



**NAVAL
POSTGRADUATE
SCHOOL**

MONTEREY, CALIFORNIA

THESIS

**RESOURCE BURDEN OF LOGISTICS TO NAVY SHIPS
UNDER THREAT SCENARIOS**

by

Brendon Hathorn

March 2013

Thesis Advisor:
Second Reader:

Eva Regnier
Dan A. Nussbaum

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 26-3-2013		2. REPORT TYPE Master's Thesis		3. DATES COVERED (From — To) 2011-01-07—2013-3-29	
4. TITLE AND SUBTITLE Resource Burden of Logistics to Navy Ships Under Threat Scenarios				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Brendon Hathorn				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Department of the Navy				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited					
13. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol Number: N/A					
14. ABSTRACT What is the fully burdened cost of supply to combatant ships in remote locations? Currently, there are directives that require an estimate of the fully burdened cost of energy in a number of analyses in acquisition, but the approved method(s) for estimating this cost are still being developed. Several analyses fail to account for the indirect costs associated with supplying logistics assets. Therefore, we propose a method for estimating the fully burdened cost of supply in a self-sustaining logistics network in which local infrastructure cannot be counted on to supply logistics assets. This thesis develops this method for the US Navy by building a model of Navy supply transport and using it to estimate the Total Resource Requirement of supply at various points in the network, and explore how that cost changes as a function of the force protection required for the logistics vessels.					
15. SUBJECT TERMS Fully Burdened Cost of Energy, Naval Logistics, Acquisition, Convoy, Escorts					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 63	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)

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**RESOURCE BURDEN OF LOGISTICS TO NAVY SHIPS UNDER THREAT
SCENARIOS**

Brendon Hathorn
Lieutenant, United States Navy
B.S., Management, Old Dominion University, 2005

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

**NAVAL POSTGRADUATE SCHOOL
March 2013**

Author: Brendon Hathorn

Approved by: Eva Regnier, Associate Professor
Thesis Advisor

Dan A. Nussbaum, Visiting Professor
Second Reader

Robert F. Dell, Professor
Chair, Department of Operations Research

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ABSTRACT

What is the fully burdened cost of supply to combatant ships in remote locations? Currently, there are directives that require an estimate of the fully burdened cost of energy in a number of analyses in acquisition, but the approved method(s) for estimating this cost are still being developed. Several analyses fail to account for the indirect costs associated with supplying logistics assets. Therefore, we propose a method for estimating the fully burdened cost of supply in a self-sustaining logistics network in which local infrastructure cannot be counted on to supply logistics assets. This thesis develops this method for the US Navy by building a model of Navy supply transport and using it to estimate the Total Resource Requirement of supply at various points in the network, and explore how that cost changes as a function of the force protection required for the logistics vessels.

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List of Acronyms and Abbreviations

AOR Area of Responsibility

ASD (OEPP) Assistant Secretary of Defense for Operational Energy Plans and Programs

CAIG Cost Analysis and Improvement Group

CONUS Continental United States

CG Guided-missile Cruiser

CLF Combat Logistics Force

CLFP Combat Logistics Force Planner

CNO Chief of Naval Operations

CVN Aircraft Carrier (Nuclear)

DAG Defense Acquisition Guidebook

DAU Defense Acquisition University

DDG Guided-missile Destroyer

DESC Defense Energy Support Center

DFM Distillate Fuel Marine (NATO F76)

DFSP Defense Fuel Support Point

DHNDAA Duncan Hunter National Defense Authorization Act

DLA-E Defense Logistics Agency Energy

DOD Department of Defense

DON Department of the Navy

DSB Defense Science Board

FBCF Fully Burdened Cost of Fuel

FBCE Fully Burdened Cost of Energy

FFG Guided-missile Frigate

HVU High Value Unit

ILP Integer Linear Program

IO Input-Output

JP5 Naval Aviation Fuel (NATO F44)

LCC Life Cycle Costs

LCS Littoral Combat Ship

LHD Amphibious Assault Ship

LPD Amphibious Transport Dock Ship

LSD Amphibious Dock Landing Ship

MSC Military Sealift Command

MDAP Major Defense Acquisition Programs

NTFBCM Naval Threat-Based Fully Burdened Cost Model

NPS Naval Postgraduate School

OASN Assistant Secretary of the Navy

OCONUS Outside the Continental United States

OES Operational Energy Strategy

OESIP Operational Energy Strategy: Implementation Plan

USD (AT&L) Under Secretary of Defense (Acquisition, Technology, and Logistics)

PACOM Pacific Command

QDR Quadrennial Defense Review

SECDEF Secretary of Defense

SECNAV Secretary of the Navy

SSBN Ballistic Missile Submarine (Nuclear)

SSGN Guided-missile Submarine (Nuclear)

SSN Submarine (Nuclear)

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

TRR Total Resource Requirement

UNREP Underway Replenishment

USG United States Government

USMC United States Marine Corps

USN United States Navy

VAMOSOC Visibility and Management of Operating and Support Costs

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Executive Summary

The United States Navy serves both at home and in forward-operating areas all over the globe. As a result the Navy has the most far-reaching global supply network in the Department of Defense (DOD). Replenishment of Navy assets, at virtually any position on the globe, is a massive and complex undertaking, with proportionate costs and planning required. The total resource requirement (TRR) of delivering energy (fuel) includes second-order costs such as food, personnel, protection assets, and repair parts for logistics activities. The TRR is even higher if additional naval combatants must be employed to protect logistics assets that are under threat.

This thesis seeks to estimate the TRR for a challenged logistics network that requires a combat escort, using a spreadsheet-based input-output (IO) model based on a logistics network. Vessel planning factors (consumption rates) determine the costs on each stage. In each scenario, supply follows a route from a single source to a single destination node. Each stage has a specific threat level that determines the force protection required to safely allow Combat Logistics Forces (CLF) to transit the stage. A user-defined convoy composition is applied to counter the specific threat level. IO analysis is then applied to determine the TRR for the entire route, from source to destination. The model is implemented in a spreadsheet, in which the user may define the final demand destination node. The source node can be explicitly defined by the user or be determined by a shortest path optimization.

The result is a robust, flexible model that can give insight into fully burdened costs of fuel—or other supply—anywhere within the global realm of naval operations under various threat scenarios, using any surface naval combatant mixture in the United States naval inventory. Six separate scenarios are modeled to supply forces operating near the Spratly Islands. The scenarios vary the CLF assets utilized, the threat level, as well as the source node. For a scenario in which the supply must come from the continental United States (CONUS), the TRR is found to be between 1.258 to 1.914 additional short tons required per short ton delivered, depending on the CLF asset employed. Using the TRR, as well as stage-specific estimates of operating and support (O&S) costs, total costs may be estimated, which gives a lower bound on the fully burdened cost of supply for a given scenario. With the same scenario of supply originating in CONUS, the total cost per delivered short ton is observed to be \$1,639 to \$3,144.

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Acknowledgements

I would first like to acknowledge my wonderful wife, Kelly, for her unyielding support of not only me but my career as well. She is an amazing mother, wife, and person. You are unshakable and I am so blessed to be able to call you my wife and friend. I love you.

I would also like to acknowledge my amazing sons, Colin and Logan. The two of you were the perfect medicine to remedy the ‘Thesis Blues.’ I love you both.

I would also like to thank my parents who seem to have instilled this idea to constantly challenge myself to difficult things. This was among the more challenging undertakings in my career. Thank you for your love and example.

Lastly, I would like to thank the diligent, patient help of my thesis advisers, Dr. Regnier and Dr. Nussbaum. Your availability and devotion to this project was instrumental to its completion. I would also like to thank Dr. Carlyle for being available for my coding questions. Literally, I could not have done it without all of you.

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CHAPTER 1:

Introduction

The United States Navy serves both at home and in forward-operating areas all over the globe. As a result the Navy has the most far-reaching global supply network in the Department of Defense (DOD). Replenishment of Navy assets, at virtually any position on the globe, is a massive and complex undertaking, with proportionate costs and planning required. The total resource requirement (TRR) of delivering energy (fuel) includes second-order costs such as food, personnel, protection assets, and repair parts for logistics activities. The TRR is even higher if additional naval combatants must be employed to protect logistics assets that are under threat. The 2009 Duncan Hunter National Defense Authorization Act (DHNDAA), passed in 2008, directs the services to calculate the fully burdened cost of fuel (FBCF) for use in acquisition decisions within the DOD. To date, the TRR for sea-based sections of the global supply network that would require convoys or escorts to meet operational demands, due to threat conditions, has not been evaluated. This thesis seeks to apply the principles of Input-Output (IO) analysis to understand the FBCF implications of threatened, or opposed, access for sea-based logistics.

1.1 DOD Energy Policy

Energy has not traditionally played a vital role in policy and acquisition decisions. In 1999, considerations regarding energy, and the costs associated with its use and transport, began in earnest. Recently, the DOD has made a significant push to determine the impacts of the energy demand of its weapons systems upon the supply chain as a whole. The Office of the Under Secretary of Defense (Acquisition, Technology, and Logistics) (USD [AT& L]) requested that the Defense Science Board (DSB) “identify the technologies that improve fuel efficiency of the full range of weapons platforms (land, sea, and air) and assess their operational, logistics, costs, and environmental impacts for a range of practical implementation scenarios” (USD[AT&L], 1999). The DSB (2001) called for DOD to base investment decisions on the true cost of delivered fuel on warfighting and on environmental benefits; to strengthen the linkage between warfighting capability and fuel logistics requirements through wargaming and new analytical tools; and to explicitly include fuel efficiency in requirements and acquisition processes.

In 2006, a study performed by the JASON Group sought to determine methods to reduce the DOD’s overall reliance upon foreign fossil fuels (Dimotakis et al., 2006). The group not only

looked at the sources of fuels but also at alternatives and overall efficiencies of the systems dependent upon such fuels. The report demonstrated that fuel use is characterized by large multipliers and co-factors. At the simplest level, it takes fuel to deliver fuel (p. iv). Also, JASON emphasized that “fuel use imposes large logistics burdens, operational constraints and liabilities, and vulnerabilities: otherwise capable offensive forces can be countered by attacking more vulnerable logistics-supply chains...The rear is now vulnerable, especially the fuel line” (p. iv).

Reducing the in-theatre fuel burden lessens the support required by the supply chain, and therefore requires fewer fuel burning logistics assets, or a reduced frequency of their use, to meet operational requirements. In addition to the fuel savings, other commodity consumption savings could be realized as well (e.g., stores, ordnance). Indeed, Bochman (2009) states “Logistics costs drive up energy costs and are tightly correlated to the type of environment into which the fuel is being delivered.”

Citing a need to again analyze the DOD Energy Strategy, USD (AT&L) tapped the DSB to conduct another examination in 2006. First, the DSB (2008) reported that the recommendations of the DSB 2001 report were not implemented, and that the recommendations had not changed. Second, the report called out a lack of strategy, policies, metrics, information, and governance structure necessary to properly manage its energy risks. The lack of fuel-based metrics was a significant deficiency noted by the DSB, which specifically called for accelerating implementation of FBCF. Moreover, the DSB pointed to a lack of “analytical capabilities to establish meaningful value” and called for the DOD to “build fuel logistics into campaign analyses and other analytical models and simulations to inform the requirements process of the operational, force structure and cost consequences of varying battlespace fuel demand” (DSB, 2008, p. 5).

In 2007, the Office of Force Transformation and Resources contracted LMI Government Consulting to develop a construct to create a DOD Energy Strategy. The LMI report (LMI Government Consulting, 2007, pp. 2-7 to 2-11) illuminated strategic, operational, fiscal, and environmental disconnects between the current energy consumption practices and the capability requirements of its strategic goals. LMI (2007) highlights actions for DOD’s corporate processes. Of note, LMI calls for analysis regarding energy logistics required to support operational plans. The report also recommends that the DOD address energy considerations in all future concept development, capability development, and acquisition actions—and that it make “reducing energy vulnerability a focus area of the next strategic planning cycle and Quadrennial Defense Review (QDR)” (LMI, 2007, p. v).

On the heels of these mounting recommendations, as well as the failure to implement the majority of the recommendations from the DSB and other sources, it was time for official, direct, and authoritative direction. In 2007, President George W. Bush signed Executive Order 13423, *Strengthening Federal Environmental, Energy, and Transportation Management*. This order would become the precursor to a robust undertaking regarding FBCF.

1.1.1 Fully Burdened Costs

Following Executive Order 13423, USD (AT&L) enacted policy that specifically addresses FBCF and its implementation, stating

...effective immediately, it is DOD policy to include fully burdened cost of delivered energy in a trade-off analysis conducted for all tactical systems with end items that create a demand for energy and to improve the energy efficiency of those systems, consistent with mission requirements and cost effectiveness. (USD [AT&L], 2007, p. 1)

Mr. Chris DiPetto, the Deputy Director of USD [AT&L], gave testimony to the House Committee on Armed Services Readiness Subcommittee in March 2008 illuminating the reasoning behind the implementation of the FBCF analysis. Specifically, Mr. DiPetto states:

From an operational perspective, our current and future forces face serious challenges from opponents who are smart enough to try and avoid contact with our combat forces and to concentrate on our large logistics tail...Emerging challenges from long-range cruise and ballistic missiles also pose growing complication to our fuel logistics forces...First, we want to understand the magnitude of our operational risk from our huge fuel demand so we will better understand what its[sic] worth to make operational systems more energy efficient and to reduce our resupply risk. The sustainment rate of our forces in operations is a major limiting factor in our operational tempo. Fuel, ammunition, food and water and spare parts resupply are all factors. (DiPetto, 2008, 8)

In other words, fuel demand does not just create costs, it creates operational risk and may limit capability.

In October 2008, Congress passed the DHNDAA, which mandates “life-cycle cost analysis for new capabilities include the fully burdened cost of fuel during analysis of alternatives and evaluation of alternatives and acquisition program design trades” (DHNDAA 2008).

Several directives between 2010 and 2012 furthered the incorporation of FBCF into DOD planning. The 2010 QDR, the 2011 Operational Energy Strategy (OES), and the 2012 Operational Energy Implementation Plan (OESIP) each either called for, or implemented, FBCF measures and milestones. In addition, the fully burdened cost concept was extended to non-fuel energy, such as electric power. This expansion, the fully burdened cost of energy (FBCE), was addressed in the OES and has been the term of art used since. The term includes FBCF.

In 2012, USD [AT&L] released complete guidance on how to calculate the FBCE, which they incorporated into the Defense Acquisition Guidebook (DAG). FBCE was defined by the DAG as “the cost of fuel itself plus the apportioned cost of all fuel logistics and related force protection required beyond the Defense Logistics Agency Energy (DLA-E) point of sale” (Defense Acquisition University [DAU], 2012, p. 84). The DHNDAA definition reads slightly differently, instead defining FBCF as the “commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use” (DHNDAA, 2008, p. 67).

Following the implementation of USD [AT&L] directives, several theses were published by the Naval Postgraduate School (NPS) applying and analyzing FBCF across multiple areas. Corley (2009) examined the application of FBCF across the Department of the Navy (DON) Major Defense Acquisition Programs (MDAP) to ascertain the impact of such calculations. Further, using USD [AT&L] methodology, Corley calculated the FBCF for a notional DDG-51 fleet to understand its impacts on the overall life cycle costs (LCC). Interestingly, Corley found that roughly 50% to 70% of the true cost of fuel is comprised of non-fuel costs. Corley recommended that the FBCF calculation be applied to aviation assets as well.

Truckenbrod (2010) then applied FBCF to Naval Aviation, specifically to F/A-18 E/F platforms using the USD [AT&L] methodology. The results were very telling, as he showed how the FBCF for an F/A-18 E/F aircraft is roughly double that of DDG-51 vessels. The major contribution to the higher FBCF was in-flight refueling.

Roscoe (2010) compared the methodologies used by all Service Branches in their calculation of FBCF. Roscoe found that the Service Branches used different calculations. The DON utilized

the USD [AT&L] methodology while the Air Force and Army had (or were developing) their own processes to compute FBCF. Roscoe then compared the two models used by USD [AT&L] and the Air Force. His findings showed no statistical difference between them—however, two of his recommendations called for a uniform implementation of methodologies across all Service Branches and the use of scenarios in FBCF calculations.

In August of 2012, the ASD [OEPP] published updated guidance on the methodology for calculating FBCE. The DAG was subsequently updated to contain new methodologies to calculate the new metric. Of particular note, the DAG requires use of appropriate scenarios within FBCE analysis, as follows:

DOD Components should present a realistic and analytically defensible scenario and cost elements. The proponents scenario assumptions for fuel logistics must be consistent with Service future force plans and Concepts of Operation. (DAU, 2012, p. 85)

1.1.2 Logistics Models

DAG guidance highlights that the logistics models should underpin the computation of FBCE. NPS has developed a logistics model, the Combat Logistics Force Planner (CLFP). Brown and Carlyle (2008) provide a formulation of the model, that was developed through a series of five NPS student theses.

The CLFP was first described by Borden (2001). Borden developed independent logistics planning factors that fed into a mixed-integer linear program modeling a global sea-route network. Borden then analyzed three single battle group scenarios, and three multiple battle group scenarios, over a 90-day time horizon to determine the quantity of T-AKE class vessels required. Additionally, Borden supplied insights into the optimal delivery mix of the convertible storage holds of the vessels, as well as the method of best employment.

Subsequently, Givens (2002), DeGrange (2005), and Doyle (2006) expanded the CLFP's scope and functionality. Givens refined Borden's logistics planning factors, and also implemented finer details of UNREP operations (e.g., approach time, rig/unrig time, transfer rates) in an effort to model a proposed CLF vessel acquisition. Using the context of a 90-day scenario with every surface naval combatant in the Fleet at that time, Givens discovered potential fuel run-outs which called into question the sufficiency of CLF assets.

DeGrange developed an optimization model to determine the required CLF assets to maintain a Sea Base consisting of three Carrier Strike Groups, two Expeditionary Strike Groups, and one Maritime Propositioning Group. The model implemented a 60-day scenario using minimum safety stock levels for commodities to determine the necessary CLF assets.

Doyle again analyzed the potential acquisition of a new CLF vessel class, and conducted a comparison between two separate CLF management schemes: fleet ownership and global allocation. The Doyle model introduced an optimization-based scheduling tool that modeled a 181-day peacetime scenario that tracked inventories of 13 battle groups to determine the best form of employment.

Mock (2012) applied Brown and Carlyle (2008) to analyze the sufficiency of current CLF assets in the event that a different surface combatant fleet structure was implemented. The more numerous, more distributed bi-modal fleet would be comprised of distinct littoral and open-ocean elements. A notional 100-day “war-at-sea” scenario was applied, as well as three variations. This work illustrated the need for a more robust CLF fleet in the event of adoption of the new fleet structure.

1.1.3 Input-Output Analysis

The DOD seeks “insight into the second and third order cost of design, technology and performance decisions on the energy demand of systems” (ASD [OEPP] 2012). One method that can capture higher order effects is Input-Output analysis. Input-Output analysis (IO) was developed by Wassily Leontif in the late 1930s. Leontif was awarded the Nobel Prize in Economic Science for this work. At its most basic level, IO was designed to illuminate the inter-industry flows of goods and services. IO has been one of the most widely applied methods in economics and has been extended to include many additional scenarios (Miller and Blair, 2009, p. 1). As Wu and Chen (1990) illustrated, Leontif’s work is well suited to capture the relationships and multiplier effects of all entities in the economy, and energy usage in terms of output.

IO, at its most fundamental level, is a system of linear equations that track the transactions or flows from a “selling” sector to a “buying” sector. These transactions are constructed into a matrix that represents all n flows from “seller” to “buyer”, or put another way, “inputs” into “outputs.” The total output required of a given sector i can be calculated by summing all transactions between sector i and other sectors j , as well as the total final demand for sector i ’s output (Miller and Blair, 2009). As Miller and Blair put it, “the demand from the automobile sector for

the output of the steel sector is very closely related to the output of automobiles.” This construct provides an understanding of how various sectors rely upon the function of the others, and it can capture the higher order effects desired for DOD energy analysis.

Previous work utilizing the framework pioneered by Leontif has been varied and far-reaching. Lin and Polenske (1998) developed a micro-level IO process model to include environmental management. The model captured all the production processes and the IO structure of a company or plant, noting “the model is flexible and can be extended or modified in other ways to meet the analytical needs of the company” (Lin and Polenske, 1998, p. 224).

Ozhan, Akcaoz, and Fert (2004) employed IO to analyze the energy usage in the Turkish agricultural sector from 1975-2000. Their comprehensive study sought to determine the current efficiency of the industry and environmental impacts. It revealed inefficiencies in the agricultural sector and highlighted a need for improved producer efficiency to mitigate environmental impact.

Machado, Schaeffer, and Worrell (2001) used IO to determine the impacts of international trade on Brazilian energy use and carbon dioxide emissions. This study showed yet another way IO could be used to inform large policy decisions.

Albino, Dietzenbacher, and Kutzt (2003) applied IO to an industrial district in an effort to capture insight into sustainable development with a specific intent to capture resources, energy, and pollution flows within an industrial district—in this case leather sofas produced in the Murgia Area of Italy. Albino et al. note that IO models can be useful for both accounting purposes and planning purposes.

Lu and Rencheng (2007) developed an IO model for an international supply chain, since globalization has caused products to be manufactured in multiple plants that may be dispersed globally. The model not only captures consumption during the production activities themselves, but also factors in the additional consumption caused by the dispersed nature of the supply chain.

Two military applications of IO are Dubbs (2011) and Hills (2011). Dubbs applied the concepts of IO to an existing supply chain utilized by the United States Marine Corps (USMC) in Afghanistan in order to determine the fuel multipliers to expeditionary and forward operations conducted by the USMC. The model was then run through six separate scenarios to determine the fuel multiplier for each component in the supply chain. Dubbs found that force protection fuel usage was a smaller contributor than previously believed, and that air-assets within a supply

chain are, on occasion, more efficient than ground counterparts. In addition, in some scenarios mission effectiveness may be lost if energy purchasing projections, in the short term, do not account for potential change in mission operational tempo or scale.

Hills (2011) developed a model of Defense Logistics Agency Energy (DLA-E) global supply chain to estimate the FBCF to deliver three distinct fuel types to each Defense Fuel Support Point (DFSP). This illustrated that although DLA-E charges the same price for fuel at any DFSP, their true costs can differ substantially. An IO model can incorporate these effects.

A significant shortcoming of other FBCE estimates described within Dubbs (2011), and highlighted by Regnier and Nussbaum (2011), is that some do not incorporate the effects of multiple stages on supply chains, which can lead to an underestimation of the total resource requirements incurred by the finer complexities within the distribution network.

1.2 Military-Historical Context

The need to adequately supply and re-supply the war effort is as old as conflict itself. History is replete with examples of war-fighting efforts whose outcomes hinged upon, or were significantly impacted by, the logistics behind provisions. Indeed, in 1946, just after the completion of World War II (WWII) Fleet Admiral Ernest King said:

The war has been variously termed a war of production and a war of machines. Whatever else it is, so far as the United States is concerned, it is a war of logistics. (Carter, 1998, p. xix)

The Admiral's sentiments were echoed in 1997 by the Commandant of the Industrial College of the Armed Forces:

American Logistics in World War II were big by just about any measure one can devise. There is no question that it played a dominant role in the allied victory and thereby shaped the history of the rest of the century. (Carter, 1998, p. xx)

The priority of logistics has remained a major tenet of USN operations and planning ever since. In June 2010, the Chief of Naval Operations (CNO) released OPNAV Instruction 3380.5 declaring that Military Sealift Command (MSC) vessels carrying munitions, unit movements, or military essential materiel in support of actual combat operations were designated as high value

units (HVU). This placed those logistics vessels on par with strategic assets such as CVNs, SSBNs, SSGNs, LHAs/LHDs, and SSNs. Such a designation emphasizes that the impacts of logistics upon a conflict are vital, varied, and far reaching.

Access to energy, and the ability to effectively distribute it, was one of the dominant themes throughout WWII. Energy, more specifically oil, was the life blood pumping through the veins of all war machines. As Walter Long, the Secretary of State for the Colonies expressed in an address to the House of Commons in 1917:

Oil is probably more important at this moment than anything else. You may have men, munitions, and money, but if you do not have oil, which is today the greatest motive of power that you use, all your other advantages would be of comparatively little value. (quoted in Yergin, 1991, p. 161)

One incident demonstrating how the availability of energy could influence large military objectives is illustrated by Benito Mussolini preceding World War II. Yergin (1991) notes that in 1935 Mussolini invaded Ethiopia, then Abyssinia, as it shared borders with some Italian colonies. Mussolini dreamt of creating a vast empire unto himself, and this was an easy first step. In response to Mussolini's actions, the League of Nations contemplated placing an oil embargo upon Italy. Mussolini, after conquering Abyssinia in 1936, later confided to Hitler: "If the League of Nations had followed Eden's advice on the Abyssinian dispute, and had extended economic sanctions to oil, I would have had to withdraw from Abyssinia within a week. That would have been an incalculable disaster for me!" (Yergin, 1991, p. 315).

The LMI report recalls the "stalling of General Patton's Third Army following its campaign across France in August and September 1944" as a telling example of the implications that cumbersome logistics requirements, equipment degradation due to overuse, and other operational priorities can have. Patton's forces were reduced to local operations for a period of nearly two months (LMI Government Consulting, 2007, pp. 2-8 and 2-9). Patton's case is particularly interesting because it was not direct, kinetic attacks upon Patton's logistics tails that caused the decrease in functionality.

Japan's experience demonstrates how access to energy, including standing reserves of energy, can dictate operations. On two occasions Japan launched operations for access to oil, to resupply its dwindling reserves. As a response to Japanese aggression in Asia, in July 1941 foreign powers had essentially placed an oil embargo upon Japan and the nation was thirsting to keep

its war machine turning. Foreign Minister Teijiro Toyoda's messages to ambassadors in Berlin and Washington conveyed the logic behind the resulting Japanese action:

Commercial and economic relations between Japan and third countries, led by England and the United States, are gradually becoming so horribly strained that we cannot endure it much longer. Consequently, our Empire, to save its very life, must take measures to secure the raw materials of the South Seas. (Yergin, 1991, p. 303)

The attack on Pearl Harbor was driven by the Japan's meager oil reserves. In September 1941 the Japanese oil stockpile was approximately 50 million barrels with daily a consumption of 75,000 barrels, which meant the country would be dry within two years without new sources (Goralski & Freeburg, 1987, p. 102). Extended military operations in the Pacific would decrease those reserves even faster. Historian Herbert Feis notes "If Japan was to fight, the longer it waited the greater the risk that the battle might be lost for lack of oil or other essential raw materials. So, the oil gauge influenced the time of the decision" (Goralski & Freeburg, 1987, p. 102). Goralski & Freeburg point out, "Just as oil was a principal factor in Japan's aggression, the conflict's outcome would also depend on oil" (p. 102).

Logistics tails were also a key target of kinetic operations in the Atlantic. In the Battle of the Atlantic, German U-boats relentlessly preyed upon the long logistics lines between U.S. and UK ports, as well as ports from the Gulf Coast to the East Coast of the United States. German Admiral Erich Raeder made clear the benefits of attacking the supply lines between the U.S. and the UK, stating "The more ruthlessly economic warfare is waged the earlier it will show results and the sooner the war will end" (Yergin, 1991, p. 355). German Admiral Karl Donitz had claimed during prewar planning that 300 submarines could defeat Britain (Baer, 1993, p. 190). Even more poignantly Donitz stated:

Can anyone tell me what good tanks and trucks and airplanes are if the enemy doesn't have the fuel for them? Yet, the High Command can't see it. (Goralski & Freeburg, 1987, p. 103)

In fact, the German High Command did not heed Donitz and at the onset of the war only 10 German U-boats were on station in the Atlantic (Murray & Millet, 2000, p. 238) and construction of additional German naval assets was performed at a leisurely pace (Baer, 1993, p. 190).

Despite these limitations, Donitz' U-Boats wreaked havoc upon the trans-Atlantic supply lines. By July 1941, there were only five weeks of motor gasoline and only two months of fuel stocked in the UK for the Royal Navy prompting Churchill to call the German tactic "The blackest cloud which we had to face" (Yergin, 1991, p. 355). Significant efforts by the U.S. Navy, Royal Navy, and British Intelligence—combined with the Lend Lease, the transfer of tankers, and reduced demand—gave Britain temporary respite. The total picture may be best stated by the official history of the British Intelligence, stating "It was only by the narrowest of margins that the U-boat campaign failed to be decisive during 1941" (Yergin, 1991, p. 356).

The second such example of predatory tactics on logistics, notably oil, began in January of 1942 when Donitz ordered Operation PAUKENSCHLAG ("Roll of the Drums"), which launched attacks along the American shorelines (Goralski & Freeburg, p. 105). Since 85% of oil for the East Coast of the U.S. came via sea from the Gulf Coast (as did British oil originating from the Caribbean), the results were significant and immediate (Goralski & Freeburg, p. 106). Donitz reported to the High Command that "Our U-boats have inflicted damage comparable to that of 80,000 bombers," and he later argued "If we engage all our Grey Wolves along the American coast, we will be able to bleed enemy shipping to death" (Goralski & Freeburg, pp. 108-109). In December 1942, the European front would again be jeopardized by the U-boat menace, prompting General Alan Brooke, Chief of the Imperial General Staff to state "The shortage of shipping was a stranglehold on all offensive operations, and unless we could effectively combat the U-boat menace we might not be able to win the war" (Yergin, 1991, p. 358). By the end of March 1943, the German U-boat campaign was finally permanently mitigated after 45 months of logistics nightmares.

1.3 Thesis Objectives

The DOD, particularly the DON, is undergoing a strategic shift to the Pacific, as underlined in a speech by SECDEF in June 2012 in Singapore. By 2020, the Navy will have the majority of its assets in the PACOM AOR (Panetta 2012). The PACOM AOR contains the largest, most exposed logistics lines on the planet, and the AOR itself encompasses over 50% of the world's surface area. Several countries that operate within that AOR have capable submarine fleets (both nuclear and non-nuclear). They possess significant stand-off, over-the-horizon anti-ship cruise missiles, as well as robust mining capabilities to augment growing surface fleets. Decreasing fiscal resources at the disposal of the DON increases the need to understand the supply chain effects of threats upon logistics.

This thesis looks to capture the impacts of a challenged logistics network that requires escort or convoy operations. This is performed by creating a Naval supply network and applying a threat scenario to portions of that network. Then, the FBCE can be determined by applying IO principles. The FBCE is reflected in the total resource requirement.

CHAPTER 2:

Methodology

This chapter introduces the Naval Threat-Based Fully Burdened Cost Model (NTFBCM), a network-based model of the transportation of supplies to US naval assets worldwide that estimates the TRR of supply as a function of: 1) the position of the warfighting asset within the network, and 2) the force protection that is required for the logistics vessels. Force protection consists of escorts, or convoys, consisting of surface naval combatants that accompany the logistics vessels into opposed or threatened sea spaces. Arc costs are the supply consumption rates for vessels used to transport and protect the supply.

2.1 Supply Network

The global supply network contains 313 nodes, indexed i and j , of which 144 are supply nodes. Supply nodes, M , are those nodes from which all commodities may be obtained from external sources and loaded onto CLF vessels. The destination node can be an existing node within the network or an additional node that is manually input into the model. There is only one destination node per scenario.

Arcs refer to the pairwise connections among nodes in the network. The global supply network can be seen in Figure 2.1, with nodes and arcs represented by circles and lines, respectively. Each arc is associated with many stages. A stage, s , expands upon the arcs by adding contextual information and indicating the direction of transport (from i to j). Each stage's cost reflects the resources consumed by CLF vessels and the accompanying vessels as they load, transport, and unload supply. Those resources consumed are determined by logistics planning factors. Stages are unidirectional between nodes, and each stage is associated with a threat level (t) and a single commodity (c). All supply nodes are connected to a global dummy supply node, j^* . Arcs between the supply nodes and j^* are unlimited capacity with no consumption incurred. The global dummy supply node is discussed further in Section 2.2.

CLF assets are loaded at the chosen supply node—and all vessels, both CLF vessels and escorting surface combatants, are assumed to be at full capacity at the moment of departure. The CLF vessel and any assigned escort ships will then transit the network to the destination point. At no point during the transit will the CLF assets UNREP with any other CLF or USN assets, as its

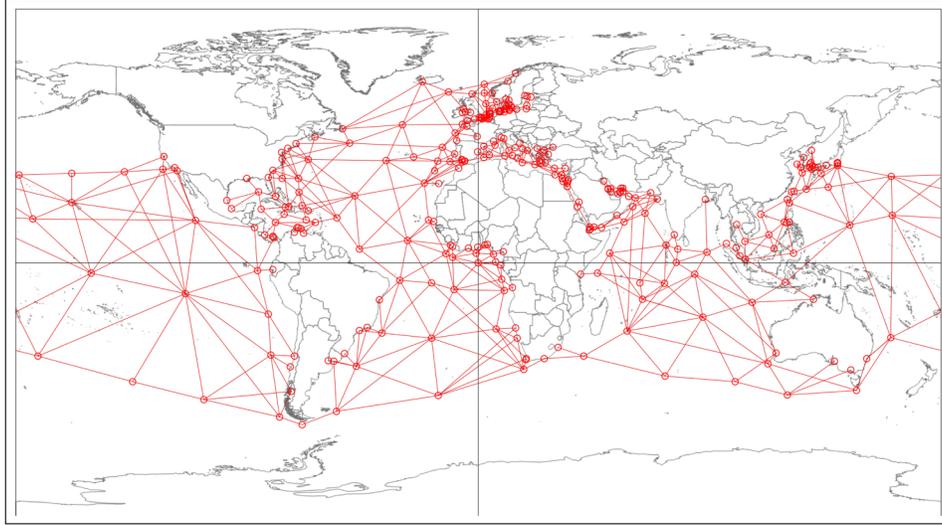


Figure 2.1: Global Supply Network

delivery load will be delivered only to the destination node. This means that CLF assets do not UNREP with the accompanying escort vessels in this model.

Planning factors for each ship are drawn from the CLF Planner. A sample is shown in Figure 2.2. The planning factors utilized within the CLFP have been created and refined by OPNAV N42, and are contained within NWP 4-01.2 (CNO 2007). These planning factors are evaluated and updated by OPNAV N42 as necessary. The planning factors are a constant consumption rate per day, for each of four general categories of supply: distillate marine fuel (DFM) and naval aviation fuel (JP5) in barrels (bbl), stores and ordnance in short tons. Planning factors are given for each vessel class, and are indexed k ; note that they can vary depending on operational state. The CLFP categorizes these operational states as: InTransit, AtAnchor, Docked, OnStation, Training, PreAssault, Assault, and Sustain. The CLFP also contains the ships' overall capacity for each of the four general categories of supply.

Stage costs reflect the aggregate consumption by all vessels attributed to a convoy. Convoy compositions, $v_{k,t}$, are threat dependent, which also renders stage costs threat dependent. Specifically, $t = Low$ denotes peacetime steaming with no threat anticipated upon CLF assets, $t = Med$ indicates that a potential attack upon CLF assets is possible but not likely, and $t = High$ denotes that attacks upon CLF assets are probable or even expected.

In order to consistently estimate the consumption of supply on an arc, it is assumed that the

CLF		Ship Planning Factors										
		ShipType	Commodity	Capacity	InTransit	AtAnchor	Docked	OnStation	Training	PreAssault	Assault	Sustain
	Dashhnart	CVN	DFM	0	0	0	0	0	0	0	0	0
	Scenario	CVN	JP5	74,642	3000	0	0	4000	4000	3000	5000	4000
	Horizon	CVN	STOR	1,710	53	53	53	53	53	53	53	53
	Shuttles	CVN	ORDN	1,765	2.5	0	0	5	20	15	150	100
	Shuttle Classes	CG	DFM	15,032	757	151.4	151.4	605.6	757	1429	757	757
	Shuttle Commodities	CG	JP5	475	8.5	0	0	17	25.5	17	39	25.5
	Ports	CG	STOR	66	2	2	2	2	2	2	2	2
	Route Nodes	CG	ORDN	94	0.075	0	0	0.15	0.6	0.6	5	3
	Route Arcs	DDG	DFM	10,518	646	129.2	129.2	516.8	646	1200	646	646
	Battle Groups	DDG	JP5	475	8.5	0	0	17	25.5	17	34	25.5
	RC Shuttle Activities	DDG	STOR	55	2	2	2	2	2	2	2	2
	RC Voyage Plans	DDG	ORDN	48	0.05	0	0	0.1	0.4	0.4	3	2
	Ship Planning Factors	FFG	DFM	4,286	304	60.8	60.8	243.2	304	600	304	304
		FFG	JP5	475	8.5	0	0	17	25.5	17	34	25.5
		FFG	STOR	35	1	1	1	1	1	1	1	1
		FFG	ORDN	16	0.02	0	0	0.0375	0.15	0.15	1	0.75
		LCS	DFM	2,663		72	0.2	288		360	180	180
		LCS	JP5	579		0	0	19		19	0	0.5
		LCS	STOR	5	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
		LCS	ORDN	20	0.025	0	0	0.05	0.2	0.2	2	1
		LHD	DFM	43,091	1071	214.2	214.2	856.8	1071	2000	1071	1071
		LHD	JP5	14,452	72	0	0	512	512	72	759	512
		LHD	STOR	520	15	15	15	15	15	15	15	15
		LHD	ORDN	391	0.45	0	0	0.9	3.6	3.6	33	18
		LHA	DFM	45,125	1071	214.2	214.2	856.8	1071	2000	1071	1071
		LHA	JP5	10,450	72	0	0	512	512	72	759	512
		LHA	STOR	641	15	15	15	15	15	15	15	15
		LHA	ORDN	391	0.45	0	0	0.9	3.6	3.6	33	18
		LPD4	DFM	17,700	528	105.6	105.6	422.4	528	1142	528	528
		LPD4	JP5	443	17	0	0	221	221	17	324	221
		LPD4	STOR	187	5	5	5	5	5	5	5	5
		LPD4	ORDN	88	0.1	0	0	0.2	0.8	0.8	6	4
		LPD17	DFM	23,750	1071	214.2	214.2	856.8	1071	2000	1071	1071
		LPD17	JP5	6,785	17	0	0	512	512	17	759	512
		LPD17	STOR	195	6	6	6	6	6	6	6	6
		LPD17	ORDN	88	0.1	0	0	0.2	0.8	0.8	6	4

Figure 2.2: Sample of Planning Factors from within CLFP

speed of advance (SoA) for all vessels is 15 knots regardless of threat level. The time required for loading all vessels associated with the scenario is assumed constant at 3 days, while the time to unload the CLF asset is 0.5 days. The loading time value implies that port facilities at any origin point have the necessary infrastructure in place to accommodate loading all vessels to capacity prior to getting underway. The unloading time value implies that the UNREP with the forces at the destination represents a worst case scenario of 12 hours in length.

The consumption rate of stores is almost insignificant compared to that of fuels. Taking for example the T-AO class of CLF vessel fuel, specifically DFM, accounted for 99.3% of all daily consumption by short ton for vessels in a sea transit posture. A similar picture emerges for the combatant fleet as well. For a DDG in a transit posture, 96.6% of daily consumption consisted of DFM. This pattern was prevalent throughout the fleet. Additionally, the availability of stores is vastly different than the availability of fuels. Stores can be purchased at nearly every source node in the network while fuel is more restricted. As a result, the model consists of only two commodities, *fuel* and *other*.

The second class, *other*, accounts for ordnance and shows greater variability with respect to the threat scenarios. Consumption of ordnance has very different characteristics from the three other commodities. Ordnance is not readily available in all supply ports. The United States must have specific permission from a home country to enable ordnance onloads from shore. Additionally, there are specific pier requirements to accommodate onload for certain forms of

ordnance. As a result of these additional constraints, ordnance is not aggregated into the stores planning factors and remains separate throughout.

The NTFBCM builds on the underlying network of ports, routes, potential transfer points, and planning factors in the CLFP. Like the CLFP, this model represents the transport of supplies to USN vessels worldwide using CLF vessels, and it models the consumption of more than one type of supply by CLF and other Navy vessels.

While the CLFP and NTFBCM may share a few similar underpinnings, they look at two decidedly different problems in two decidedly different ways. Since the NTFBCM is designed to estimate the TRR of the supply network in order to support the estimation of the FBCF, there are important differences. The NTFBCM is static, based on average consumption rates over time. The position of the destination is fixed, while combatants move in CLFP. Moreover, this model does not optimize. While it uses linear programming (LP) to identify the lowest TRR path through the logistics network (Section 2.2), its purpose is not optimization but estimation. This model includes use of combatant vessels in protecting logistics assets with no constraints based on the number of vessels, time, or fuel usage.

While the NTFBCM may be used to estimate the total amount of supply required by the logistics system per unit delivered to the warfighter, the fully burdened cost includes additional cost elements that are not included. Moreover, these other elements are also affected by a multiplier effect created by the fact that the early stages will need to deliver larger amounts of supply to sustain later-stage logistics activities. The other cost elements should increase proportionally with the amount of supply delivered in the early stages.

One of the biggest cost elements required to operate CLF and escort vessels is Other Operating and Support (O&S) costs. I obtained estimates of the daily O&S cost, excluding supplies (h_k), from Laura Whitney (personal communication, February 19, 2013). She used data from the Naval Visibility and Management of Operating and Support Costs (VAMOSOC) database to estimate the daily average O&S costs for each escort vessel class (h_k). VAMOSOC arranges cost data in hierarchical categories to allow user-defined granularity for more accurate analysis. These categories are referred to as cost elements. In order to avoid double-counting the cost of supplies that are captured in the TRR, cost elements for fuel and other supplies were excluded. Specifically, the cost elements utilized are: Personnel, Repair Parts and Repairables, Purchased Services, Maintenance—Intermediate, Maintenance & Modernization—Depot, and Other Operating & Support were included in the annual estimate for the total cost of operating

each combatant ship. The total annual cost, excluding supplies, was divided by the total annual days. The average of this value over all ships in that class for 2012 was used as the h_k . MSC uses slightly different cost element definitions and uses the Cost Analysis and Improvement Group (CAIG) categories—however, the same approach was used to calculate the average total O&S cost (excluding supplies) per day for each vessel class.

The network model is formulated as follows:

Indices and Sets

i, j = node indices

c = commodity type, $c \in \{norm, other\}$, $norm$ =fuel and stores whereas $other$ = ammo

t = threat level, $t \in \{Low, Med, High\}$

$s_{i,j,t,c} = S$, stage from i to j carrying commodity type c in threat environment t

$c(s)$ = commodity delivered by stage s

$t(s)$ = threat scenario applied to stage s

$i(s)$ = indicates starting node of stage s

$j(s)$ = indicates ending node of a stage s

j^* = global dummy source node

j^D = scenario destination node

N = the set of all nodes

M = INREP nodes (source nodes), $M \subseteq N$

D = demand nodes, $D \subseteq N$

W = waypoints (transshipment nodes), $W \subseteq N$

k = index of each class of ship

$v_{k,t}$ = number of ships of class k in convoy for threat scenario t

Planning Factors

FPF_k = daily fuel consumption rate from CLF Planner for ship class k [barrels]

SPF_k = daily stores consumption rate from CLF Planner for ship class k [pallets]

OPF_k = daily ordnance consumption rate from CLF Planner for ship class k [short tons]

Other Data

SoA = speed of advance (assumed constant throughout) $\left[\frac{\text{nm}}{\text{day}} \right]$

$dist_s$ = distance of stage s [nm]

LPF = planning factor for loading [days]

UPF = planning factor for unloading [days]

y_c = unit cost of commodity c at source $\left[\frac{\text{dollars}}{\text{short tons}} \right]$

$cap_{k,c}$ = payload capacity for ship of class k of commodity c [short tons]

h_k = vessel cost per day excluding supply items for vessel class k [dollars]

Each barrel of JP5, or DFM, is 42 U.S. gallons. Each gallon of DFM is treated as weighing 7 pounds per gallon, according to the F76 (DFM) Material Safety Data Sheet (CITGO 2007). JP5 is treated as materially identical to DFM.

Derived Parameters

$$\begin{aligned}
 r_{c,k} &= \text{daily consumption rate of commodity } c \text{ by vessel class } k \text{ [short tons]} \\
 &= \frac{7\text{lbs.}}{\text{gallon}} \frac{42\text{gallons}}{\text{barrel}} \frac{\text{short tons}}{2000 \text{ lbs.}} \cdot FPF_k + SPF_k, \text{ where } c = \textit{norm} \\
 &= OPF_k, \text{ where } c = \textit{other}
 \end{aligned}$$

$$\begin{aligned}
 d_s &= \text{number of days to transit from } i(s) \text{ to } j(s) \\
 &= \frac{\textit{dist}_s}{\textit{SoA}}
 \end{aligned}$$

$$\begin{aligned}
 CAP_{s,c} &= \text{total payload capacity for transporting commodity } c \text{ on stage } s \\
 &= \sum_k v_{k,t(s)} \cdot \textit{cap}_{k,c}
 \end{aligned}$$

$$\begin{aligned}
 CDT_{s,c} &= \text{consumption of commodity } c \text{ during transit on stage } s \\
 &= \sum_k v_{k,t(s)} \cdot r_{c,k} \cdot d_s
 \end{aligned}$$

$$\begin{aligned}
 CDL_{s,c} &= \text{consumption of commodity } c \text{ during loading on stage } s \\
 &= \begin{cases} \sum_k v_{k,t(s)} \cdot r_{c,k} \cdot LPF & \text{for } i(s) \notin W \\ CDL_{s,c} = 0, & \text{otherwise} \end{cases}
 \end{aligned}$$

$$\begin{aligned}
 CDU_{s,c} &= \text{consumption of commodity } c \text{ during unloading on stage } s \\
 &= \begin{cases} \sum_k v_{k,t(s)} \cdot r_{c,k} \cdot UPF & \text{for } j(s) \in W \\ CDU_{s,c} = 0, & \text{otherwise} \end{cases}
 \end{aligned}$$

$$\begin{aligned}
 R_{s,c} &= \text{total consumption of commodity } c \text{ on stage } s \text{ per unit of commodity } c(s) \text{ delivered to } j(s) \\
 &= \frac{CDT_{s,c} + CDL_{s,c} + CDU_{s,c}}{CAP_{s,c(s)}}
 \end{aligned}$$

It is assumed that all CLF vessels deliver the entirety of its cargo capacity to the destination. This construct allows comparison between vessels of differing capacity to be evaluated on a per short ton delivered basis. Further, this allows examination of TRR and FBCF without requiring the exact quantity demanded of each commodity by the surface combatants at the destination point. The $R_{s,c}$ numerator denotes the consumption of commodity c , while the denominator denotes the amount of $c(s)$ delivered, in which $c(s)$ may or may not be commodity c . The implementation of scenarios into the model provides for the ability to preclude the availability

of desired arcs within the network. Militarily, this can be seen as enemy-occupied sea-space that should be avoided. A scenario may call for certain source nodes to be unavailable, or call specifically for a certain source node to be used. Those same choices apply to potential demand nodes as well. To accommodate those choices, the following notation is utilized within the threat scenario formulation:

$$\begin{aligned}
 b_s &\in \{0, 1\}, \text{ binary variable for stage transit availability} \\
 q_{c,j^D} &\in \{0, 1\}, \text{ demand for commodity } c \text{ at node } j^D \\
 w_{c,n} &\in \{0, 1\}, \text{ supply for commodity } c \text{ at node } n.
 \end{aligned}$$

2.2 The Input-Output Model

As previously discussed, IO is fundamentally a system of linear equations that track flows from one sector to another. Flow from each sector i to each sector j is captured in the input coefficient a_{ij} . In this model, the notation $a_{s',s}$ represents the amount of commodity of type $c(s')$ delivered by stage s' to node $j(s')$ for use by stage s . Stages correspond to sectors.

Where x_s satisfies the following set of mass balance equations:

$$\begin{aligned}
 x_s &= \text{total amount of output from stage } s \text{ (amount of commodity } c(s) \text{ delivered to } j(s)) \\
 &\quad \text{[short tons]} \\
 &= \sum_{\substack{s':i(s')=j(s) \\ c(s)=c(s')}} a_{s,s'} x_{s'}, \quad \forall s \in \mathcal{S} \\
 X_c &= \text{total commodity } c \text{ required of source nodes to meet demand at the destination plus} \\
 &\quad \text{CLF and escort vessels [short tons]} \\
 &= x_{s^*}, \text{ where } i(s^*) = j^* \\
 Y &= \text{Total Resource Requirement cost} \\
 &= \sum_c X_c y_c, \text{ total system-wide supply cost.}
 \end{aligned}$$

For j^D , there are no arcs exiting the destination node. Therefore, when $j(s) = j^D$, $x_s = q_{c(s),j^D} = 1$. However, there may exist many s that could supply each commodity c to a given s' . For this reason, we do not use $a_{s,s'} = R_{s,c(s')}$. We need a method to ensure that just one inbound stage supplies each commodity to each outbound stage. The option to allow the user to determine which arcs/stages are used was considered. We chose to implement an optimization solution to select a single path to j^D for each commodity.

2.3 Route Selection Model

The network shown in Figure 2.1 contains multiple paths from a given source node to the desired destination node. In order to select one path from source to destination, a shortest path integer linear program (ILP) was utilized to ensure that the route through the network would be the optimum path, and as such, provide a “best-case” scenario. The shortest path model implements a global dummy source node that is connected to all source nodes. The arcs from the global dummy node j^* to all source nodes has zero costs associated with their selection and use. This ensures that—if desired by the scenario—the ILP will choose the most cost-efficient source node. The costs associated with each arc consists of the $CDT_{s,c}$. The dummy source node is given one unit of supply, and the demand location demands one unit of supply.

The input coefficients, a_{ij} , when summed as a linear path through a network, will represent the amount of total required commodities to meet the final demand at j^* . This analysis allows for the estimation of the TRR through the network model as described within Section 2.1.

An additional functionality is included in the model by the objective function with weighted terms for the two commodities of *norm* and *other*. This gives the ability to specify the relative importance of minimizing *norm* versus *other*. Consideration was given to employing preemptive goal programming, but ultimately this was abandoned in favor of using weighted programming. The main reason is that it allowed the Excel-based model to be employed much more easily by a user who is less familiar with the use of the built-in Solver (Frontline Systems 2010), or another analysis tool such as OpenSolver (Mason & Dunning 2012). Additionally, it permits sensitivity analysis over the parameter, λ . The choice of the value of λ directs the objective function to minimize one commodity preferentially over the other.

Notation

$z_s \in \{0, 1\}$, binary variable for stage use in LP solution

$$a_{s',s} = \begin{cases} z_s \cdot R_{s,c(s')} & \text{if } c(s') \neq c(s) \\ z_s \cdot (1 + R_{s,c(s)}) & \text{if } c(s') = c(s) \end{cases}$$

Objective

$$\min \lambda \sum_{s \in S} d_s z_s \left(\sum_k r_{norm,k} v_{k,t(s)} \right) + (1 - \lambda) \sum_{s \in S} d_s z_s \left(\sum_k r_{other,k} v_{k,t(s)} \right)$$

Constraints

$$\begin{aligned} 1 &\leq \sum_{s:i(s)=j^*} z_s \\ \sum_{s:j(s)=j^D} z_s &\geq q_{c,j^D} \\ \sum_{s:j(s)=n} z_s &\geq \sum_{s:i(s)=n} z_s \quad \forall n \in W \end{aligned}$$

2.4 Normalized Commodity Model

The model makes several important assumptions regarding the implementation of scenarios, the physical characteristics of the CLF vessels, and the commodities which are transported in a convoy/escort situation. Ordnance presents a primary difficulty. Vessels tasked with escort duties will carry two forms of ordnance: strike ordnance and threat ordnance. Strike ordnance is offensive in nature, and the amount used is based on the nature of attack operations—it is a choice variable. Threat ordnance is defensive in nature, and is a required expenditure based upon the threat. An example of strike ordnance for a DDG would be Tomahawk cruise missiles, whereas a threat ordnance example would be the Mk-46 or Mk-50 torpedoes. Since our model seeks to understand additional consumption incurred along a threatened route, only

threat ordnance is relevant.

NPS professor CAPT (ret.) Steven Pilnick (personal communication, February 2, 2013), describes threat ordnance as “so bizarrely sensitive” to threat assumptions that the ordnance requirements for escorts would range from negligible to infeasible. If any specific threat is assumed, logistics operations likely cannot be sustained—so the assumption of average ongoing supply is violated. CAPT Pilnick adds that in every analysis that he has performed, exhausting ordnance stops operations—unless the constraint is ignored, which will lead to a consumption of more than is available.

While ordnance and stores are contributors to the total volume of consumption in the model, the dominant factor is fuels. As a result, the model was implemented utilizing a single, normalized commodity that would be accounted for in short tons, and its cost is given at \$156.24 per barrel (DLA-E 2012). All capacities and consumption rates of all ships—combatant and non-combatant—would utilize this single measure. Changing from a multiple commodity model to the normalized, singular commodity model also resulted in changes to the shortest path implementation. The change consisted of removing the weighed optimization functionality, since only minimization of the consumption of the singular commodity was necessary. This change suppresses the commodity c from all previous notation.

The objective of the Route Selection Model (Section 2.3) is rewritten as:

$$\min \sum_{s \in S} d_s z_s \left(\sum_k r_k v_{k,t(s)} \right).$$

The IO coefficients may now be expressed as:

$$a_{s',s} = z_s \cdot (1 + R_s).$$

The TRR may be written as:

$$TRR = X \prod_s a_{s',s} z_s.$$

However, the TRR may also be calculated by taking advantage of the sequence of stages selected by the Route Selection Model. Let $N =$ number of stages s.t. $x_s = 1$ (i.e., stages that are used for the given scenario in the path selected by the Route Selection Model). Now order the stages, $n = 1, \dots, N$, where $j(s^N) = j^D$ and $i(s^1) = j^*$ and $j(s^n) = i(s^{n+1}) \quad \forall n = 1, \dots, N-1$. By definition $x_{s^N} = q_{c(s), j^D} = 1$. Since the path resulting from the Route Selection Model is a chain,

$$x_{s^{n-1}} = (1 + R_{s^n}) x_{s^n} \quad \forall n = 1, \dots, N-1$$

and

$$x_{s^n} = \prod_{m=n+1}^N (1 + R_{s^m}).$$

Since stage $n = 1$ originates at j^* , which is a dummy node, and stages originating at j^* have no resource requirements, $R_{s^1} = 0$. Therefore, the TRR of the system is equal to the total resource delivered by stage s^1 to the source node $j(s^1)$ determined by the Route Selection Model. Therefore,

$$X = \prod_{s \in S} z_s (1 + R_s) = \prod_{n=1}^N (1 + R_{s^n}).$$

2.5 Monetary Costs

Utilizing the per day O&S costs provided by Whitney (2013), h_k is used to estimate the monetary costs associated with the scenarios. Further, using the DLA-E Standard Prices (DLA-E 2013) per gallon of DFM, we compute the cost of fuel per short ton as follows:

$$\text{Fuel Cost (\$ per short ton)} = \frac{\$156.24}{\text{barrel}} \frac{\text{barrel}}{42 \text{ gallon}} \frac{\text{gallon}}{7 \text{ lbs}} \frac{2000 \text{ lbs}}{\text{short ton}} = \frac{\$1063}{\text{short ton}} \quad (2.1)$$

$$\text{Total non-supply O\&S cost} \left(\frac{\$}{\text{short tons delivered}} \right) = \underbrace{\sum_s z_s d_s x_s}_A \frac{\overbrace{\sum_k v_{k,t(s)} h_k}^B}{CAP_s} \quad (2.2)$$

$$\text{Total cost per short ton delivered} = \sum_s z_s d_s x_s \frac{\sum_k v_{k,t(s)} h_k}{CAP_s} \frac{\$1063}{\text{short ton}} X \quad (2.3)$$

Factor A, in Equation (2.2), represents the number of units of supply delivered to $j(s)$ per unit of supply to j^* . Factor B represents the daily convoy cost per unit of supply delivered. Using (2.3), we generate the Total Cost per Short Ton delivered. This cost is a lower bound due to the limited costs that have been captured in this thesis as discussed further in Chapter 3.

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CHAPTER 3:

Analysis

The analysis that follows is a scenario-driven exploration of the effects that force protection—in the form of surface naval combatant escorts—has upon the larger supply network. Utilizing the NTFBCM described in Chapter 2, we can examine the TRR for a scenario describing the global position of warfighter demand and the threat environment.

3.1 Scenario Construct

Scenarios are composed of the following:

- Elimination of any source nodes if deemed “unavailable”
- Elimination of any arcs from the network if deemed “impassable”
- Convoy composition required for three separate threat levels: *Low, Med, and High*
- Geographic demarcation of threat levels
- Destination position

The source node will always be a supply node which can be specifically chosen if a specific escort route is being scrutinized. If none is given, then the Route Selection Model will ascertain the source node that provides the lowest total resource consumption to the destination. It is important to note that all source nodes default as available. If any source node, i , is unavailable for any reason (e.g., threat, political concerns, infrastructure) then it must be trimmed from the list ($b_{s_{i,j,t}} = 0, \forall j, t$).

The convoy composition represents the number and type of CLF and combatant vessels for each of the three threat levels. An example of the allocation of assets based on threat is shown in Figure 3.1. The low-threat convoy vector, consisting of just a single CLF vessel, can be thought of as peacetime steaming with little to no threat posed to the CLF vessel. Additionally, it should be noted that comparisons among scenarios with different CLF assets in the convoy should be made with caution. Since the denominator of the R_s term is the CLF capacity, changing the type and/or number of CLF assets can lead to non-comparable results. The medium and high threat convoy vectors contain increasing combatant assets dedicated solely to the protection of the CLF asset(s). These allocations of combatants can be tailored for virtually any scenario requiring surface vessels.

	Low	Medium	High
CVN	0	0	0
CG	0	0	0
DDG	0	1	2
FFG	0	0	1
LCS	0	0	0
LHD	0	0	0
LHA	0	0	0
LPD4	0	0	0
LPD17	0	0	0
LSD	0	0	0
MCM	0	0	0
TAOE	0	0	0
TAO	0	0	0
TAE	0	0	0
TAFS	0	0	0
TAKE	1	1	1
WHEC	0	0	0
WMEC	0	0	0
GE_AFSH	0	0	0
UK_AORH	0	0	0
UK_AFSH	0	0	0
UK_AORLH	0	0	0
HSV	0	0	0
MOWCA	0	0	0

Figure 3.1: Example of Threat Level Escort/Convoy Compositions

The geographic demarcation of threat levels determines at what point the escort begins, and is implemented in the model by having at most one $b_s = 1$ for each i,j pair. Specifically, $b_{s_{i,j,t}} = 0$ for all threat t levels that do not apply between nodes i and j in the scenario. In addition, threat includes the elimination of any arcs or source nodes as determined above. The elimination of both arcs and source nodes can occur for a variety of reasons. Those reasons may be threat based, or simply to investigate the TRR along a specific route.

The destination point is input into the model as a latitude/longitude point. The destination may be anywhere in the world. The model includes this destination in the network as a node, j^D , and subsequently connect it to the nearest node in the existing network, creating a unidirectional arc. This arc is given a threat level ($t = Low, Med, High$) by the user and the associated consumption costs are applied (CDT_s, CDL_s , and CDU_s).

3.2 Notional Scenarios

The following scenarios are entirely fictional, and were chosen simply as a demonstration of the model’s utility. Any resemblance to an explicitly-planned scenario is coincidental and unintentional. Due to the USN shift in focus to the Pacific, the selected destination point is in that AoR, since it will be the most relevant for future planning purposes. Further, due to the vast nature of the Pacific, a point was chosen that would emphasize the long logistical lines in which the USN will be operating. The destination point, j^D , is the Spratly Islands.

Table 3.1: Standard Convoy Composition A

Vessel	Low	High
DDG	0	2
FFG	0	1
T-AKE	1	1

Table 3.2: Standard Convoy Composition B

Vessel	Low	High
DDG	0	2
FFG	0	1
T-AO	1	1

In order to see the full flexibility of the model, three separate starting points were used: Manila, Guam, and San Diego. The first source node was chosen by letting the Route Selection Model find the optimum starting point from the full network to j^D , with the result being Manila. The second source node, Guam, was manually selected. It was sufficiently distant from Manila to yield additional insights. Guam was also selected because it is the eastern-most bound on the threat area, for both *Med* and *High* scenarios. The final source node, San Diego, was chosen an estimate of the TRR to get logistics support from CONUS to the AoR.

The convoy compositions for these scenarios, shown in Table 3.1, were chosen to allow significant flexibility regarding the prosecution of various threats. The USN assets included have organic air assets in the form of helicopters, which are a significant force multiplier. Additionally, the DDG and FFG classes of ship are the most numerous in the fleet, and would likely be the available assets assigned to handle escort—or convoy—duty. This scenario utilizes the T-AKE dry cargo/ammunition ship. This is the second-most numerous class of ship in the current MSC inventory for CLF assets. There are eleven in the fleet. Additionally, it has the smallest overall capacity of the CLF assets.

To compare the differences which the type of CLF asset can have on the TRR, Table 3.2 contains the identical allocation of surface combatants as the previous scenario—except that it utilizes the T-AO fleet replenishment oiler class. This is the most numerous subset of CLF ships. Further, it has significantly greater overall capacity than the T-AKE. The T-AO does not have an allowance for ordnance capacity.

Each of these escort/convoy compositions was run through the model for each of the previously stated starting locations. The Manila-to-Spratly Islands route was run on the low and high threat

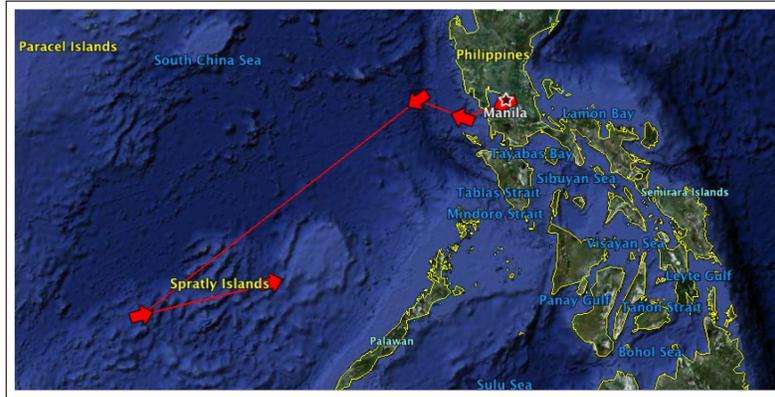


Figure 3.2: High Threat Level Route from Manila to Spratly Islands

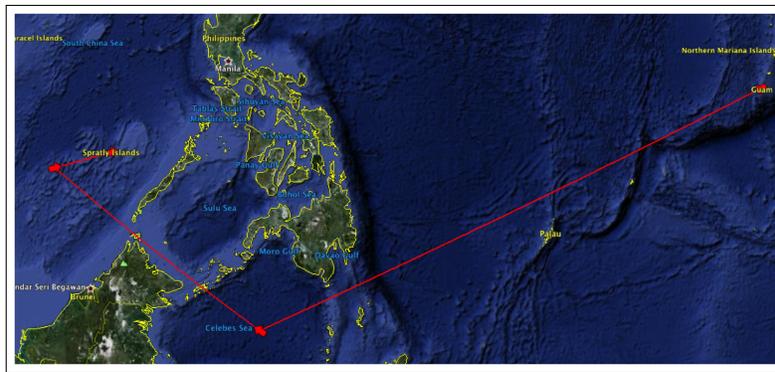


Figure 3.3: High Threat Level Route from Guam to Spratly Islands

level for both Composition A and Composition B. The same was done for the Guam-to-Spratly Islands route. The San Diego-to-Spratly Islands route was run with the nodes west of Guam under a high threat level, while the nodes to the east of Guam were under a low threat level. Only the routes under high threat are shown for Manila and Guam in Figure 3.2 and Figure 3.3. In scenarios that start in Guam and Manila, the escort vessels are in-port with the CLF assets at the time of loading, whereas for the San Diego route they meet the CLF assets at sea. The model does not account for resources required by escorts as they steam to this rendezvous point.

3.3 Results

Total Consumption by Route ($CDT_{s,c} + CDL_{s,c} + CDU_{s,c}$), shown in Table 3.3, represents the consumption of the normalized commodity for each route according to Threat Level. Only low and high threats were run for analysis, in order to investigate the bounds of TRR for each route. As previously mentioned, San Diego is the origin of a multi-threat level route in which all nodes



Figure 3.4: High Threat Level Route from San Diego to Spratly Islands

in the network west of Guam are low threat, while all nodes east—including Guam—are high threat. These values are identical for convoy Compositions A and B since the planning factors for both the T-AO and the T-AKE are identical.

However, since different CLF assets have different capacities, the TRR will change depending upon the CLF asset chosen. This provides an additional insight into the relative efficiency of the CLF asset, while also demonstrating the second-order effects on the supply chain due to the escort/convoy vessels. The San Diego route holds to the same split-threat route as described above. The TRR results are shown in Table 3.4.

Table 3.3: Total Consumption by Route (Short Tons)

Route	Threat Level	
	Low	High
Manila → Spratly Is.	528	1306
Guam → Spratly Is.	1478	3672
San Diego → Spratly Is. (mixed threat)	6415	

Table 3.4: Total Resource Requirement Per Unit Delivered to Destination by Route

Route	Composition A	Composition B
Manila → Spratly Is. (Low)	1.059	1.020
Manila → Spratly Is. (High)	1.152	1.050
Guam → Spratly Is. (Low)	1.149	1.050
Guam → Spratly Is. (High)	1.429	1.136
San Diego → Spratly Is. (mixed threat)	1.914	1.258

As evidenced by Table 3.4, the addition of threat to the operating environment causes a substantial increase in the TRR. On both the Manila and Guam Routes, the threat presence nearly triples

the TRR. The increase is demonstrated more significantly in Composition A, since T-AKE has a significantly lower total capacity. However, the results are fairly consistent.

The overall results, when displayed graphically (as shown in Figure 3.5), demonstrate the value of CLF assets that are more “TRR efficient,” especially as distances increase. The San Diego → Spratly Islands route shows that the T-AO has a significantly greater long-range efficiency due to its larger capacity.

Table 3.5: Total Dollar Cost Per Short Ton Delivered By Route (FY12 Dollars)

Route	Composition A	Composition B
Manila → Spratly Is. (Low)	\$1193	\$1106
Manila → Spratly Is. (High)	\$1664	\$1256
Guam → Spratly Is. (Low)	\$1356	\$1159
Guam → Spratly Is. (High)	\$2505	\$1488
San Diego → Spratly Is. (mixed threat)	\$3144	\$1639

Utilizing the data Whitney provided, the total dollar cost per short ton delivered may be calculated by scenario, as shown in Table 3.5. In addition, total dollar cost per delivered gallon of DFM are shown in Table 3.6. A similar theme is present in these results, due to the differing capacities of the chosen CLF vessels. Further, the San Diego → Spratly Islands route emphasizes the importance of being able to minimize the distance traveled in a higher threat environment. These values are not comprehensive, and serve as a lower bound, since several factors are excluded from these monetary values (port labor costs, environmental costs, costs incurred while steaming into starting positions, etc.). However, it does illustrate in a fiscal sense the increased burden of convoys.

Table 3.6: Total Dollar Cost Per Gallon DFM Delivered By Route (FY12 Dollars)

Route	Composition A	Composition B
Manila → Spratly Is. (Low)	\$4.17	\$3.87
Manila → Spratly Is. (High)	\$5.82	\$4.39
Guam → Spratly Is. (Low)	\$4.75	\$4.06
Guam → Spratly Is. (High)	\$8.77	\$5.21
San Diego → Spratly Is. (mixed threat)	\$11.01	\$5.74

The trends in the results show that longer routes are more costly, as expected. When viewed on a basis of dollar cost per short ton delivered in Table 3.5, larger capacity CLF vessels prove to be more cost efficient. The point is illustrated even more concisely when the results are shown

in terms of the total cost per gallon DFM delivered, as shown in Table 3.6. The FY13 Standard Price per gallon of DFM is \$3.72 (DLA-E 2012). The values in Table 3.6 are comparable to the results in Corley (2009). Corley estimated the contribution of primary fuel delivery assets to DDGs at \$0.72/gallon. In Table 3.6 for the low-threat scenarios, the cost of CLF vessels (net of the \$3.72 commodity price of fuel consumed at the destination) is \$0.45 for the Manila to Spratly Islands and \$1.03 for the Guam to Spratly Islands route.

The increases in cost with threat and distance are not surprising. However, it should be noted that the two increases compound each other. Increasing threat from low to high on the shorter route (Manila to Spratly Islands) increases the cost by a factor of 1.39, while increasing threat from low to high on the Guam to Spratly Islands route increases the cost by a factor of 1.85. Similarly, under low threat, the Guam route is 1.05 times as costly as the Manila route, but under high threat, the ratio is 1.19.

The USN has operated from a relative safe-haven on the world's oceans for several decades. Indeed, in our logistics decisions, we have been able to choose efficient operating practices and models as a direct result of that safety. In the presence of a threat, our CLF fleets—which are all considered HVUs—must be protected. The required protective assets will incur a burden upon the logistics network. The NTFBCM has clearly demonstrated the overall impact that a threat could have upon the logistics lines, and moreover, has estimated the scope of those impacts.

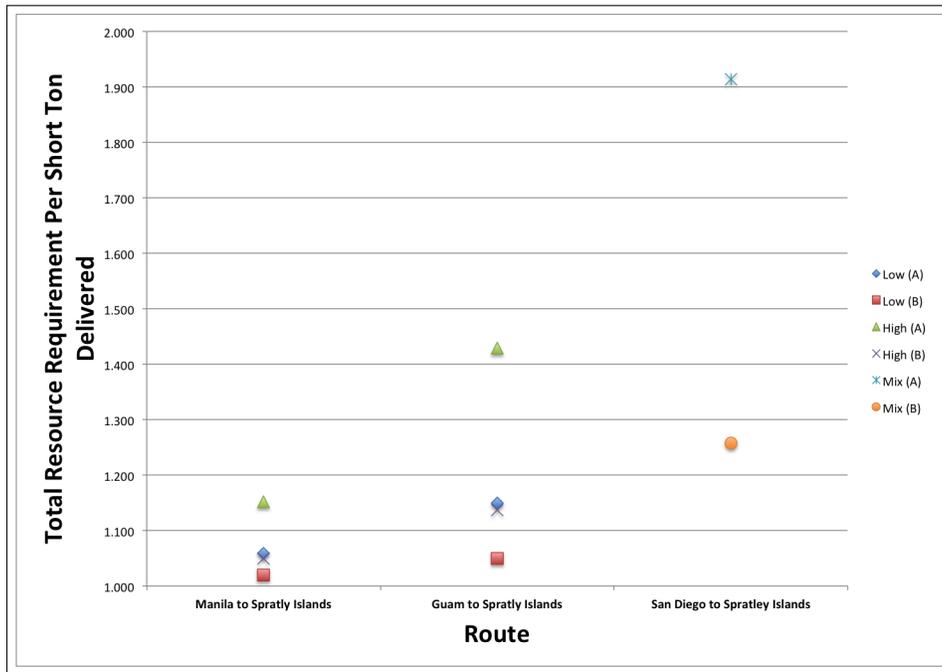


Figure 3.5: Total Resource Requirement By Route

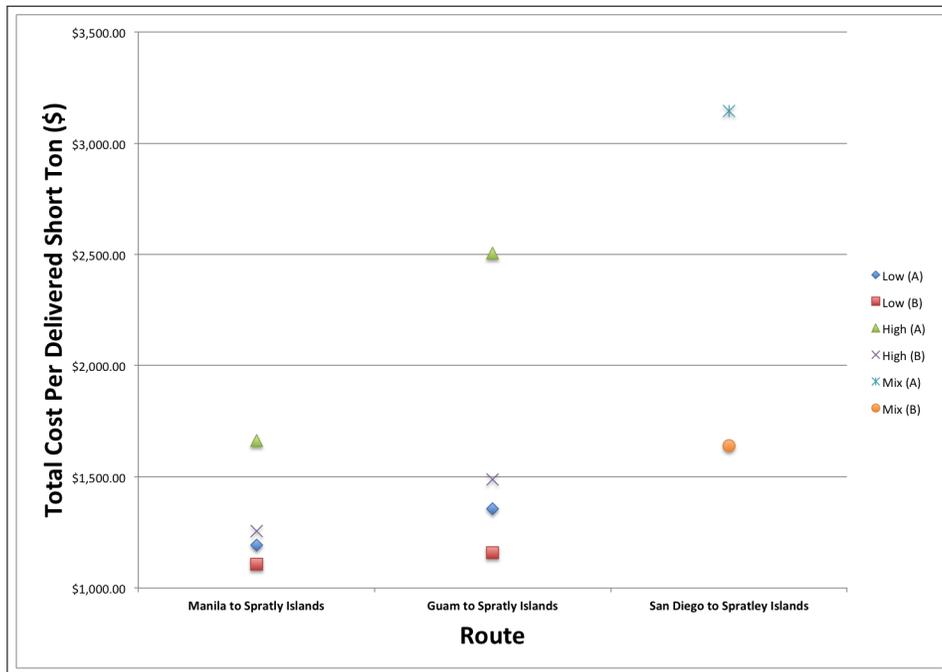


Figure 3.6: Total Dollar Cost Per Short Ton Delivered By Route

CHAPTER 4: Conclusions

The NTFBCM described in this thesis provides an effective tool that can allow for operational-level planning and estimation of the higher-order effects that force protection can impose on naval logistics supply lines under threat. The model is flexible enough to support any current USN fleet assets in an escort/convoy scenario anywhere in the world. The model can also be used to estimate the monetary costs of assets utilized in such a capacity.

Results from the model show both qualitative and quantitative insights. While it is to be expected that longer and/or high-threat routes would be more expensive, the model demonstrates that this is not only the case for TRR, but also the total dollar cost per short ton delivered, as well as the total dollar cost per gallon DFM delivered. This is shown when looking at a route from San Diego to the Spratley Islands. This mixed-threat route has an estimated TRR of 1.258 to 1.914 depending on the selected CLF asset being escorted. For the more efficient CLF vessel, the total logistics costs per delivered short ton are \$1,639 and the cost per gallon DFM delivered is \$5.74. For the less efficient CLF vessel, the cost per gallon DFM delivered balloons to \$11.01. The cost is nearly three times the commodity cost of fuel, although only a portion of the route is contested, and excluding costs such as vessel depreciation, round-trip travel, and environmental impacts to name a few.

The model currently utilizes a normalized commodity, due to the sheer dominance of fuels in daily consumption, as well as difficulties capturing ordnance accurately—yet still provides insight into the monetary costs and total supply chain burdens of escort/convoy operations. There is also the potential to fully explore multi-commodity supplies in the original model, which would yield further insights into the costs of such operations. The ability to incorporate an accounting of specific types of ordnance into the model would add greater depth to the estimates.

Future work that included an optimization model would add even more robust insights. The optimization model would examine the best escort compositions, with the potential to incorporate escort/convoys into a more robust CLF scheduling tool to allow for analysis of the overall burden cost. The Replenishment At Sea Planner (RASP) is an excellent tool that could provide great utility by incorporating logistics asset resource requirements.

The current model only examines the costs associated with a single CLF vessel enroute to a demand destination, with no UNREPs along the way for either the CLF asset or those assigned to its protection. Incorporating the model with RASP would grant the ability to allow UNREPs to those vessels, as well as increased granularity of commodity consumption, all of which would increase the accuracy of FBCE estimates. Further, more accurate analysis of the planning factors of the CLF vessels consumption rates would give more insight when making comparisons between CLF vessels since the current planning factors have identical consumption rates for all CLF ships.

Since the present model seeks to understand threat scenario impacts, a further step would be to incorporate attrition of CLF assets over threatened routes. This would add more realism to the estimates, and would additionally provide value that could be incorporated into Operational Planning at the Classified level, as well as general Concept of Operations development.

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