physically located (waiting) at the ALSS.

Commodity incompatibility is represented by Equations (2.18) and (2.19). We ensure that two incompatible commodities are not loaded together on the same shuttle (e.g., fuel and ammunition are not allowed to be loaded at the same time on a T-AKE type vessel) and, at the same time, ensure the amount of each commodity type cannot exceed the shuttle capacity for the commodity.

Inventory balance at the sea-base is represented by equations (2.20) to (2.28). The amount of inventory at the sea-base must not exceed the total capacity of the sea-base and each commodity's capacity.

Equation (2.29) represents logical constraints. At most one of the following can occur simultaneously for each shuttle: Departing an ALSS, waiting at an ALSS, returning to an ALSS, and waiting at the sea-base.

The first objective function formulation (2.32) minimizes penalties imposed on the shuttles (i.e., the smaller the penalty assigned implies a more economical shuttle type). Also, the first formulation discourages departure from an ALSS and waiting at the sea-base, if not needed. Minimizing the penalties imposed on shuttle types, forces the first formulation to choose the most economical mix of shuttles. When multiple optimal

solutions exist, the small penalty term minimizing departures from an ALSS makes our model choose the solution with fewest number of trips. Likewise, by minimizing the wait at the sea-base, the model reduces ships waiting unnecessarily, and prevents shuttles from unloading at lower rates per day than are actually possible.

The objective function for the second formulation (2.33) replaces the first objective in equation (2.32). The second formulation minimizes unmet demand assuming a pre-specified shuttle mix is given. Penalties for unmet demand are imposed on the commodity type, i.e., the higher the penalty assigned to a commodity type implies the more important that commodity type is (e.g., we can make fuel more important than ammunition, and ammunition more important than provisions). As in the first formulation, other small penalties are added for consistency.

In addition to the second objective function, the second formulation replaces constraint (2.27) by an elastic demand constraint (2.34).

III. RESULTS

A. OVERVIEW

We test our three scenarios with the first and second formulations described in Section II.E. Table 7 displays the overall results for the two formulations.

The results presented are generated using three scenarios shown in Table 7. The scenarios represent a geographic region in which shuttles will travel from an ALSS to the sea-base. All scenarios are analyzed using the surge consumption rate for the first five days at the start of the operation and the remaining 40 days are consumed at a sustain rate. An exception is the second of Nigeria's scenarios with the first formulation (see Table 7), where we use a 45-day surge rate for the duration of the operation. This consistent surge-rate is chosen to demonstrate the adaptability that our models provide for cases where a military operation may extend its surge consumption rate beyond a planned time.

The first formulation uses a shuttle pool (undisclosed number of shuttle types available) and determines the best mix of shuttles to be used. This resultant mix from the first formulation ensures that the reserve levels are never violated. The second formulation takes as a given the manually entered number or available shuttles and computes average unmet demand, and worst day unmet demand. The second formulation attempts to minimize the reserve level violations. Results are analyzed in more detail in the following section.

Scenario	Consumption Rate by Day	First Formulation		Second Formulation		
		Shuttle Pool	Best Mix	Available Shuttles (manually inputted)	Average Unmet Demand (% below reserve level)	Worst Day (% below reserve level)
Iran	5 days surge 40 days sustain	T-AO T-AKE T-AOE	1 T-AKE 1 T-AOE	1 T-AOE	Fuel: 0.0 Prov: 0.0 Ammo: 3.7	N/A N/A 7.2
Nigeria	5 days surge 40 days sustain	T-AO T-AKE T-AOE	1 T-AKE 1 T-AOE	1 T-AOE	Fuel: 0.0 Prov: 0.0 Ammo: 6.5	N/A N/A 10.0
	45 days surge	T-AO T-AKE T-AOE	1 T-AKE 2 T-AOE	2 T-AKE 1 T-AOE	Fuel: 8.9 Prov: 0.0 Ammo: 3.1	21.8 N/A 4.6
North Korea	5 days surge 40 days sustain	T-AO T-AKE T-AOE	1 T-AOE	N/A	N/A	N/A
		T-AO T-AKE	1 T-AO 1 T-AKE	N/A	N/A	N/A

Table 7.   Results Matrix for the First and Second Formulations

B.   ANALYSIS OF RESULTS

Figures 2 to 7 and Figure 9 to 10 represent a Time-Space Transportation Network. For example, Figure 2 shows the location of two shuttles by period: the T-AOE will depart the ALSS in period 6 (after being loaded), and will arrive at the sea-base in period 10. The T-AKE will depart the ALSS in period 24 and will arrive at the sea-base in period 29.

In the Iran scenario, the first formulation yields the use of one T-AKE and one T-AOE. Each shuttle makes two trips to the sea-base in the 45-day horizon.

Although the demand is met by keeping each commodity above its reserve level, the inventory levels are maintained at a superior level (defined as being above 55% during 80% of the time) with an inefficient use of shuttles. (We deem the use of shuttle capacity as inefficient when either shuttle departs an ALSS and is not loaded to at least 80% of its capacity.) This prompts us to remove the T-AKE type vessel in order to test the second formulation with the remaining T-AOE. Figure 3 represents the Iran scenario for the second formulation. The T-AOE makes a total of three trips to the sea-base. The average reserve level violation for ammunition is 3.7%, with the worst day (% below reserve level) yielding 7.2%. This, although below the desired reserve level of 50%, can be considered acceptable.
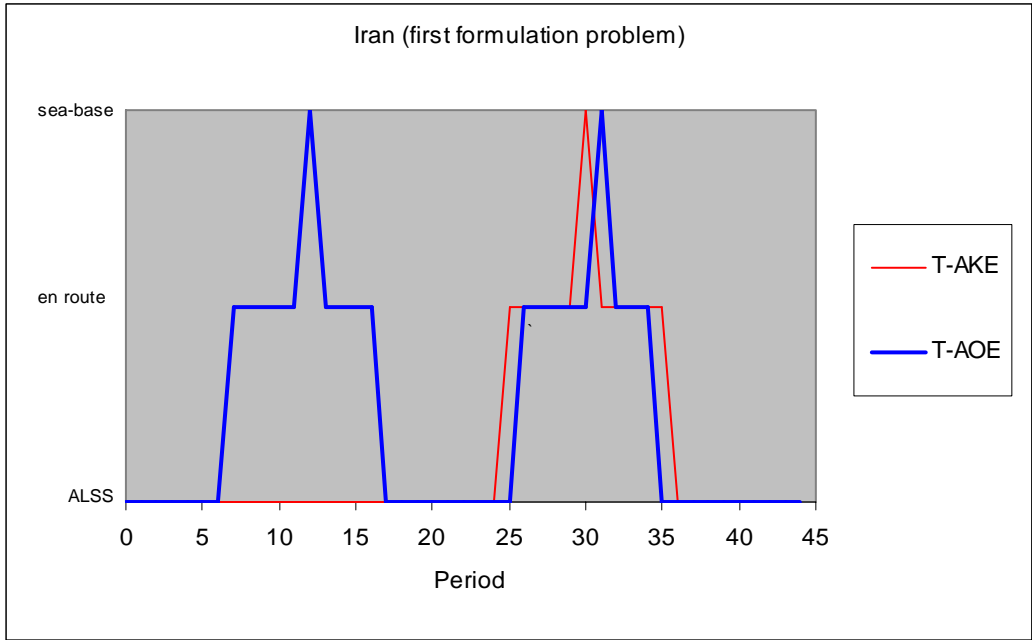
Figure 2.   Iran Scenario (first formulation), 5 Days Surge, 40 Days Sustain
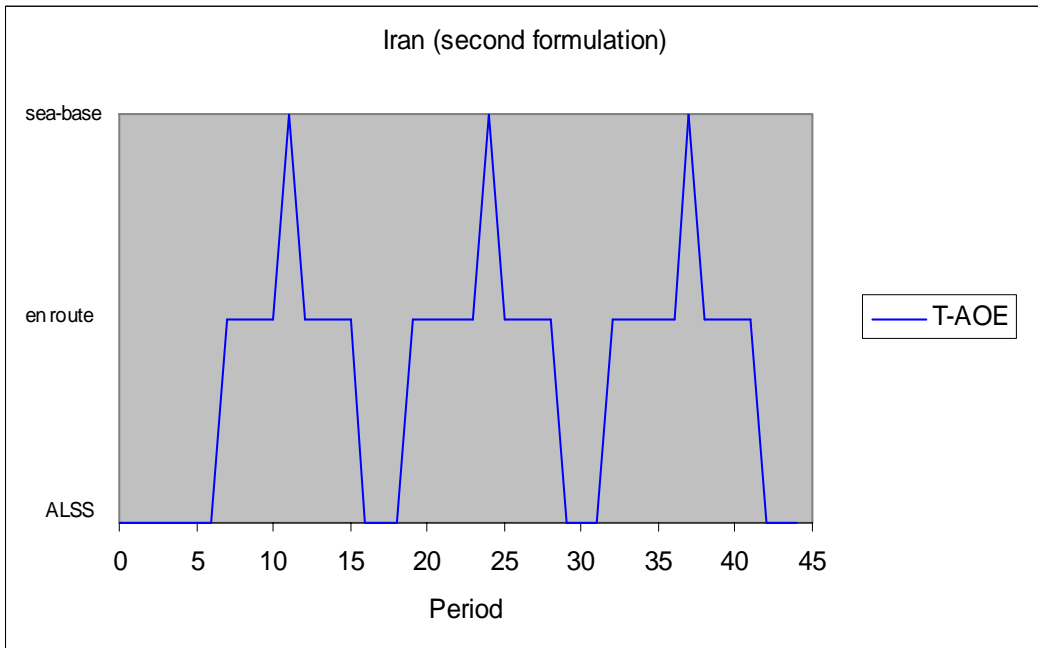

Figure 3.   Iran Scenario (first formulation), 5 Days Surge, 40 Days Sustain

Figure 4 represents the Nigeria scenario with the second formulation. Inventory levels are similar to the Iran scenario with the first formulation and the same optimal shuttle mix is chosen: One T-AKE and one T-AOE. However, because the Nigeria

scenario has a distance of 3,500nm (1,000nm further than the Iran scenario), shuttles are loaded up to their maximum capacity. Owing to these mixes of shuttles and inventory levels, we remove one T-AKE leaving one T-AOE for the Nigeria scenario with the second formulation (Figure 5). The average reserve level violation for ammunition is 6.5% with the worst day yielding 10% below reserve level. Like the Iran scenario, this solution may be considered acceptable.
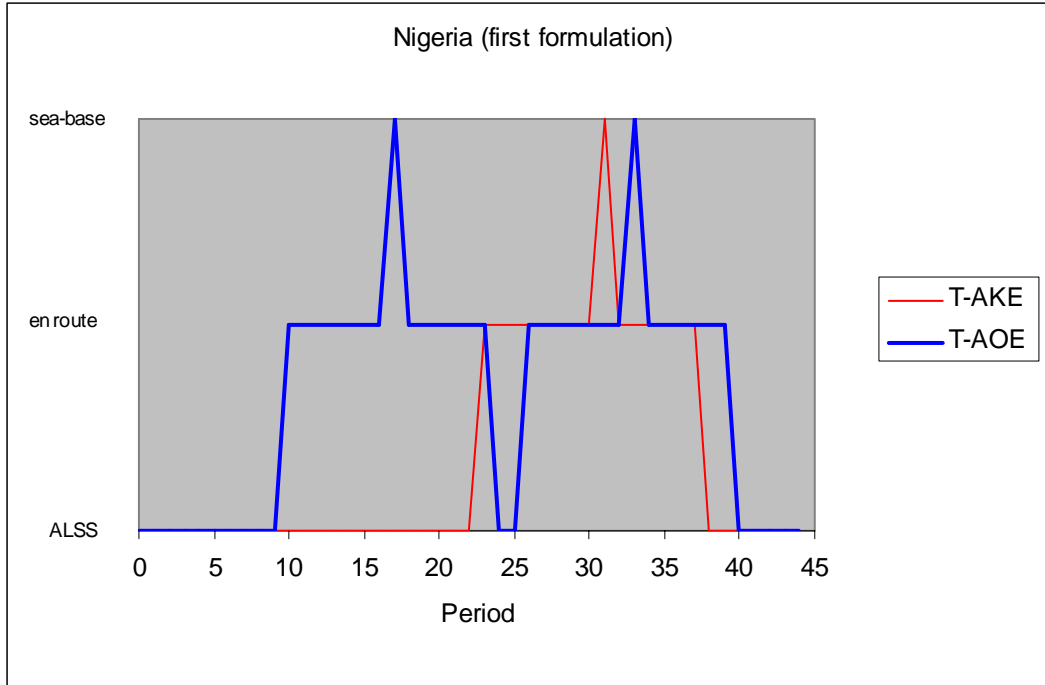

Figure 4.   Nigeria Scenario (first formulation), 5 Days Surge, 40 Days Sustain

The T-AOE is usually not a shuttle ship. Its role is typically a station ship at the sea-base. We use it in the shuttle role in our thesis because it is a three-commodity ship, which provides more capability, and to gain insight into the benefits of its use as a shuttle ship. The T-AKE will be typically delayed between 5 to 10 days before arriving to an ALSS at the start of an operation. We account for a 10-day delay in our models. As mentioned in Section II.C, the speed for the T-AOE, T-AKE and T-AO are assumed to be 24, 20, and 20 knots, respectively.
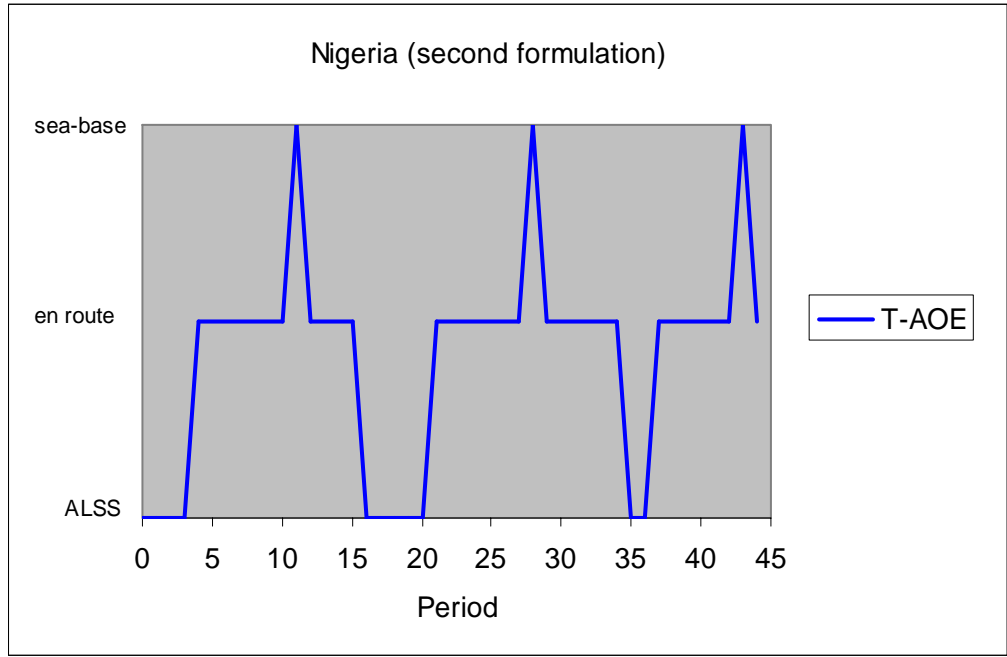
Figure 5.   Nigeria Scenario (second formulation), 5 Days Surge, 40 Days Sustain

To further show the complementary capability in the first and second formulations, a difficult hypothetical situation is implemented for the Nigeria scenario. Although unlikely, a surge demand of 45 days is applied. Figure 6 represents this scenario with the first formulation. All shuttle types are available for use. The results yield the use of one T-AKE and two T-AOEs. The inventory levels and loads are sufficient; however, the commodity provision shows the most superior levels of inventory by maintaining inventory levels at or above 57.72%. Although this mix of shuttles is adequate, we try a different combination that will yield a more economical mix. Figure 7 represents the solution with the second formulation. Two T-AKEs and one T-AOE are chosen for this scenario (i.e., we replace one T-AOE from the first formulation solution by one T-AKE). The average unmet demand for fuel is 8.9% with the worst day yielding 21.8%. The average unmet demand for ammunition is 3.1% with the worst day yielding 4.6%. The inventory levels for each commodity type with the second formulation are depicted in Figure 8. A comparison is shown between Figure 7 and Figure 8. For example, when the T-AKE 1 and T-AOE vessels reach the sea-base in time period 10 (see Figure 7), after unloading ammunition, it is clear that the inventory level goes up

28

(see Figure 8) from 80.55% to 90.41%. Although there a few days (by the end of the planning horizon) when average inventory levels for fuel are remarkably lower than the required level, they may still be considered acceptable.
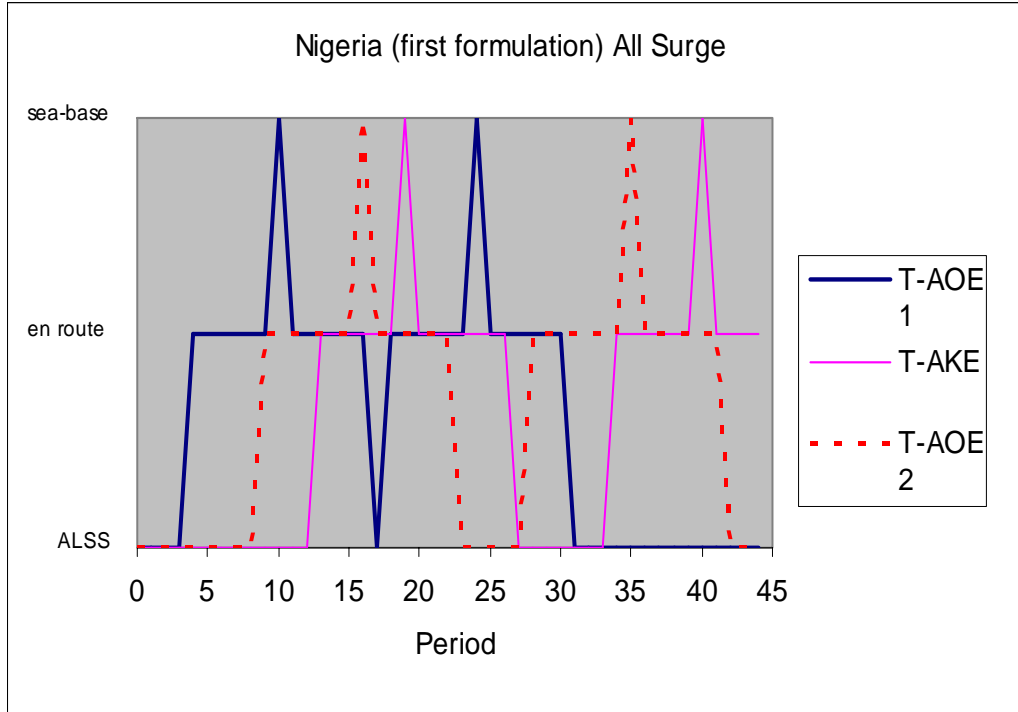

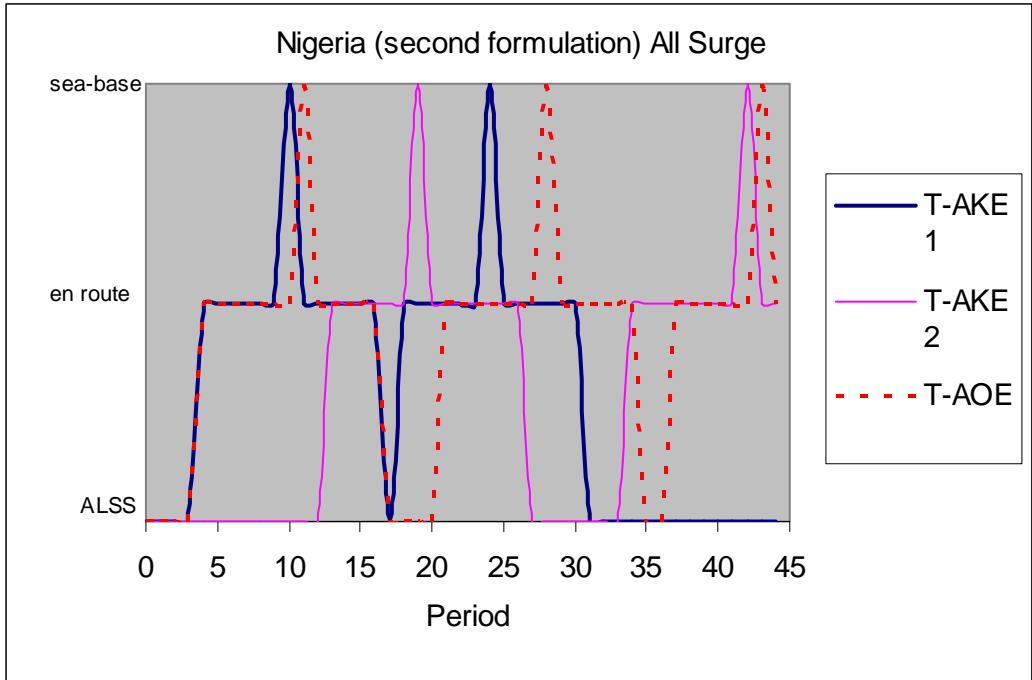Figure 6.   Nigeria Scenario (first formulation), 45 Days Surge

Figure 7. Nigeria Scenario (second formulation), 45 Days Surge
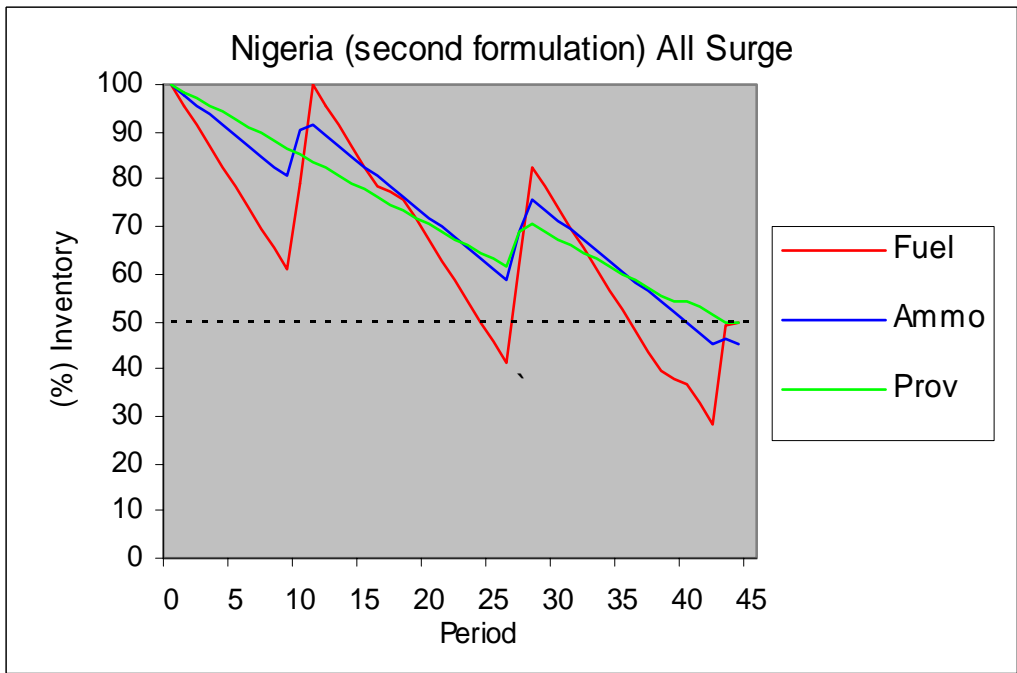

Figure 8. Nigeria Scenario (second formulation), 45 Days Surge

Figure 9 represents the North Korea scenario with the first formulation. The distance from an ALSS to the sea-base is 1,600nm. The first formulation yields the use of one T-AOE with efficient commodity stowage and superior inventory levels maintained at the sea-base. At this point, we explore a new contingency: The T-AOE is deemed unavailable. The updated results yield the use of one T-AKE and one T-AO (Figure 10). This is less economical than one T-AOE. In this case, however, the second formulation is not used because the optimal results from the first formulation render an efficient use of shuttles.

The North Korea scenarios demonstrate the validity of the first formulation solution. Once there is an efficient mix of shuttles chosen by the first formulation it is not possible to find a better solution (in terms of the first formulation) without leaving unmet demand.
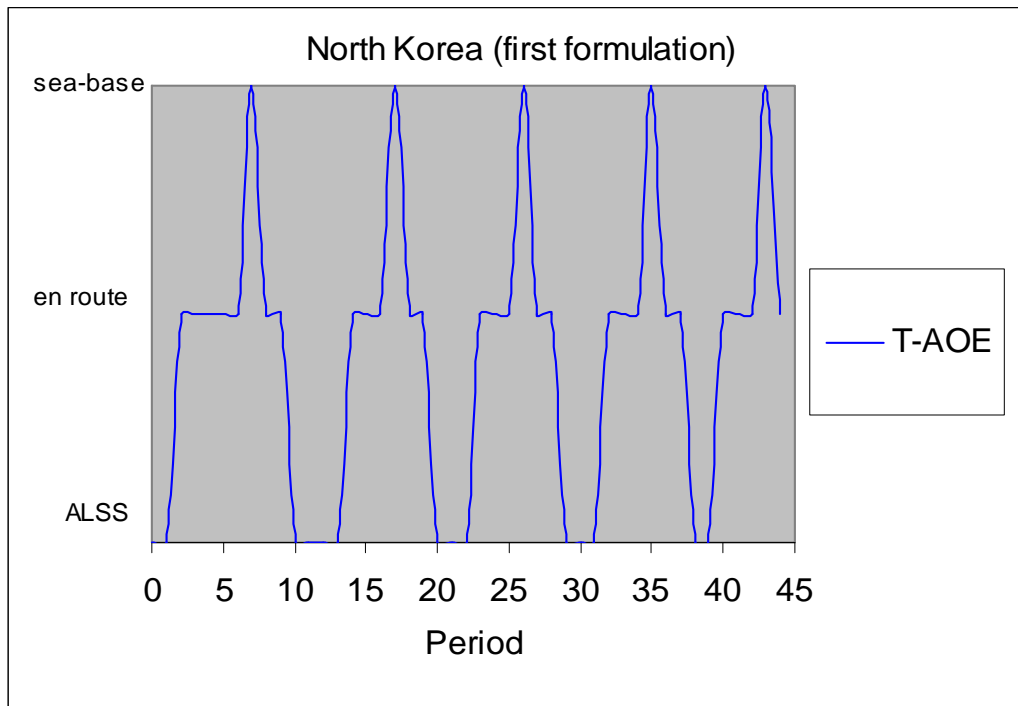

Figure 9.   North Korea Scenario (first formulation), 5 Days Surge, 40 Days Sustain
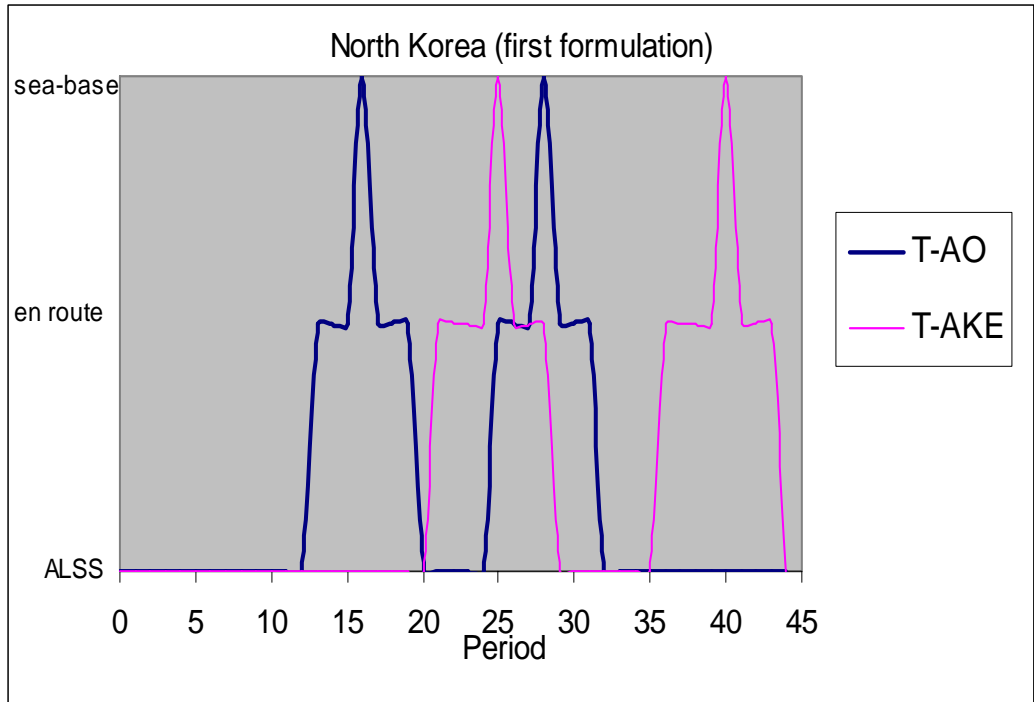
Figure 10.   North Korea Scenario (first formulation), 5 Days Surge, 40 Days Sustain

IV.   CONCLUSIONS

A.   OVERVIEW

Sea-based logistics place a demand on the USN supply system. The USMC will have to adopt a USN supply system in order to foster one of its tenants of Sea-based Logistics namely In-Stride Sustainment. This thesis may help us to identify strains that may be placed on the USN. The optimization models in this thesis use logistical constraints that are part of Sea-based Logistics to identify shuttle requirements. The models in this thesis accommodate (and are driven by) required inventory levels by time period, in addition to the other features as part of the sea-base resupply logistics. Unlike simulation models, our optimization models capture logistical constraints and use two formulations that complement each other. Models are represented through a time-space transportation network from an ALSS directly to the sea-base.

For a sea-base at a distance of between 3,500nm and 2,500nm from an ALSS, it appears that one T-AOE is efficient for meeting the requirements for sustainment with minimum unmet demand (assuming 5 days surge, 40 days sustain). At a distance of 1,600nm either one T-AOE, or one T-AKE and one T-AO will suffice. In cases where supplies are being consumed at a surge rate for longer periods planned, this model provides adaptability and can possibly be used to enhance crisis planning. For distances further than 3,500nm, the availability of more shuttles will be required. However, this thesis provides a potential tool for optimally choosing the most economical mix of shuttles while minimizing unmet demand (if any).

B.   RECOMMENDATIONS FOR FURTHER STUDIES

Additional work would allow our two formulations to be incorporated into one model as one objective function. The challenge here is to analyze tradeoffs between the two conflicting objectives: minimizing costs and minimizing unmet demand.

The model presented in this thesis could be enhanced if more Maritime Prepositioning Ships (MPS) configurations were considered. For the scenarios we tested,

additional research could involve actual supply rates from CONUS to an ALSS (i.e., incorporate accurate availability of commodity types at an ALSS via CONUS). Test scenarios with more than one ALSS and using MPS as a shuttle (if its load at the sea-base is zero) could also be conducted.

Another consideration is the potential for an enemy to disrupt our logistics network. Interdiction can be considered at different levels, such as an ALSS, to shuttle in route to and from the sea-base, and even at the sea-base.

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