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OPTIMAL PRE-POSITIONING OF BULK FUEL RESOURCES

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THESIS

OPTIMAL PRE-POSITIONING OF BULK FUEL RESOURCES

by

Steven D. Kasdan

June 2020

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13. ABSTRACT (maximum 200 words)

The Navy-Marine Corps Team as informed by A Design for Maintaining Maritime Superiority 2.0 and the 38th Commandant of the Marine Corps' Commandant's Planning Guidance (CPG) is planning to conduct distributed maritime operations and expeditionary advanced base operations. These highly distributed and mobile operations require new material and operational solutions for the storage and distribution of bulk fuel to sustain forces in the area of responsibility. The challenge of conducting distributed operations in contested environments disrupts the employment of current Combat Logistics Force platforms. This study investigates the bulk fuel cache (BFC) concept of minimally manned or unmanned pre-positioned bulk fuel storage systems as an alternative method for sustaining forward deployed operations in contested environments.

This study considers a facility location model with stochastic demand and dynamic location to establish a baseline of operating considerations and concepts for the integration of BFCs into the naval logistics enterprise. This study explores BFC quantity, capacity, location, and dynamic movement for optimal sustainment of a distributed maritime force and informs future planning and acquisitions efforts.

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OPTIMAL PRE-POSITIONING OF BULK FUEL RESOURCES

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ABSTRACT

The Navy-Marine Corps Team as informed by A Design for Maintaining Maritime Superiority 2.0 and the 38th Commandant of the Marine Corps' Commandant's Planning Guidance (CPG) is planning to conduct distributed maritime operations and expeditionary advanced base operations. These highly distributed and mobile operations require new material and operational solutions for the storage and distribution of bulk fuel to sustain forces in the area of responsibility. The challenge of conducting distributed operations in contested environments disrupts the employment of current Combat Logistics Force platforms. This study investigates the bulk fuel cache (BFC) concept of minimally manned or unmanned pre-positioned bulk fuel storage systems as an alternative method for sustaining forward deployed operations in contested environments.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOR	Area of Responsibility
ARG	amphibious readiness group
BFC	bulk fuel cache
BFSCM	Bulk Fuel Supply Chain Model
CG	guided missile cruiser
CLF	combat logistics force
COCOM	Unified Combatant Commands
CONPLAN	Concept Plan
CPG	Commandant’s Planning Guidance
CSG	carrier strike group
DDG	guided missile destroyer
Design 2.0	Navy’s A Design for Maintaining Maritime Superiority 2.0
DFM	Diesel Fuel Marine
DFSP	Defense Fuel Support Points
DLA	Defense Logistics Agency
DMO	distributed maritime operations
DOD	Department of Defense
DOE	Design of Experiment
EAB	expeditionary advanced base
EABO	expeditionary advanced base operations
FON	freedom of navigation
JP5	Jet Propellant 5
JP8	Jet Propellant 8
JPO	Joint Petroleum Office
MSC	Military Sealift Command
NATO	North Atlantic Treaty Organization
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
OPLAN	Operation Plan
PLA	People’s Liberation Army

PLAN	People's Liberation Army Navy
POL	Petroleum, Oil, and Lubricants
POLDIST	Petroleum, Oil, and Lubricants Distribution
RAS	replenishment at sea
SLOC	sea line of communication
UNREP	underway replenishment
USA	U.S. Army
USAF	U.S. Air Force
USMC	U.S. Marine Corps
USN	U.S. Navy
USINDOPACOM	United States Indo-Pacific Command
USV	unmanned surface vessel
WEZ	weapon engagement zone

EXECUTIVE SUMMARY

This study investigates the Bulk Fuel Cache (BFC) concept of minimally manned or unmanned pre-positioned bulk fuel storage systems for sustaining forward deployed operations in contested environments. The Navy and Marine Corps are planning for distributed maritime operations (DMO) and expeditionary advanced basing operations (EABO) against peer competitors in contested environments. The operations proposed under the Navy's A Design for Maintaining Maritime Superiority 2.0 and the 38th Commandant of the Marine Corps' Commandant's Planning Guidance require agile and scalable expeditionary logistics solutions to ensure that the Navy and Marine Corps team do not operationally overextend capabilities to refuel, rearm, resupply, and repair. Bulk fuel specifically, represents a critical logistics requirement for Navy and Marine Corps units, and the current use of Combat Logistics Force (CLF) vessels in a contested environment may be untenable. Current replenishment at sea (RAS) operations require CLF ships to provide direct and intermediate support to surface combatants which requires them to enter regions of high-risk during wartime. Exposing high value, multi-commodity CLF ships to adversary kill chains presents unnecessary risk to Navy and Marine Corps operations. This introduces a requirement to identify novel storage and distribution methods to sustain operations. The BFC concept provides a scalable, distributable, and relatively attritable option for conducting bulk fuel operations in a highly contested environment. This study develops a facility location optimization model that incorporates variable supported unit demands and dynamic unit locations within simulated scenarios to assess the performance characteristics of the BFC concept.

The study specifically addresses the efficacy of BFC network composition, location, capacity, and characteristics for optimal employment in support of a distributed maritime force. The central scenario is based upon a kinetic maritime conflict in the South China Sea. Additional scenarios provide an opportunity for sensitivity analysis of the optimization model which enables the study to uncover important aspects of the BFC concept relating to the central research questions of how to best employ a BFC network in a contested maritime environment.

Study results demonstrate that a network that distributes capacity to areas of high anticipated demands will generate consistently low mean objective function values so long as supported unit demands are fully met. This requires developing good estimates of logistics supportability prior to deploying a BFC network, and understanding the concept of operations for DMO and EABO that will be supported. Furthermore, the study demonstrates that building excess capacity into BFC networks will result in high rates of return on performance relative to the additional materiel investment required to build in this increased network capacity. Essentially, paying a little more on the front end to build a larger, more resilient network will provide a greater return on investment than attempting to simply meet expected demands as computed. Networks demonstrated up to seventeen percent gains in performance for less than an eight percent increase in the quantity of assets required. An important finding from the model was that when demands exceed capacity within any network, system performance depends more on the overall capacity of the network rather than the characteristics of the individual network elements. This means that a network with less desirable platforms, but with a higher overall capacity will perform better than the network with the best possible platform composition with insufficient capacity.

Furthermore, BFCs that are mobile via self-propulsion or towable by other minimally manned or unmanned vessels can lend operational flexibility to a BFC network and reduce the overall number of BFCs required to maintain a high level of logistics readiness by completing resupply operations at the seam between the high risk and low risk zones to conduct replenishment from larger tankers and then returning to assigned BFC locations within the operating area.

The study is fuel-type agnostic and BFC technology agnostic. Remaining intentionally broad permits developing a general understanding of the capabilities and limitations of the BFC concept without allowing current materiel solutions to influence the inputs or outputs of the study. Having developed a basic framework for the study of BFC employment, this study provides a natural bridge to investing in innovative technologies capable of meeting and exceeding the baseline of performance developed in this study.

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Finally, thank you to the United States Marine Corps for providing the opportunity to attend the Naval Postgraduate School and broaden my academic knowledge and critical-thinking skills. This opportunity will ultimately benefit the Marines I am charged to lead, so that I may make sound decisions and advise my future commands on the decisions that will shape our future as a Marine Corps.

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I. INTRODUCTION

A. BACKGROUND

The Navy and Marine Corps are planning for distributed maritime operations (DMO) and expeditionary advanced basing operations (EABO) against peer competitors in contested environments thousands of miles from the American Homefront. The operations proposed under the Navy's A Design for Maintaining Maritime Superiority 2.0 (Design 2.0) and the 38th Commandant of the Marine Corps' Commandant's Planning Guidance (CPG) require agile and scalable expeditionary logistics solutions to ensure that the Navy and Marine Corps team do not operationally overextend capabilities to refuel, rearm, resupply, and repair. Bulk fuel specifically, represents a critical logistics requirement for Navy and Marine Corps units, and the current use of Combat Logistics Force (CLF) vessels in a contested environment may be untenable. Current replenishment at sea (RAS) operations require CLF ships to provide direct and intermediate support to surface combatants which requires them to enter regions of high-risk during wartime. Exposing high value, multi-commodity CLF ships to adversary kill chains creates unnecessary risk to Navy and Marine Corps operations. This introduces a requirement to identify novel storage and distribution methods to sustain operations.

The USN's Design 2.0 Line of Effort Blue, "Strengthen Naval Power at and from the Sea," defines the necessary characteristics of future logistics force in task 7:

> Posture logistics capability ashore and at sea in ways that allow the fleet to operate globally, at a pace that can be sustained over time. Assess and develop options for improved ability and resilience to refuel, rearm, resupply, and repair. (United States Navy 2018)

Current efforts to develop an expeditionary logistics capability in support of DMO and EABO focus largely on modernizing existing platforms, informing future fleet design, and reliance upon current logistics concepts of operation. In defeating a peer adversary, new material and operational options must be developed and implemented.

An alternative bulk fuel storage and distribution system is necessary in supporting increasingly distributed operations in the presence of coordinated anti-access area denial

(A2AD) in the United States Indo-Pacific Command (USINDOPACOM) Area of Responsibility (AOR). Planning for DMO and EABO requires the logistics concepts to sustain highly distributed and kinetic operations. Current logistics platforms represent scarce, high value capabilities that are unlikely to be placed within close proximity to adversarial precision fires. Additionally, the current CLF and Marine Corps Maritime Prepositioning Force (MPF) squadrons are insufficient for the highly distributed and mobile operations proposed under Design 2.0 and the 38th Commandant of the Marine Corps' CPG.

This study will investigate the Bulk Fuel Cache (BFC) concept of minimally manned or unmanned pre-positioned bulk fuel storage systems for sustaining forward deployed operations in a contested environment. This BFC concept provides a scalable, distributable, and relatively disposable option for conducting bulk fuel operations in a highly contested environment. This study will develop a stochastic facility location model that incorporates important aspects of both wartime and peacetime environments. The output and data analysis will yield a well-informed strategy for implementing the pre-positioning of bulk-fuel resources in the USINDOPACOM AOR.

B. THESIS MOTIVATION

This thesis confronts the challenges faced by the Navy and Marine Corps in USINDOPACOM to address Bulk Fuel Operations in an era of great power competition. The analysis developed advises a means of employing BFCs in an optimal manner to support operations across the spectrum of peace and conflict. Optimizing prepositioning of bulk fuel resources in USINDOPACOM alleviates the burden placed on CLF shipping, assures commanders that resources will be available in a contested environment, and ensures that U.S. Forces do not operationally overextend due to intra-theater fuel shortages.

The great advantage of the BFC concept, over current CLF refuelers, is the ability to scale and preposition fuel capacity based on anticipated operational demands. Current Underway Replenishment at Sea (UNREP) operations require that Navy ships transit to a designated location based on the operational requirements of CLF ships to meet the demands of many ships in an AOR and adhere to force protection requirements. In combat operations against a peer adversary, UNREP operations require that surface ships travel long distances and divest from combat operations until refueling is complete. Prepositioning BFCs where they are needed based on forecasted demands will put resources where and when they are required by the operating forces. BFCs have an additional advantage in that they spread bulk fuel resources across an AOR instead of massing in a few high value CLF assets. Greater numbers of BFCs can enhance the survival of resources and reduce the risk to CLF ship crews. The ultimate goal is to enhance the operational effectiveness and survival of U.S. Forces, and the BFC concept presents an opportunity for the Navy and Marine Corps to do both.

C. THESIS OBJECTIVE

This thesis presents a min-cost, max-flow optimization model for a bulk fuel distribution network. The distribution network is modeled as a set of BFC locations from which fuel can be delivered to supported unit demand locations. The model encompasses the Sea Lines of Communication (SLOC) in Southeast Asia, centered on the First and Second Island Chains surrounding China. The operational situation for this analysis is lifted from Kline's (2019) Naval Postgraduate School unclassified scenario Global War 2030, in which the United States and its allies are at war with China, Russia, and North Korea. Figure 1 shows the operational environment with emphasis on the First and Second Island Chains. This scenario provides context for supported unit composition, location, and demands throughout USINDOPACOM. The locations of Navy and Marine Corps Forces in the scenario are stochastically determined based upon most likely friendly courses of action. This stochastic location model provides insight into geographic fuel demand patterns of activity in order to inform decisions on quantity, capacity, and location of BFCs.

Figure 1. Southeast Asia Emphasizing the First and Second Island Chains. Source: Defense Intelligence Agency (2019).

The model provides flexibility in defining the quantity and capacity of BFCs to structure the distribution network to fulfill desired performance objectives. The model evaluates all possible seaward locations within the First and Second Island Chains as potential BFC locations and then uses the locations of Navy and Marine Corps units in the AOR to determine the optimal locations at which to station BFCs. The model considers unit location and demand in determining an optimal distribution network. The model seeks to minimize the distance between BFCs and supported units and minimize unmet units demands by assessing a penalty for every barrel of unmet demand. The goal of the model is to minimize costs in the form of barrel-nautical miles, minimize unmet demands, and maximize flow through the network. By evaluating model results through simulation, we can develop a robust distribution network of BFCs.

The outputs from this thesis will advise logistics planners in how to employ the BFC concept in a manner that maximizes utility to the Navy and Marine Corps. Planners can weigh the benefits of BFC quantity, capacity, and location with the costs of procurement, attrition, and operational risk. This thesis also explores BFC attributes that will make them more survivable and operationally effective across the range of military operations.

D. THESIS ORGANIZATION

Chapter II of this thesis will address the concept of bulk fuel storage and distribution and a literature review of related contributions to the subject. Chapter III will cover the methods used to build an optimization model reflecting the BFC concept. Chapter IV employs a notional scenario to test the effectiveness of the BFC concept as envisioned. The scenario provides context on which to base an analysis of the strengths and limitations of the linear program as developed and the BFC concept more broadly. Chapter V will address conclusions, policy recommendations, and recommendations on future studies.

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II. BACKGROUND AND RELATED WORK

This chapter will address current bulk fuel supply chain operations in USINDOPACOM, modernization of bulk fuel operations using emerging technologies, and an overview of related research into military fuel logistics.

A. NAVAL BULK FUEL SUPPLY CHAIN

1. Current Storage and Distribution in USINDOPACOM

Cribbs (2016) provides a narrative of the current storage and distribution of bulk fuel for USN ships at sea. USN vessels operating in the USINDOPACOM AOR must return to port or conduct RAS to remain operational. Returning to a friendly port is time consuming, detracts from operations, and requires a permissive environment for navigation. Military Sealift Command (MSC) Far East Region is responsible for conducting RAS operations to meet logistics demands at sea, which have the benefit of increasing operational duration without the requirement to seek a friendly port. During a conflict with a peer adversary, the advantages of RAS far outweigh reliance on port infrastructure. However, current RAS operations are reliant on CLF ships that are limited in number and thus have competing demands. Long (2011) points out that CLF ships are divided into station ships and shuttle ships. Station ships transit with a Carrier Strike Group (CSG) and are responsible for direct logistics support to the strike group. The benefit of these ships is that their close proximity enables rapid replenishment. Shuttle ships serve as an intermediate supply capability, and are generally responsible for the resupply of station ships. However, shuttle ships can also be used in direct RAS operations for ships that are not directly supported by a station ship.

Naval Surface Warfare Center (NSWC), Carderock Division (2019) recommends against the use of high value CLF assets in an At Sea Fight scenario due to the high value nature of these assets. In such a scenario, it is envisioned that any Defense Fuel Supply Point (DFSP) within the theater of operations would be in jeopardy, and any bulk fuel resupply must come from extra-theater DFSPs. The role for CLF shipping would be to transit bulk fuel from the DFSP across a low-risk zone and conduct RAS operations along the operational seam between zones of high and low risk. This operational concept is shown in Figure 2 in which combatants operating in the high risk zone must transit out of their AOR in order to conduct resupply. The paradigm shown in Figure 2 demonstrates that the use of current CLF ships alone is insufficient to meet the operational demands of USN ships and cannot address the fuel demands of Marine Corps EABs operating well within the high risk and threat zones. Meeting these operational challenges requires logistics capabilities that bridge the gap between existing CLF ships and those forces operating in a highly contested environment.

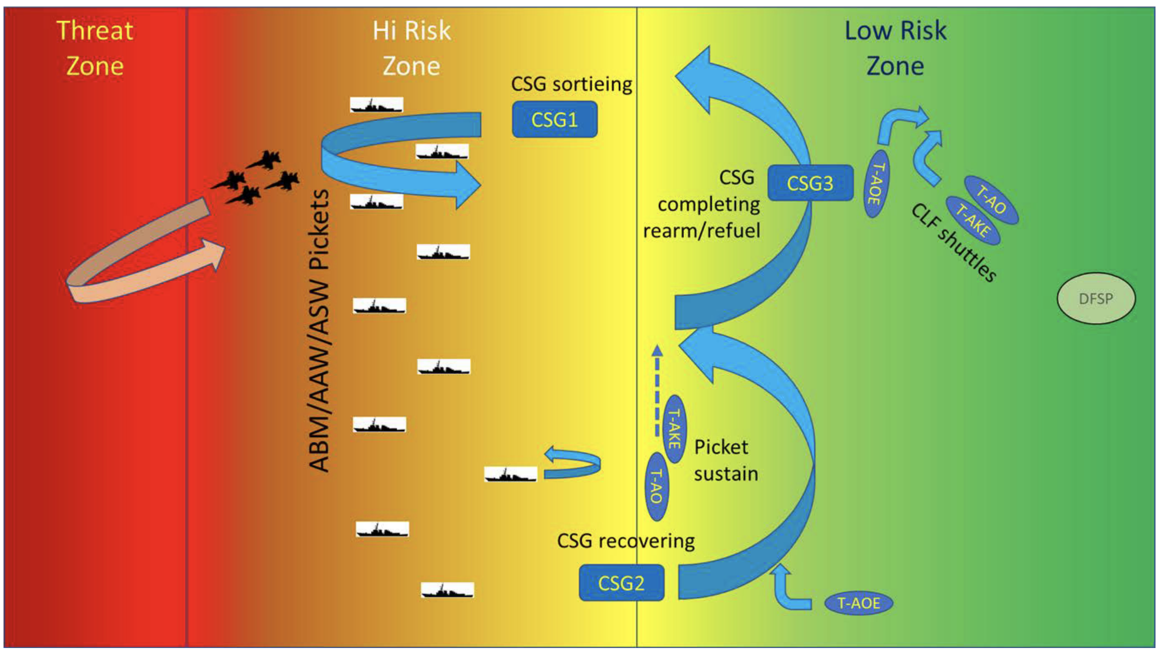

Figure 2. At Sea Fight Scenario Depicting a Carrier Strike Force with Three Carrier Strike Groups Cycling Between Strike and Replenishment Operations While Screened by a Destroyer Picket. Source: NSWC Carderock (2019).

2. Emerging Technologies for Bulk Fuel Storage and Distribution

NSWC Carderock (2019) examines near-term, mid-term, and far-term goals for implementing new technologies for bridging identified logistics capability gaps in the At Sea Fight scenario. Their study recommends the following:

> The Navy and USMC continue to pursue autonomous solutions in the mid and far terms; emphasize technologies that can "free up" CLF assets; concentrate on operational and tactical-level fuel distribution improvements; focus on developing technologies that can store, deliver and transfer smaller quantities of fuel "just in time" in the right amounts; and consider technology solutions that can be repurposed and integrated with existing and funded technologies. (NSWC Carderock 2019)

Focusing on "just in time" logistics capabilities requires diversifying the CLF away from large capacity, large cost assets toward smaller more attritable platforms. Several platforms identified by the NSWC Carderock for near and mid-term implementation are Mini-Combat Logistics Force (CLF) Improvements, Seabased Petroleum Distribution System (SPDS), Joint Offshore Fuel Farm (JOFF), Beachable Barge Improvements, Small Unmanned Surface Vehicle with Cache, Unmanned Logistic Surface Vessel, Surface Mobile Fuel Cache, and Semi-Submersible Fuel Barge. The salient characteristics shared by these assets which make them attractive are reduced manpower requirements, reduced visual signature, reduced cost, increased use of autonomous technologies, and scalability.

Hebert (2019) investigates alternatives for delivering bulk fuel from ship to shore in support of Marine Corps EABs ashore. His analysis provides an overview of technologies explored by NSWC Carderock that have dual use capability for RAS for naval vessels and can be used for refueling USMC units ashore. He finds that the SPDS, Mini-CLF Improvements, fuel barges, and unmanned submersible bladders such as the Pipefish represent promising technologies for meeting USMC requirements within the first island chain.

B. RELATED WORK

Alderson (2019) provides an overview of the past twenty years of research conducted at the Naval Postgraduate School on military fuel logistics. He divides research into two broad categories of Optimization-Based Decision Support Aids and Operational Modeling & Analysis for Resilience, Survivability, Mission Assurance. The study overview demonstrates that optimization has been used with great success to improve the performance of existing CLF assets and RAS operations. His discussion of modeling and analysis reinforces the importance of identifying and protecting critical military fuel chains and ensuring sufficient resources to meet operational needs during contingencies. His overview concludes with synopses of recent and current research into military fuel studies in support of the USINDOPACOM mission centered around DFSP infrastructure and their optimal employment.

Rosenthal et al. (1978) employ stochastic decision processes to advise facility location decision making. The model employed in the study accounts for uncertainty in customer locations and demands by employing an infinite-horizon Markov chain. The solution of the model provides a server location and allocation based on the desire to minimize expected costs associated with distance and time. In the model, both the server and the customer can change locations, which generates substantial computational complexity as noted in the study. The study finds that solving for a single server and customer can be computed exactly, while computing for multiple customers requires a heuristic solution due limited computing resources at the time of publication.

Devlin (2001) studied the impact of changes in demand locations and attacks on a fuel network. He builds upon the Japan Petroleum Distribution Model (JPDM) developed in previous research and establishes a bounding model, a deterministic model, and a stochastic model for analyzing the effectiveness of current networks and advising their optimal employment for use in notional operational plan scenarios.

Harmon (2001) builds upon the JPDM and includes an assessment of fuel storage and delivery in Korea. He employs linear programs to account for demand in notional operational plan scenarios and also presents the concept of fuel replacement when unmet demands can be satisfied using similar compatible fuel types.

Snyder (2006) provides an overview of facility location under uncertainty. He provides context for fifty years of methods for decision-making under uncertainty. He generally frames these efforts into those methods that seek to minimize cost by analyzing the nature of uncertainty in space and time using stochastic modeling and those that seek to minimize the maximize regret associated with a selected course of action using robust designs. Snyder introduces the concept of "distribution maps" to resolve uncertainty in the system to be analyzed. This method was first employed by Wesolowsky (1977) for facility location by employing weighted multivariate normal demands on a line to serve as a heuristic for where demands will likely occur. This methodology of distribution maps is highly relevant in the study of expeditionary energy. While the exact demand locations for USN and USMC units cannot be predicted, general knowledge of geographic locations for operations and general ship locations can allow planners to use distribution maps to assess probability peaks as ideal locations for logistics hubs.

Long (2011) studies the effectiveness of existing planning metrics for Replenishment-At-Sea-Planner (RASP) against a new methodology that accounts for additional geographic and operational considerations. Long studies consumption data within the Fifth Fleet AOR to conduct his analysis and finds that current methods for estimating surface ship consumption rates are inflated and reduce the effectiveness of optimization strategies for CLF ships. His study provides important insights on USN ship fuel capacities, consumption rates, and additional planning factors for conducting logistics operations in support of deployed maritime units.

Carline (2013) serves as a motivating benchmark for the aims of this thesis. Carline studies the optimal prepositioning of fuels in the USINDOPACOM AOR using existing DFSP infrastructure. She employs optimization to advise a prepositioning strategy which encompasses two separate weighted operational plans to underscore the most effective strategy. The study considers fifty-two existing DFSPs for prepositioning locations and examines the several scenarios to advise how and when to store, redistribute, and deliver fuel to customers to meet operational demands. The major drawback in this study was the constraint that only existing DFSP locations could be employed for prepositioning of military fuel.

Rodgers (2015) explores bulk fuel production, storage, and transport in the USINDOPACOM AOR. He uses optimization to minimize the maximum regret which is computed as the sum of all the penalties for unmet demands and penalties for failure to obtain minimum safe stockage levels. Similar to Carline (2013), Rodgers uses two NPS operational plan scenarios to analyze the model using ninety-day time horizons with additional lead times for selected design points.

Cribbs (2016) studies the effectiveness of CLF ships before and after the 2013 implementation of RASP. He finds that the Fast Combat Support Ship (AOE) was the optimal logistics hull design during CLF recapitalization efforts aimed at enhancing logistics support to the fleet. His analysis argues that implementing new logistics optimization techniques using legacy CLF platforms results in failure to obtain desired outcomes.

Beaumont (2017) expands on the work of Carline (2013) and Rodgers (2015) in studying the effectiveness of bulk fuel production, storage, and transport in the USINDOPACOM AOR. Beaumont builds on previous studies with his Reachability Analysis of Bulk-Fuel to Intermediate Transportation-Nodes (RABIT) which employs a Design of Experiments (DOE) approach to analyze over 200,000 design points across fifty-four DFSPs in the AOR. His work assesses the impact of distance and availability on logistics fulfillment to meet operational demands.

Cabana (2018) develops a cascade optimization model to assess responses to changes in demands to regional DFSPs. His method assesses thirty-day operational windows in which he optimizes the movement and storage of fuels to minimize negative impacts from changes in geographic and fuel-type demands. His optimization model builds upon previous NPS thesis work to develop robust and responsive fuel networks in USINDOPACOM.

Hebert (2019) uses simulation to explore ship-to-shore delivery of bulk fuel to support Marine Corps EABO. He investigates a 2017 USMC wargame that examined truck convoys and air delivery of bulk fuel in support of operations and notes that the wargame identified a gap in bulk fuel delivery capacity. Hebert's recommendations include Navy and Marine Corps investment in existing and emerging technologies to better meet fuel demands in contested environments. An emphasis is placed on automated technologies and using greater numbers of assets, each storing and distributing smaller quantities of fuel to distribute capabilities across the AOR and reduce the risk to mission posed by low quantity, high value logistics assets.

III. MODEL FORMULATION

This chapter presents the concepts underlying the proposal for an expeditionary fuel supply chain and the model formulation employed to validate the efficacy of the network as envisioned.

A. ESTABLISHING AN EXPEDITIONARY FUEL NETWORK

Operating in contested maritime environments requires a novel approach to establishing a fuel supply chain for replenishment of Navy and Marine Corps units decisively engaged in sea control operations. The thought process underlying this concept of establishing an expeditionary fuel supply chain is that traditional DFSPs and CLF assets are high visibility and present relatively easy targets for enemy kill chains. A temporary expeditionary network that responds to supported units demands presents a scalable and resilient option. Generating a supply chain in the absence of existing infrastructure in the context of optimization relied upon the use of techniques borrowed from facility location modeling. The AOR in this context is the First and Second Island Chains of the South China Sea. The study chose to implement a facility location model that relies upon a linear program in order to reduce computational complexity and generate relatively intuitive solutions. In order to keep the problem linear, we develop a finite set of possible BFC locations from which a network can be established. We build a grid of all potential BFC locations across the entire AOR and then selectively constrain possible locations based on enemy held territory, suitable oceanographic conditions, and geography. Figures 3 and 4 show the BFC location generation process by which possible locations are assigned by latitude and longitude to the AOR in an unconstrained manner. In this view, no considerations are given to enemy-held terrain or geographic considerations required for stationing a maritime BFC. A total of 651 distinct locations are defined by this rudimentary method.

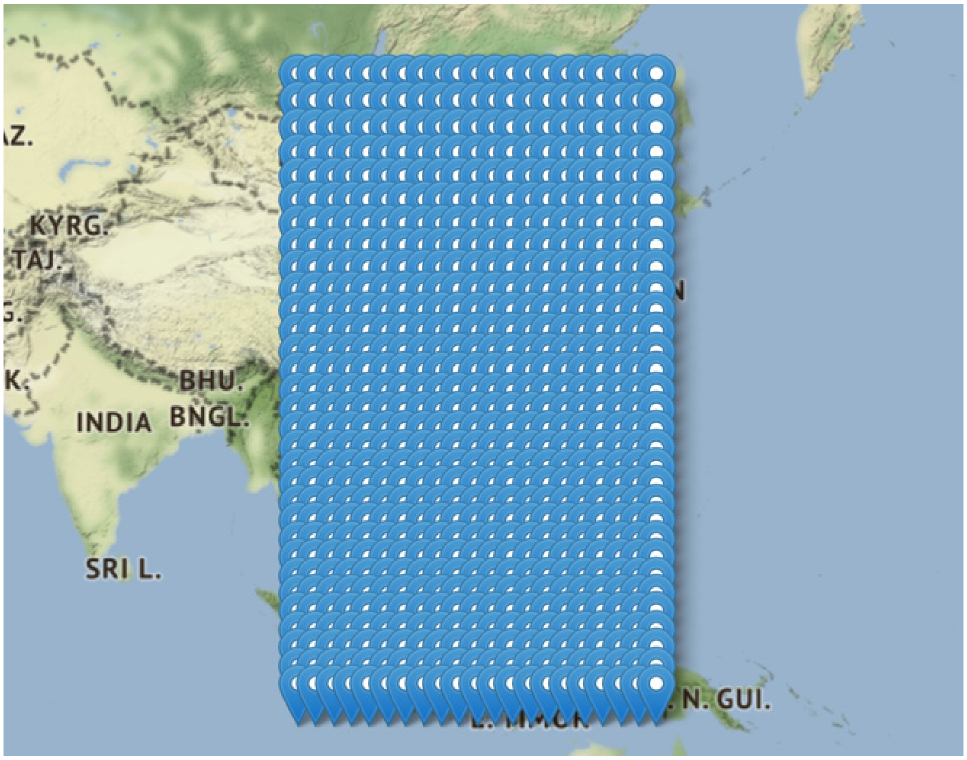

Figure 3. Potential BFC Locations Unconstrained, Macro View

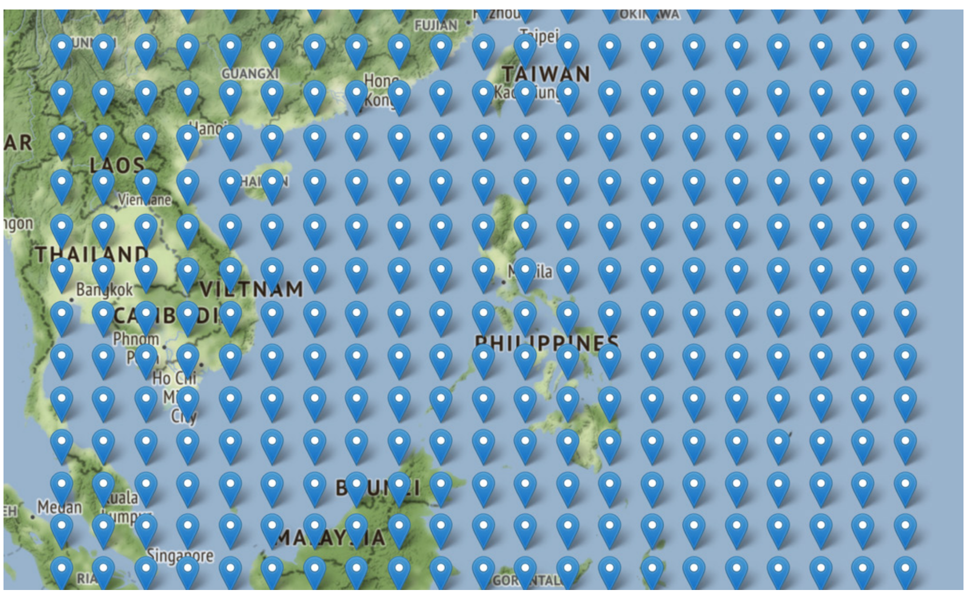

Figure 4. Potential BFC Locations Unconstrained, Close View

To account for terrain, the Github (2016) World-Countries JSON data was employed to generate polygons for known geographic features. These polygons were then employed to remove any possible BFC locations from land masses. The result is that all possible BFC locations are at sea within the defined AOR. This process reduces the number of potential locations from 651 down to 373. The next step was to account for enemy controlled territory, specifically the Nine Dash Line that dominates the South China Sea. SLOCs controlled by the adversary will greatly reduce the likelihood of USN combatant ships and logistics craft from infiltrating. Therefore, it was important to ensure that a BFC could not be placed within close proximity of Chinese controlled reef islands or within their bounds in which the PLAN exerts effective sea control. To account for these geographic areas, the study generated a polygon based on the coordinates of the Nine Dash Line and all BFC locations within this territory were removed. The result is that 329 viable BFC locations remain for consideration. Figure 5 provides an updated view of potential BFC locations across the AOR and Figure 6 shows the remaining potential BFC locations in the vicinity of the Philippines for a more detailed view.

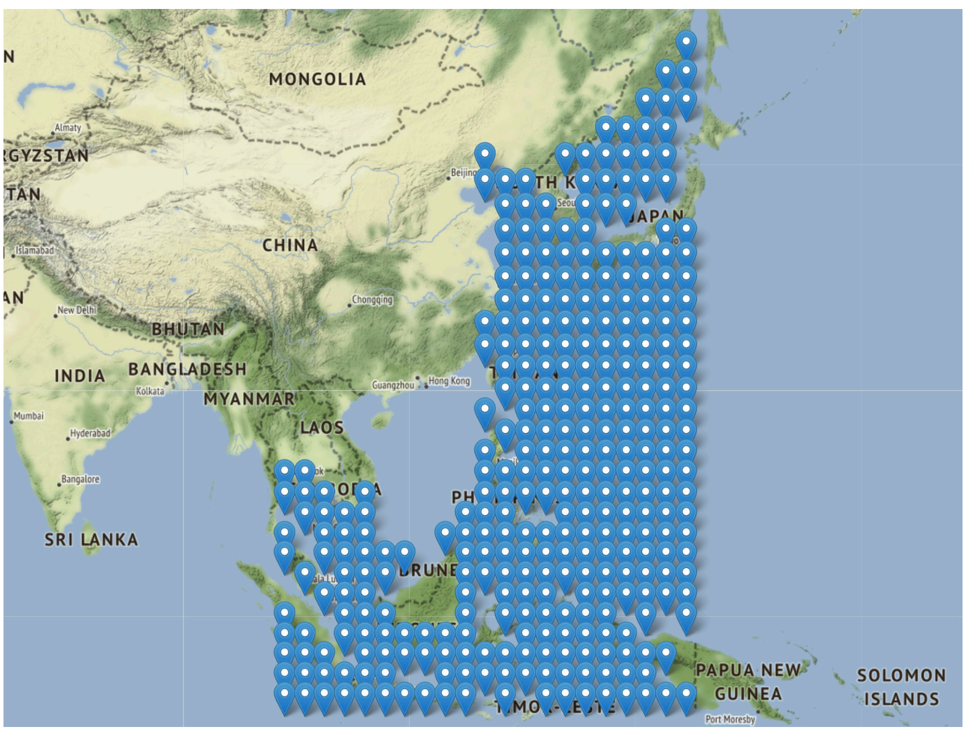

Figure 5. Potential BFC Locations with Location Constraints Applied: Macro View Showing Areas Constrained by Adversary and Terrain

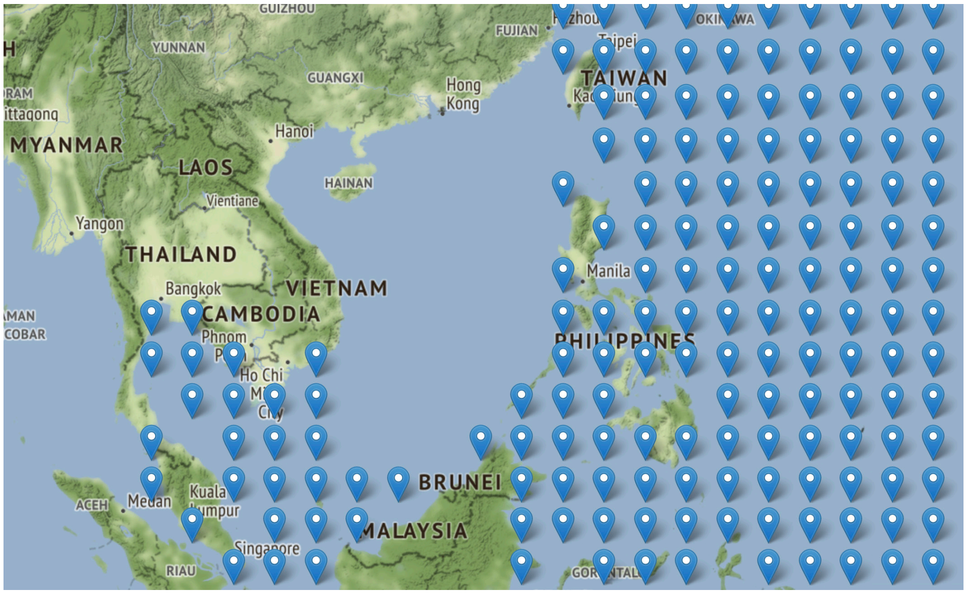

Figure 6. Potential BFC Locations with Location Constraints Applied: Close View Showing Areas of Adversary Control and Land Masses Removed

B. NODE ATTRIBUTES

The nodes in the network are supply nodes represented in the model by BFC locations and demand nodes represented by supported units in the network. The most important attributes of the supply nodes are location, given by degrees latitude and longitude, and fuel capacity in barrels. The location and capacity of supply nodes determine the span of support they provide to demand nodes in the AOR. The demand nodes in the network are represented by supported units in the AOR. Supported units are represented by USMC EABs ashore and USN surface combatants in the First and Second Island Chains. The demands of individual supported units are user-defined based on the classification of the supported unit. For the scope of this study, fuel demand in barrels is common for each type of supported unit. Furthermore, the priority of resupplying a node can be modified by adjusting a penalty term for unmet demand. The higher a relative penalty for each unit of unmet demand, the higher the priority of that node. In Chapter IV, the scenario explored will permit the introduction of stochastic principles for determining supported unit locations to test the robustness of the BFC concept explored.

C. ARC ATTRIBUTES

The arcs in the network link each BFC location to each supported unit. Each arc has infinite capacity as we consider the arcs to be a nautical-mile distance of open ocean between a supply node and a demand node. In practice, the maximum capacity on any given arc is defined by the maximum amount of fuel stored by the BFC on that arc. The length of an arc is treated as a cost incurred for employing a BFC to refuel a supported unit. In practice, a BFC must be mobile and/or a supported unit must transit to the BFC. The shorter the distance on an arc, the lower the cost incurred.

D. NETWORK OVERVIEW

The complexity in this style of network formulation is that every supply node is reachable from every demand node, which increases the number of constraints in determining the optimal BFC locations to open based on the user-defined upper bound on the available amount of resources. The use of a facility location model in a linear program requires sufficient candidate locations to provide the desired level of geographic specificity. Contrasting this approach with Carline (2013), fuel prepositioning objectives were based on known DFSP locations within the USINDOPACOM AOR and the model determined how best to allocate fuel resources amongst those locations to minimize costs. The approach in this study considers both where to station prepositioned stocks across the undeveloped SLOCs of the First and Second Island Chains as well as quantity of fuel to preposition. The network in this case must be built to best predict fleet demands based on anticipated concepts of operation. This network addresses the NSWC Carderock (2019) defined goal of storing and delivering smaller quantities of fuel at the right place and the right time to best support fleet demands.

E. MATHEMATICAL FORMULATION

1. Indices and Sets

b	BFC location (b = 1, 2, ... n)
s	Supported unit (s = 1, 2, ... m)
B	Set of all BFC Locations
S	Set of all supported Units

2. Data [Units]

$demand_s$	Demand for fuel by Supported Unit Location s [Barrels]
$capacity_b$	Fuel capacity at BFC Location b [Barrels]
$distance_{sb}$	Distance from Supported Unit s to BFC Location b [Nautical-Mile]
$available_b$	Maximum number of BFC Locations available for storage and delivery [Integer]
$penalty_s$	Penalty assigned per barrel of Supported Unit s unmet demand [Nautical-Mile]
$cost_b$	The cost for opening each BFC [Integer]

3. Decision Variables

$OPEN_b$	The number of BFCs placed at a Potential Location [Integer]

$DELIVER_{bs}$ — Fuel delivered from BFC Location b to Supported Unit s [Barrels]

$UNMET_s$ — Unmet fuel demand of Supported Unit s [Barrels]

4. Formulation of Model (A0)

$$\min \quad \sum_{b=1}^{n}\sum_{s=1}^{m} DELIVER_{bs} * dist_{sb} \qquad \text{(A01)}$$

$$+\sum_{s=1}^{m} penalty_s * UNMET_s \qquad \text{(A02)}$$

$$+\sum_{b=1}^{n} cost_b * OPEN_b \qquad \text{(A03)}$$

Subject to:

$$\sum_{s=1}^{m} DELIVER_{bs} \leq capacity_b * OPEN_b \qquad \forall\, b \in B \qquad \text{(A1)}$$

$$OPEN_b \leq available_b \qquad \forall\, b \in B \qquad \text{(A2)}$$

$$\sum_{b=1}^{n} DELIVER_{bs} + UNMET_s = demand_s \qquad \forall\, s \in S \qquad \text{(A3)}$$

$$OPEN_b \in \{\text{Int}\} \qquad \forall\, b \in B \qquad \text{(A4)}$$

$$DELIVER_{bs} \geq 0 \qquad \forall\, b \in B, s \in S \qquad \text{(A5)}$$

$$UNMET_s \geq 0 \qquad \forall\, s \in S \qquad \text{(A6)}$$

5. Description of Model Formulation

The BFC model (A0) represents a network flow model that captures the total cost associated with delivering fuel (flow) from a selection of BFCs to a set of supported units. A penalty is assessed for every unit of unmet supported unit demand in the network and costs are incurred for each BFC that is added to the network.

Objective function equation (A01) is the cost of delivering fuel from each BFC location to each supported unit in barrel-nautical-miles. The decision not to send flow across an arc in the network will yield a zero cost in terms of the cost of sending flow.

Objective function equation (A02) is the penalty incurred for each unit of unmet supported unit demand in the network. This penalty term is in nautical-miles and incentivizes network behavior that satisfies all unit demands in priority order. Penalty values are user defined as a method for weighting the main effort. The higher a unit value for mission accomplishment, the higher the penalty term for each unit of unmet demand to that unit. This ensures that the model prioritizes the allocation of bulk fuel resources under conditions of insufficient network capacity. By defining the penalty term as a nautical-miles; the overall penalty is expressed as barrel-nautical-miles.

Objective function equation (A03) is the cost incurred for each BFC location that is opened in the network. The purpose of this cost is to ensure that the minimum number of BFCs are opened to satisfy network demand. This ensures that the number of BFCs opened is constrained beyond a user defined maximum number of BFCs to open. The cost for opening each BFC adds a leaning effect to network behavior.

Constraint (A1) is an upper bound constraint that ensures the volume of fuel delivered from any one BFC to all supported units does not exceed the maximum capacity of that BFC location. The use of the integer variable $OPEN_b$ ensures that a BFC location only has capacity if it is activated within the network. Opening more than one BFC at any given location increases the capacity at that site as a factor of quantity and capacity.

Constraint (A2) is an upper bound constraint on the maximum number of BFCs that are available for deployment in a network. By the nature the integer variable $OPEN_b$, there is no concern that this constraint will cause negativity. Furthermore, when used in conjunction with objective function equation (A03), the network is optimal when the fewest number of BFCs are employed to meet demand and minimize penalties without exceeding the upper bound.

Constraint (A3) ensures the preservation of supported unit demand as the sum of all delivered fuel and any remaining unmet demand. $UNMET_s$ is an elastic variable that serves as the basis for penalizing each unit of demand that can't be met within the network.

Constraint (A4) is an integer constraint on the $OPEN_b$ variable. Constraints (A5) and (A6) are non-negativity constraints on the amount of fuel delivered from each BFC to each supported unit and on the unmet demand of each unit, respectively.

Figure 7 provides a network flow representation of a select subset of the network formulated in Model (A0). The figure displays the logic behind the composition of arcs and nodes in the network as currently developed. The model does not consider the resupply of BFCs, thus no inbound arcs are shown going into BFC Locations.

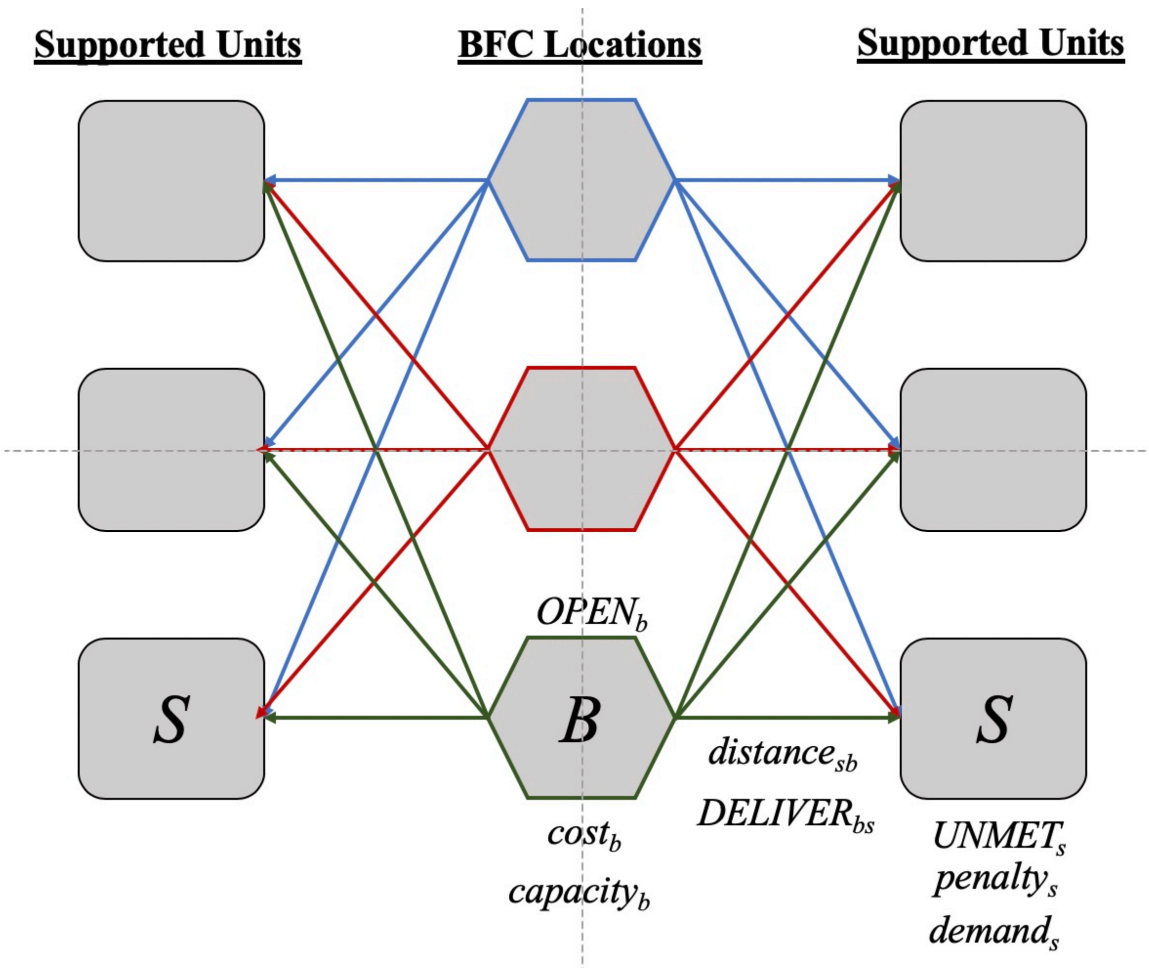

Figure 7. Network Flow Representation of The BFC Storage and Distribution Network as Formulated in Model (A0)

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IV. ANALYSIS AND RESULTS

A. OPERATIONAL SCENARIO

Kline's (2019) Global War 2030 provides the operational context for our analysis. This scenario provides an operational and tactical framework upon which to evaluate our proposed methods for sustaining U.S. forces engaged in the contact layer of the First and Second Island Chains. The scenario is paraphrased to provide a general understanding of the operating environment and the challenges faced by the U.S. and its allies.

The scenario begins in 2027 with several countries defaulting on Chinese loans for the development of critical port and transportation infrastructure along the "Belt and Silk" road. In response, China forcefully occupied key transportation and shipping facilities to guarantee against trade interruptions. These actions result in violent civil protests against Chinese companies and their workers in Malaysia, Pakistan, Djibouti, Vietnam, and Indonesia which forces China to take a harsher stance in protecting their overseas interests.

In 2029, a Chinese scientific vessel exploded 100 nautical miles north of Natuna Besar and China claimed Vietnam, Indonesia, or the Philippines were responsible. China mobilized their South China Seas fleet and threatened the use of sea denial operations against all three nations if did they did not pay reparations for the damaged vessel. Soon afterward, a Chinese surface missile launched from a barrier island in the Paracels sinks a Vietnamese ship and squadron of PLAN ships is deployed to begin the conduct of inspection and control for all vessels trafficking the South China Sea. Small skirmishes between the PLAN and Vietnamese forces occur and the intensity of China's military operations intensify in the region. Figure 8 presents the Chinese perspective on the SLOCs and islands off their coast. This view demonstrates the Chinese viewpoint that control of the littorals of the First and Second Island Chains results in the containment of their maritime capability. Their recognition of this perspective increases the stakes involved in a conflict in this AOR.

Figure 8. Chinese Perspective of the First and Second Island Chains for Strategic Context. Source: Cummings et al. (2020).

Early in 2030, China occupied Natuna Besar, Indonesia and Palawan, Philippines and Chinese maritime inspections bring about demarche protests from Japan, South Korea, Australia, Singapore, Vietnam, India and the United States. The United States, in a show of solidarity with its allies in the region, began stopping and inspecting Chinese flag ships as a response to PLAN actions in the South China Sea. Shortly thereafter, a U.S. DDG was torpedoed by an unknown submarine. This event incites a violent confrontation that rapidly escalates into a global conflict between the United States and its allies against China, Russia, and North Korea.

The war is characterized by a maritime war of attrition focused on the waters inside the first island chain and the forces on both sides threatened by the employment of submarines, ballistic missiles, and cruise missiles. The U.S. quickly moved to establish USMC EABs with mobile C4ISR, air defense and anti-ship missile capabilities throughout the first island chain to control the SLOCs in the AOR against PLAN surface combatants and PLAAF aircraft. USN DDGs and CGs establish picketing locations around and in the first island chain to contain PLAN and Chinese flag ships. The persistent threat from guided munitions in the theater of operations means that the SLOCs for resupply of USMC and USN units are in jeopardy and inaccessible to traditional logistics platforms. In order to confront the logistics challenges of the conflict, the U.S. must rely upon smaller, more numerous fuel and resupply capabilities throughout the First and Second Island Chains and retain high value CLF ships for shuttle missions outside of China's Weapon Engagement Zones (WEZ).

For the purposes of this study, we consider the operational requirements of USMC and USN units within the first and second island chain conducting sea control operations. The focus of the study is on the fuel demands of USMC EABs across the first island chain and USN DDGs and CGs conducting DMO within the WEZ. Figure 9 depicts Chinese missile capabilities within the AOR and the extent of the threat faced by allied forces. Each U.S. unit operating in the AOR has demands for fuel that must be met to continue operations. This study considers the demands and locations of each unit to determine an optimal bulk fuel prepositioning strategy to ensure that the right quantities of fuel are in the right place at the right time to meet demands. The operating environment is full of uncertainty, and therefore any prepositioning strategy must include an analysis of the uncertainty surrounding unit locations and demands. This study will employ distribution mapping to quantify uncertainty in the form of a probability distribution of unit locations across the AOR. This handling of uncertainty will permit an analysis of the expected value of perfect information and measure system performance relative to deterministic solutions to similar problems.

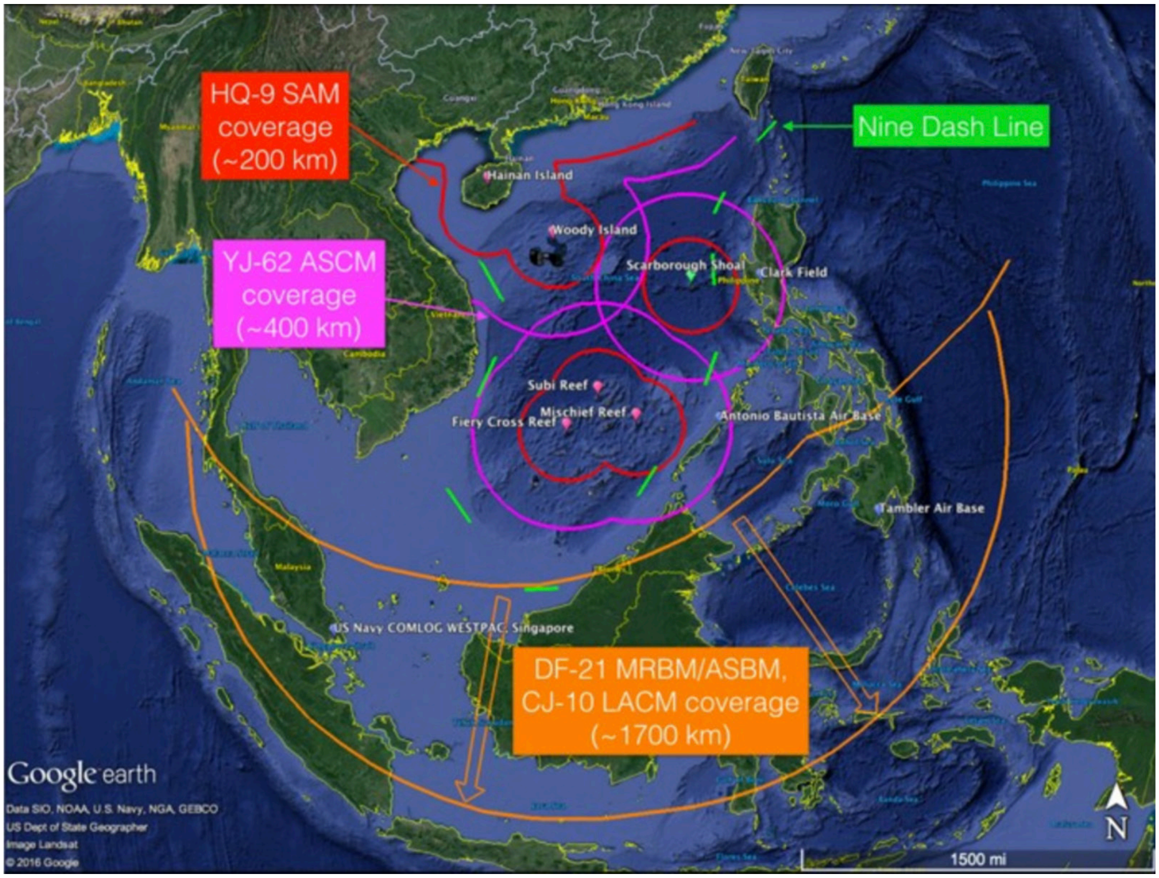

Figure 9. China's Military Capabilities in the USINDOPACOM AOR. Source: Cummings et al. (2020).

B. DATA

The model and scenario runs are implemented in the Python programming language (Python Software Foundation 2019). The optimization models are built using the Pyomo Optimization package (Hart et al. 2012) and then solved using the Coin-OR Branch and Cut (cbc) open-source mixed integer programming solver (Forrest et al. 2020).

The study requires multiple data structures for building a rich scenario, generating notional input data, and organizing and analyzing output data. Python dictionaries (Python Software Foundation 2019) and Pandas DataFrames (McKinney 2018) are employed for organizing collections of data. For visualization of geospatial and analytical data, we employ Folium Python Visualization (GitHub 2016) and Matplotlib (Hunter 2007).

1. Scenario Geography Data

The study requires a method of analyzing the terrain of Southeast Asia for the purposes of defining land masses, open water, and adversary-controlled territory. Properly defining this data within the model was imperative to ensure that BFC and supported unit locations were feasible. As discussed in Chapter 3 the Github (2016) World-Countries JSON data was employed with the Shapely (2019) Polygon data structure to build a model representation of the world's land masses against which to validate the locations of SLOCs and Ground Lines of Communication (GLOC) employed in the model in the creation of a fuel distribution network. Furthermore, Polygons were employed to define regions of adversary control within the AOR. Generating the geographic boundaries for the scenario permits all follow-on analysis. The open source data employed is not without flaws; however, the as shown in Figure 10, overlaying the Polygons generated in the model are very close to the true boundaries. The darkest regions denote Polygon representation of land masses and the lighter region denotes enemy held territory for use in the scenario.

Figure 10. Scenario Geography Data Displayed with Polygon Representation of Land Mass and Adversary Controlled Territory

2. Supported Unit Data

The supported units in the study are comprised of USN ships and USMC EAB locations. Table 1 provides the baseline planning factors for capacity and consumption rates of common ship classes. The data is adapted from Long's (2011) study of RASP effectiveness.

Table 1. USN Supported Unit Petroleum Requirements. Source: Long (2011).

Ship Petroleum Requirements				
Ship Type	Capacity (bbls)	Pre-Assault Consumption (bbls/day)	Assault Consumption (bbls/day)	Sustainment Consumption (bbls/day)
CVN	74,642.0	3,000.0	5,000.0	4,000.0
CG	15,507.0	1,434.0	796.0	776.0
DDG	10,993.0	1,205.0	680.0	665.0
FFG	4,761.0	Not Stated	343.0	323.0
LHD	57,543.0	2,072.0	1,830.0	1,583.0
LSD	20,294.0	727.0	427.0	401.0
LPD	30,450.0	1,159.0	852.0	749.0

For the purposes of this study, we addressed specifically the ships and units that are envisioned as operating within the First and Second Island Chains. This means that emphasis is placed on Destroyers, Cruisers, and Marine Corps EABs. The study employs daily consumption data to approximate aggregated requirements across a thirty-day operational window for each unit which is used to evaluate the effectiveness of a proposed BFC network. A base case scenario will be evaluated in which the outcome of unit demands is deterministic and based upon daily consumption rates at the Assault Consumption Rate. The consolidated data will advise the overall capacity needed in the network over a thirty-day period. Planning within the deterministic model will facilitate evaluation of scenarios in which ship locations and demands are stochastic.

Based on the Global War 2030 scenario, Table 2 provides an overview of the quantity and consumption rates of the integrated Navy-Marine Corps force in the AOR. The computations for ship types are derived from the planning factors defined in Table 1. The EAB requirements are derived from the USMC Marine Air Ground Task Force Planner's Reference Manual (2017). Bulk fuel requirements were based on distribution of a Marine Corps Division across forty sites at the assault consumption rate and converted from gallons per hour into barrels per operational day. This value provides a base planning factor to facilitate scenario planning.

Table 2. Base Case Scenario Petroleum Requirements

Base Case Scenario Petroleum Requirements						
Unit Type	Capacity (bbls)	Assault Consumption (bbls/day)	Operational Days	Computed Assault Consumption (bbls)	Number of Units	Total Computed Scenario Consumption (bbls)
DDG	10,993.0	680.0	30.0	20,400.0	20.0	408,000.0
CG	15,507.0	796.0	30.0	23,880.0	20.0	477,600.0
EAB	476.0	79.8	30.0	2,394.0	40.0	95,760.0
Totals	-	1,555.8	-	46,674.0	80.0	981,360.0

3. BFC Data

The study attempts to be technology agnostic in order to reduce bias in the analysis of the model. The capabilities and limitations of BFCs in the study are representative of a broad set of specific systems in development as discussed in Chapter II. The objective in defining the locations and capacities of BFCs in the study is to assess the mission essential characteristics that should be integrated into a capabilities-based assessment. To generate BFCs within the model network, we employ Python functions to generate BFCs with a user-defined upper bound on capacity in barrels of fuel. The capacities we consider in the study range from 5,000 – 25,000 barrels, where one barrel is equivalent to forty-two gallons. Specifically, we study networks comprised of BFCs with a capacity of 5,000, 10,000, 12,500, 20,000, and 25,000 barrels respectively. The 12,500-barrel capacity network is employed because 12,500 is evenly divisible into 1,000,000 whereas 15,000 is not. While this means that BFC capacities considered are no longer in 5,000-barrel increments, they all share a common 1,000,000-barrel upper bound on available network capacity which makes for a more even comparison. The networks developed in the model use homogenous upper bounds assignments on the BFCs; however, analysis of output data on the quantity of fuel delivered within specific geographic areas is assessed to better inform actual demand vs. available capacity. As discussed in Chapter III, we assign potential BFC locations across the AOR where not otherwise limited by the defined constraints on terrain and sea control. Each location retains its assigned capacity if opened and the capacity is reduced to zero otherwise. The upper bound on the total number of available BFCs is a user-defined input to the model. BFC location and capacity are input into the model as Python dictionaries. Table 3 displays a subset of BFC data as input for the model. The table is representative of the input data required for each model run to establish all possible BFC locations for consideration and their respective upper bound on capacity.

Table 3. Representative BFC Location Data

BFC Location Data			
BFC Location	Degrees Latitude	Degrees Longitude	Capacity (bbls)
BFC_Location_1	-10.0	100.0	5,000.0
BFC_Location_2	-10.0	102.0	5,000.0
BFC_Location_3	-10.0	104.0	5,000.0
BFC_Location_4	-10.0	106.0	5,000.0
BFC_Location_5	-10.0	108.0	5,000.0
BFC_Location_6	-10.0	110.0	5,000.0
BFC_Location_7	-10.0	112.0	5,000.0
BFC_Location_8	-10.0	114.0	5,000.0
BFC_Location_9	-10.0	116.0	5,000.0
BFC_Location_10	-10.0	118.0	5,000.0

In the context of the base case scenario using a deterministic model, we found that in Table 2 that the total force would require nearly 1M barrels to sustain operations for thirty-days. Based on this value, we can estimate the total number of BFCs required given an upper bound on the capacity of an individual platform. Table 4 shows the initial planning factor for planning for thirty-days of sustainment for the distributed force. The thirty-day operational cycle approximates a maximum number of days that a network can remain self-sustaining without the requirement for resupply. The underlying model can be adjusted if a different operational context is desired.

Table 4. BFC Network Planning Factors for Thirty Days of Continuous Sustainment

BFC Network Planning Data (30 Days)			
BFC Network Index	BFC Capacity (bbls)	Available BFC Qty	Maximum Capacity (bbls)
1	5,000.0	200	1,000,000.0
2	10,000.0	100	1,000,000.0
3	12,500.0	80	1,000,000.0
4	20,000.0	50	1,000,000.0
5	25,000.0	40	1,000,000.0

The BFC Network Index displays five different networks comprised of the total number of BFCs required to meet supported unit demands in the deterministic model, given a specific capacity limit per BFC. This BFC data will be used as input for the base scenario to compare the performance of a network comprised of smaller, more numerous BFC versus smaller numbers of much larger BFCs. Another way to consider the number of BFCs required by a network is to consider total sortie generation. In the case that a BFC is mobile, we require a number of sorties rather than a certain number of BFCs. In the case of BFC Index 1, if the BFCs in this network are mobile, they must generate 197 total sorties or 6.6 sorties per day. This means that far fewer BFCs can accomplish the same mission if they are able to shuttle between a larger bulk fuel resupply supply location outside of the WEZ and conduct RAS with units inside the WEZ.

C. RESOLVING UNCERTAINTY WITH DISTRIBUTION MAPPING

The Global War 2030 scenario provides a force composition and a general concept of operations upon which to develop a bulk fuel storage and distribution network. Without a means of forecasting the locations for demands within the network, the decision of where to emplace BFCs becomes a matter of chance. In order to address this uncertainty, the study turns to the concept of distribution mapping (Snyder 2006). If we possess a general understanding of where supported united demands will be located, we can exploit this data to resolve uncertainty in order to inform a facility location problem (Drezner and Wesolowsky 1981). In the context of this problem, we can identify the navigation waypoints that ships will likely follow in conducting a sea control operation in the USINDOPACOM AOR. Using these waypoints, we can develop a map of probability distributions using multivariate normal distributions in two-dimensions using degrees of latitude and longitude. Based upon our certainty regarding ship locations to these waypoints, we can adjust the standard deviation of multivariate normal distribution up to reflect greater uncertainty or down based on greater uncertainty. For the Global War 2030 scenario, we have a great deal of uncertainty regarding the precise locations of ships. In order to reflect this, the probability distribution around each waypoint (X, Y) is defined by $X \sim N(\mu_x, \sigma_x^2)$ and $Y \sim N(\mu_y, \sigma_y^2)$ where the mean is defined as the latitude and longitude of each waypoint respectively and the variance is given as twenty-five degrees squared. In order to generate a complete distribution map, 10,000 replications of ship locations generated using Python and the defined multivariate normal distribution. The locations of each ship placement is recorded and then normalized to give a probability distribution of where a ship will be located with a certain probability. We can then use the probability distribution in the context of each scenario run to inform likely ship locations and resolve the uncertainty that surrounds how to forecast locations of future demands. Constraints are placed on the distribution map to ensure that a ship cannot be placed on a landmass. We can then plot the distribution map of the waypoints defined by the scenario as shown in Figures 11 and 12. Figure 11 shows a three-dimensional view of the probability distribution map along the axes latitude and longitude. Figure 12 shows an overlay of the probability distribution map on the USINDOPACOM AOR in which darker red values indicate higher probabilities that a ship would be located in that grid-square. Each grid-square shown is one-degree latitude by one-degree longitude.

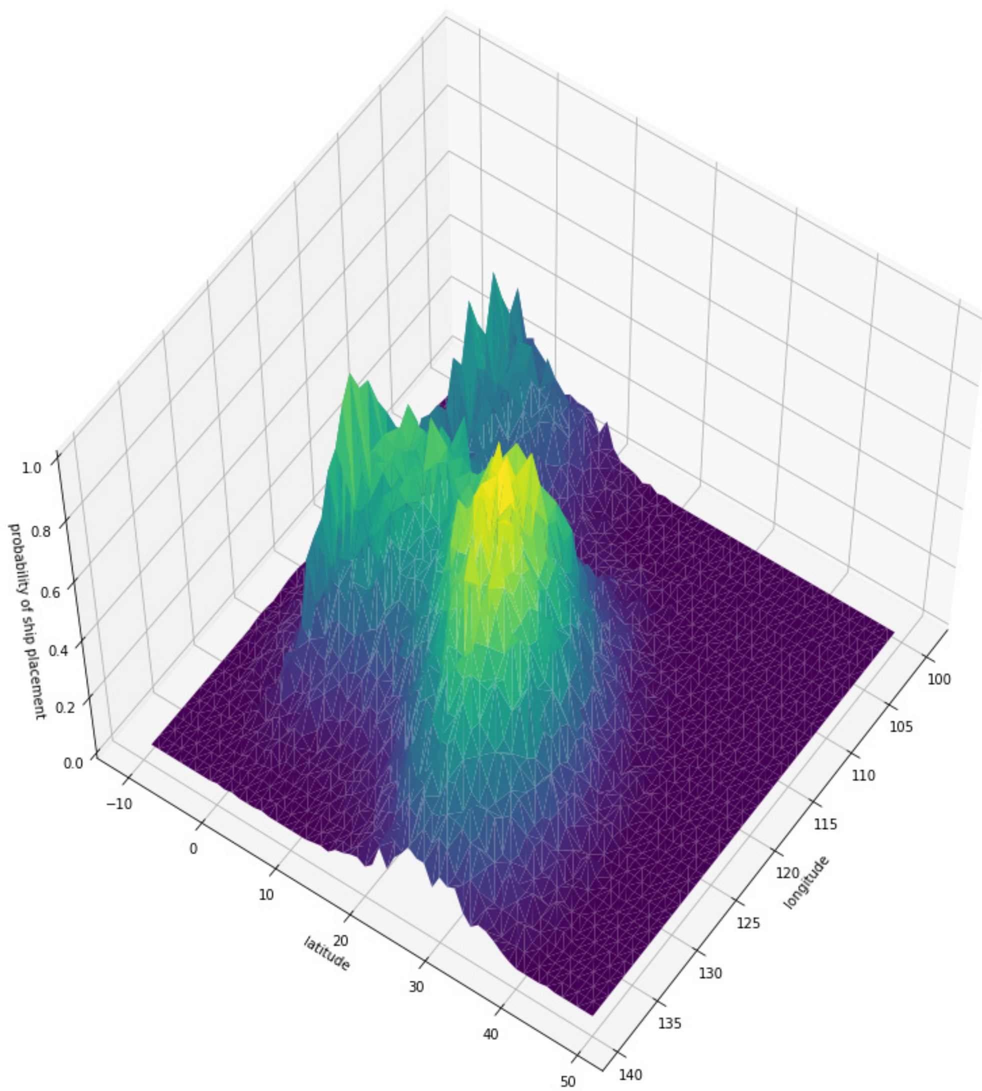

Figure 11. Graphic Depiction of Distribution Mapping for Ship Location in First and Second Island Chains by Degrees Latitude and Longitude

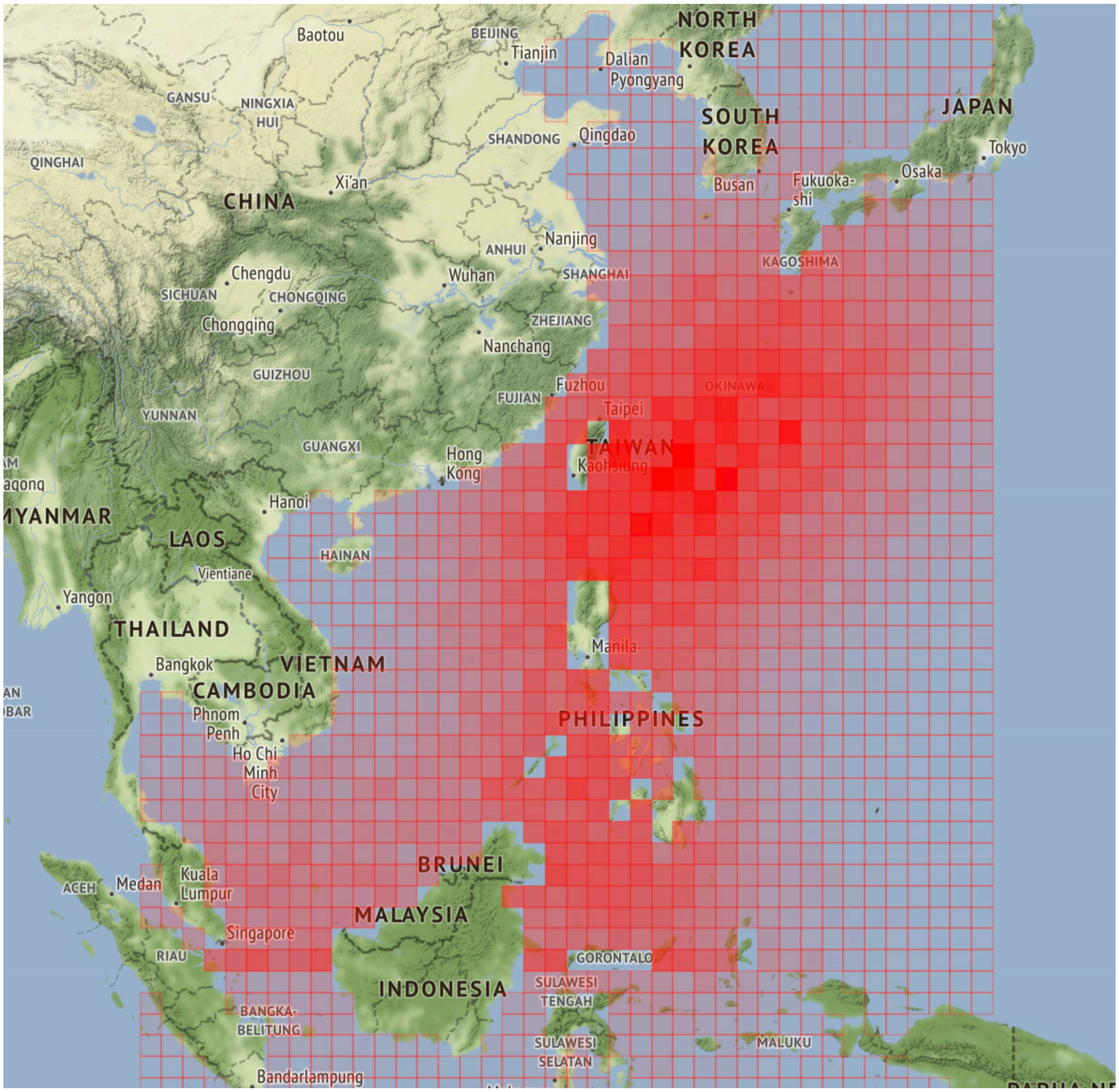

Figure 12. Graphic Depiction of Distribution Mapping for Ship Location in First and Second Island Chains by Degrees Latitude and Longitude Presented as a Folium Map Layer

D. ASSUMPTIONS AND LIMITATIONS

The model assumes that fuel resupply from traditional DFSPs and CLF assets are not available during the scenario. This presents a limitation in that we do not assess the effectiveness of BFC employment to augment existing infrastructure. This would be possible in a scenario in which the adversary does not destroy all existing DFSP locations in the AOR.

The model is fuel type agnostic for the purposes of studying the general utility of BFC employment. Looking specifically at BFC location, capacity, and quantity informs capability assessments and furthers planning efforts into the utility of employing these technologies within the naval logistics enterprise. Fuel types that could be required in the scenario are diesel fuel marine (DFM), jet-propulsion 5 (JP-5), and jet-propulsion 8 (JP-8). JP-5 and JP-8 are commonly referred to by their North Atlantic Treaty Organization (NATO) identifications, which are F-44 and F-34 respectively. The limitation of not defining fuel types in the model is that we cannot specify fuel capacity and fuel type within a single scenario. Addressing this limitation could be accomplished by running the optimization model for each of the three fuel types separately, or by adding an additional index for fuel type and incorporating BFC capacities and demands for each type into the model.

The demands that we build in the simulations are aggregated based on the number of time steps defined by the user. Time steps are defined by days and are used to compute total fuel expenditures by each supported unit. Supported Unit demand is computed as the total demand for each unit aggregated over the entire time period. In the base case deterministic model, unit demand is constant, while in later scenarios fuel consumption for each unit uses a parametric distribution to impart variance in the amount of fuel consumed each day. The mean consumption rate is based on the planning factors detailed in Table 2 as previously discussed.

The model assumes that the technologies employed for conducting bulk fuel resupply are capable of conducting RAS with ships and delivery over the shore to USMC EAB sites. The scope of the study was not to define the specific connectors required at the tactical level to permit refueling operation.

Finally, the model does not consider any classes of supply beyond bulk fuel. As a result, if a BFC is developed in such a manner as to transport multiple classes of resupply, it is possible that they could be employed in support of more diverse resupply missions.

E. VALIDATION OF MODEL USING THE DETERMINISTIC CASE

The first run of the model serves to validate the optimization and outputs of the overall model. This validation will be one run of each BFC network comprised of BFCs of differing capacities using a deterministic case in which supported unit locations are known, demands on constant, and the number of available BFCs for each network is based on the number required to meet unit demand as shown previously in Table 4. Prior to running the deterministic validation, supported unit locations are assigned using the methodology discussed previously in the chapter employing a combination of distribution mapping and randomized assignment. One location assignment is used for all five BFC networks to ensure each network is validated using the same locations of supported units and demands. The deterministic scenario runs are the only ones in the study in which unit locations are fixed across all runs.

The purpose for running a deterministic scenario is to develop intuition about the expected value of perfect information as it pertains to each network composition. Table 5 displays an overview of the output data obtained from the deterministic case of the model. In each BFC network, we observe that all unit demands are met and all available BFCs are employed in four of the networks, with 199 out of 200 possible BFCs employed in the network with 5,000-barrel capacities. Additionally, a comparison of the objective values indicates that despite a cost associated with each BFC activated, the network that employs the smallest BFCs with 5,000-barrel capacity yields the lowest overall total cost. Intuitively this makes sense, as the high number of BFCs ensures that the distances between BFCs and supported units is significantly shorter than the networks with fewer BFCs. As formulated, we observe that the sum of costs associated with activating more BFCs may prove to be lower than the cost associated with activating fewer BFCs and connecting longer distances between BFCs and supported units.

Table 5. Overview of Output Data from the Deterministic Model Scenario

Deterministic Model Output Data Overview						
Days Supply	BFC Capacity	BFC Qty	BFC Open	Objective Value	Total Delivered	Total Unmet Demand
30	5000	200	199	63908296	981360	0
30	10000	100	100	71780565	981360	0
30	12500	80	80	72632285	981360	0
30	20000	50	50	77780842	981360	0
30	25000	40	40	80015036	981360	0

Each model run captures each BFC location and the supported units serviced by that location in order to document the arcs and nodes established by the model. Table 6 represents an excerpt of the output data from a deterministic run of the model. The Table displays the locations of each BFC and Supported Unit in degrees latitude and longitude. This data can then be employed to provide a graphic representation of the network as well as analyze the geographic locations of arcs and nodes.

Table 6. Representative BFC and Supported Unit Location Data from Deterministic Scenario

Deterministic Model Output Data BFC Location and Supported Units				
BFC_Capacity	BFC_Lat	BFC_Lon	Unit_Lat	Unit_Lon
5000	-10	122	-6.385300	122.486823
5000	-10	122	-9.892049	120.528827
5000	-10	122	-7.812790	109.751993
5000	-6	122	-6.385300	122.486823
5000	-6	122	-4.642004	122.800106
5000	-4	106	-3.605342	104.823943
5000	-4	106	-3.425720	104.992814
5000	-4	106	-7.812790	109.751993
5000	-4	112	-1.899076	111.924501
5000	-4	112	-7.812790	109.751993

To further illustrate how the model develops an optimal network of BFCs to support units operating in the AOR, Figure 13 provides a graphic representation of the networks generated for each of the five defined network types according to BFC capacity. The unique characteristics of each particular network are the overall number of BFCs, the capacity of each BFC, and the relative number of BFCs to supported units. The number of supported units, their demands, and locations are constant. In the figure, BFCs are denoted by orange star icons and supported units are denoted by blue icons. The image depicts a close-up view of the Philippine Sea showing operational Destroyers, Cruisers, and EABs.

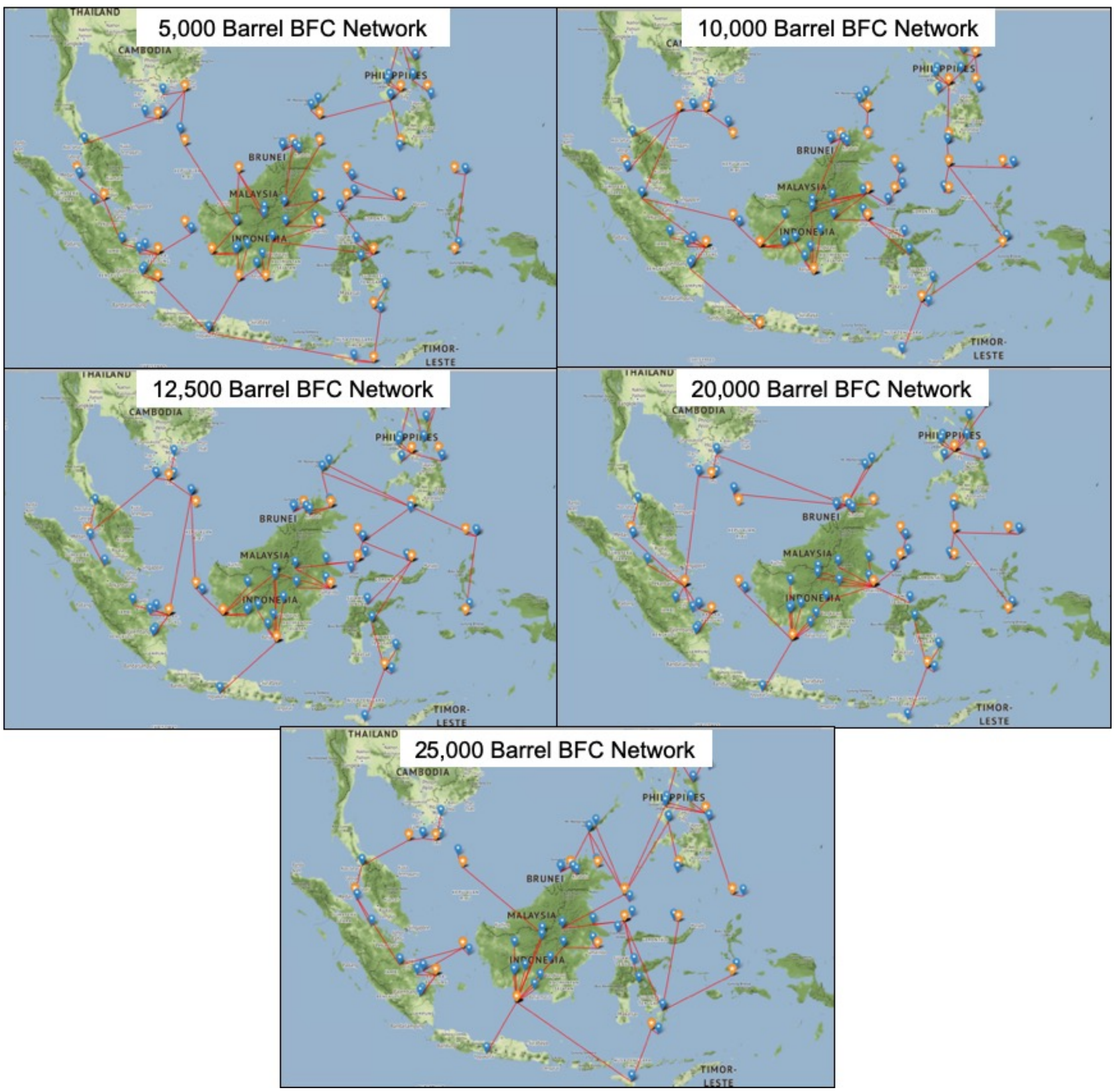

Figure 13. Graphic Depiction of Bulk Fuel Networks

In order to develop patterns of activity for optimal BFC Locations, each run of the deterministic model is analyzed to ascertain which potential locations have the highest number of opened BFCs. These represent the geographic regions of highest demand. Furthermore, as further data are collected, location data and the number of opened BFCs can be employed for future work in developing BFC networks with heterogenous BFC capacities. Table 7 provides an excerpt of the output data captured by the model. For example, a BFC Location such as BFC Location 54 in Table 7 that has five 5,000-barrel BFCs opened could ultimately be replaced with a single 25,000-barrel BFC if the results are consistent, based on further analysis.

Table 7. Representative BFC Location Data Showing Number of BFC Opened at Each Possible Location

Deterministic Model Output Data BFC Locations and Number Opened						
Days Supply	BFC Capacity	BFC Qty	BFC Location	Number Open	Lat	Lon
30	5000	200	BFC_Location_12	1	-10	122
30	5000	200	BFC_Location_54	5	-6	122
30	5000	200	BFC_Location_67	1	-4	106
30	5000	200	BFC_Location_70	1	-4	112
30	5000	200	BFC_Location_71	1	-4	114
30	5000	200	BFC_Location_88	5	-2	106
30	5000	200	BFC_Location_90	1	-2	110
30	5000	200	BFC_Location_96	1	-2	122
30	5000	200	BFC_Location_99	5	-2	128
30	5000	200	BFC_Location_110	4	0	108

F. USING SCENARIOS TO EVALUATE MODEL EFFECTIVENESS

Using scenario runs permits the incorporation of uncertainty into planning for BFC employment. The study employs four scenario variations that build in complexity to develop a better understanding of favorable BFC network characteristics for employment. Each scenario is comprised of 500 total runs, 100 runs allocated to each BFC network composition. In each scenario, supported unit locations are based on the underlying distribution map described in Paragraph C of this chapter. Supported Unit locations are randomly assigned to the map using pseudo-random number generation in order to account for the impact of dynamic location in assigned BFC location and composition. In order to determine the effectiveness of each BFC network, we consider each objective function value from the optimization model, where scenario runs are defined with the objective of minimizing the average cost over the scenarios $\omega = 1, \ldots, S$, where $S = 100$ in the study. Taking the mean objective value across all scenarios permits us to make assessments about network effectiveness. We replace the objective function of Model (A0) with $D_{b\omega}$ where b represents the BFC network under consideration ($b = 1, 2, 3, 4, 5$) and ω represents a unique scenario with unique supported unit locations. Taking the mean across all scenario runs gives the following:

$$\overline{d}_{b\omega} = \frac{1}{S}\sum_{\omega=1}^{S} D_{b\omega} \qquad \forall\ b \in B \qquad \text{(B01)}$$

For formula (B01) we compute the mean objective function values from 100 scenario runs for each of the five network types.

The first scenario considered uses constant supported unit demands and unique dynamic supported unit locations for each run. The second scenario uses variable supported unit demands and unique dynamic supported unit locations for each run. The third scenario employs variable supported unit demands, unique dynamic supported unit locations for each run, and considers the impact of adding twenty percent more BFCs to each network. The fourth and final scenario employs variable supported unit demands, unique dynamic supported unit locations for each run, and considers the impact of increasing the mean of each supported unit's demands by twenty percent. The objective of using four differing scenarios is to evaluate the positive and negative attributes of each defined BFC network to develop an understanding of the characteristics that should be incorporated into network employment.

G. ANALYSIS OF THE CONSTANT SUPPORTED UNIT DEMAND SCENARIO

The purpose of the analysis of the Constant Supported Unit Demand Scenario is to conduct a sufficient number of runs using deterministic supported unit demands to develop a baseline understanding of patterns of activity for determining optimal BFC locations. In order to accomplish this end state, 100 runs of each BFC network will be conducted and all output data recorded and analyzed. Ship locations in this stage of the analysis are dynamic based upon distribution mapping and includes generating new ship locations for analysis of thirty-days of consumption data. Each of the 100 runs across each of five networks yields a total of 500 design points, each with its own ship location data and optimal distribution network. For each BFC network type, the most frequently used BFC locations will be identified via visualization tools. The number of locations identified will be guided by the upper bound on number of BFCs required to support the scenario fleet as previously defined in Table 4. The results from these initial runs are displayed in Table 8. The average run time for each scenario run is 12.84 seconds for a total run-time of approximately one hour and forty-seven minutes running on a MacBook Pro laptop with a 2.3 GHz Dual-Core Intel Core i5 processor. The results are consistent with our five previous test runs. In this scenario, all unit demands are met across all runs we find that the 5,000-barrel BFC capacity network has the lowest overall mean objective function value. As previously discussed, this result demonstrates that the ability to locate sources of supply as close to demand locations as possible outweighs the costs associated with having to activate more assets. In this case, the 5,000-barrel BFC capacity network activates five times more assets than the 25,000 -barrel BFC capacity network.

Table 8. Constant Supported Unit Demand Scenario Results Summary

Scenario Results Summary						
BFC Capacity	BFC Qty	Mean BFC Open	Mean Objective Value (B01)	Objective Value StdDev	Mean Delivered (bbl)	Mean Unmet Demand (bbl)
5000	200	199.23	75441371.0	8362925.59	981360	0
10000	100	99.74	84131447.2	10118188.06	981360	0
12500	80	80	84662608.9	10206452.14	981360	0
20000	50	50	90774288.0	9024045.03	981360	0
25000	40	40	90055547.0	10479856.03	981360	0

The results of the scenario are better illustrated in Figure 14 in which boxplots of the objective function values are shown for each of the five networks. The figure clearly displays that the 5,000-barrel capacity network dominates the other networks with respect to lowest mean objective function value and tightest interquartile range.

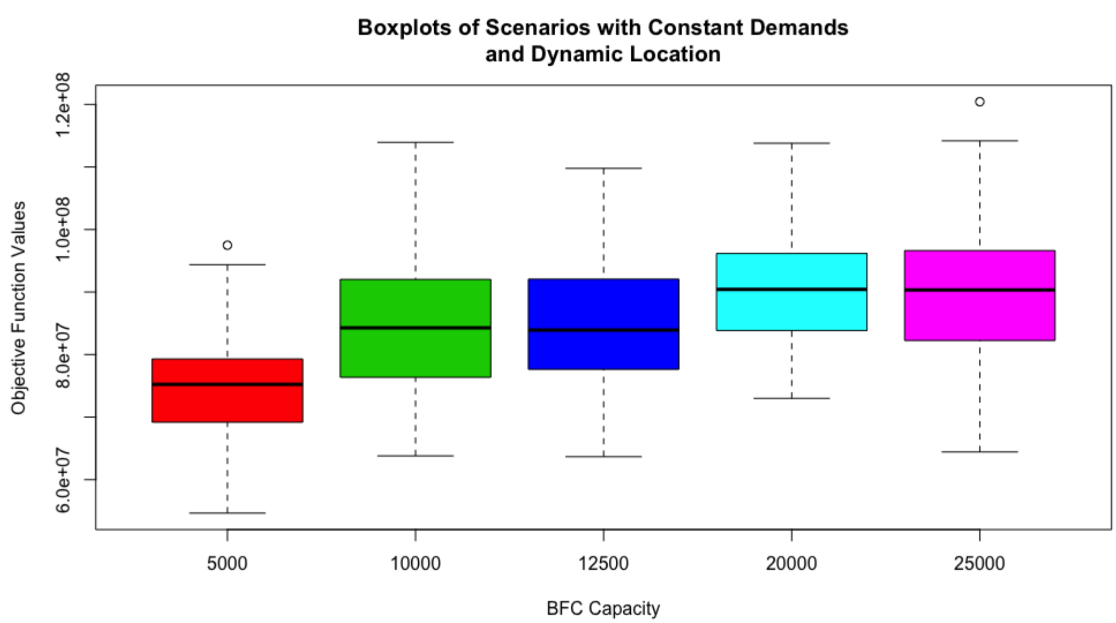

Figure 14. Boxplots of Results for the Constant Supported Unit Demand Scenario

The BFC location output data from the scenario is visualized in Figure 15 for all five networks. The visualization is done in Folium using the consolidated outputs from all 500 runs. For each network, every potential BFC location is analyzed for how many individual BFCs are activated at that location. The total sum of BFCs activated at each location is consolidated across all runs and then normalized across all scenarios and networks. The results are then plotted using Circle Markers to denote usage data. Larger circle diameters indicate higher numbers of BFCs located at a specific location. The patterns of activity for BFC placement generally reflect the underlying distribution map used to resolve uncertainty about the scheme of maneuver employed by USN vessels and USMC EABs. Clearly visible in the figure is the higher number of BFCs employed in the 5,000 and 10,000-barrel capacity networks relative to the other three networks as well as the relative similarities in distribution of BFCs in each of the networks. As expected, the networks attempt to minimize the distance between supporting and supported units to reduce costs which accounts for similarities in BFC locations in each network.

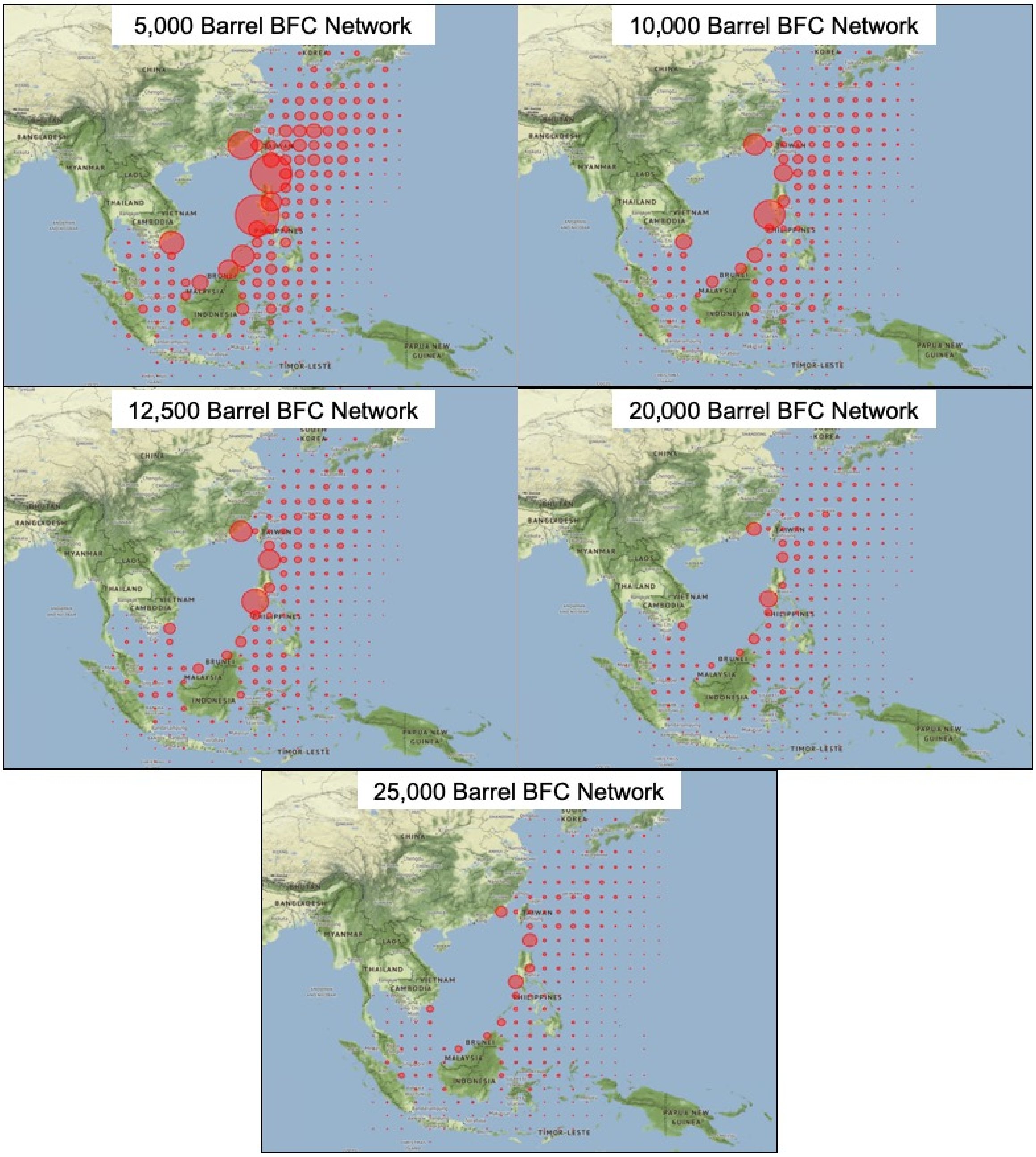

Figure 15. Locations of BFC Placement Normalized Over 100 Scenario Runs for All Five BFC Networks

It should be noted that because this scenario relied on deterministic supported unit consumption data, there were no unmet demands which simplified the analysis of this scenario. In follow-on scenarios, the study investigates the behavior of the networks when demands cannot be fully met in order to assess overall limitations in the BFC concept as developed.

H. ANALYSIS OF DYNAMIC SUPPORTED UNIT DEMAND SCENARIO

The Dynamic Supported Unit Demand Scenario incorporates variability in the consumption data of each supported unit at each time step in the thirty-day operational timeframe. Each unit's consumption data is based on the unit type mean daily consumption rate. A normal distribution using the mean daily consumption with a ten percent standard deviation is used to represent variability in consumption over the thirty-day period. At each time step, a new consumption rate is computed using pseudo-random number generation based on the parametric distribution discussed. The introduction of variability in consumption data results in overall demands either exceeding or falling short of the demands in the deterministic case. In this scenario, the study examines the impact of unmet demands on network performance. Table 9 summarizes the results from this scenario. In this scenario, the 5,000-barrel capacity network achieves the lowest overall objective function value; however, it no longer possesses the lowest standard deviation. Ship locations in this scenario are dynamic based upon distribution mapping and the introduction of variability in consumption data produce outliers in terms of supported unit locations and demand quantities. The result is that a network can be heavily penalized when a supported unit cannot be supported at a distant location.

Table 9. Dynamic Supported Unit Demand Scenario Results Summary

Scenario Results Summary						
BFC Capacity	BFC Qty	Mean BFC Open	Mean Objective Value	Objective Value StdDev	Mean Delivered (bbl)	Mean Unmet Demand (bbl)
5000	200	198.98	80706454.1	15178580.71	978725.49	543.71
10000	100	99.88	84379425.3	14025973.98	981940.99	339.81
12500	80	79.98	86106935.7	15618892.18	979750.09	390.64
20000	50	49.99	95346252.5	18456882.84	981715.18	742.49
25000	40	40	100922943.2	28830181.65	980632.75	1656.04

Figure 16 provides boxplots of the mean objective values for 100 runs of each of the five networks. What we observe is that despite having outliers in the 5,000 and 12,500-barrel capacity networks both retain relatively low mean objective values. We desire networks that exhibit robust behavior which include a low mean objective function value and a low standard deviation.

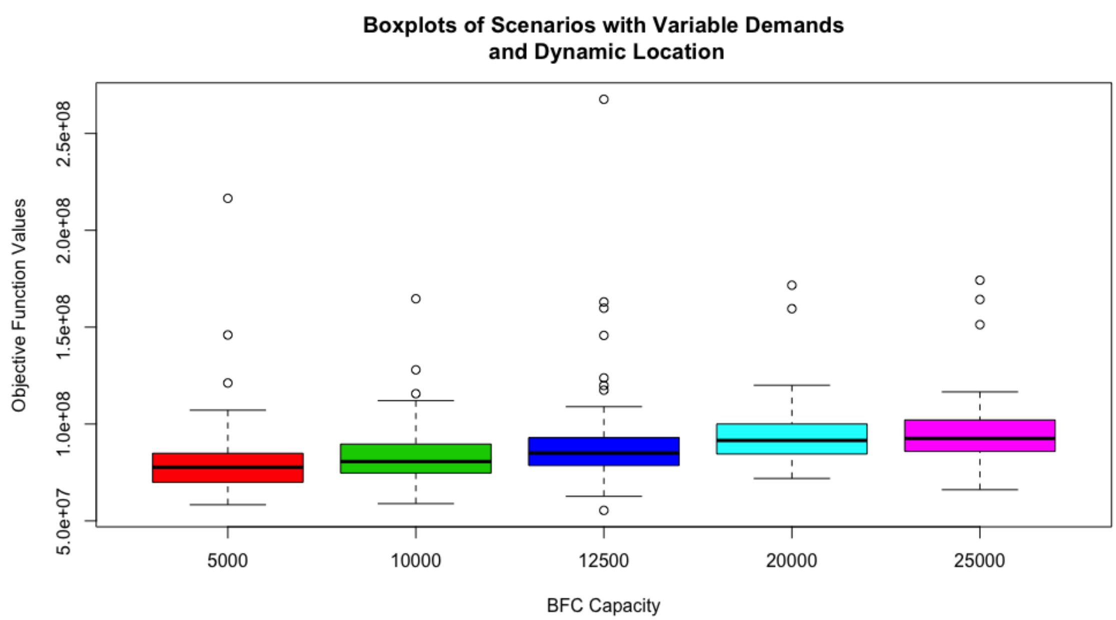

Figure 16. Boxplots of Results for the Dynamic Supported Unit Demand Scenario

The introduction of variable supported unit demands results in total demands that exceed total capacity within the network. As formulated, the network will seek to fulfill the demands of units with higher penalties and higher demands to reduce overall penalties. What we find in this scenario is that EABs are the units that have all the unmet demands. Table 10 displays the average number of supported units, by unit type, that have unmet demands across all scenario runs. What the table shows is that on average, the 5,000-barrel capacity network has the highest average number of EABs with unfulfilled demands with approximately 0.93 EABs during each of the 100 runs. The best performance in these runs was observed with the 12,500-barrel capacity network with an average of 0.19 EABs with unmet demands during each individual run. The consistent result across all network types in which EABs are the only units with unmet demands are likely the result of the relatively low demand quantities and the lower assigned penalty. There are also more EABs than any other single unit type, and because EABs are ground-based, BFCs are not able to be located as close to them as USN vessels navigating the SLOCs.

Table 10. Average Supporting Unit Unmet Demands

Average Number of Units with Unmet Demands Per Scenario Run			
BFC Capacity	CG	DDG	EAB
5000	0.00	0.00	0.93
10000	0.00	0.00	0.45
12500	0.00	0.00	0.19
20000	0.00	0.00	0.25
25000	0.00	0.00	0.41

I. ANALYSIS OF INCREASED BFC AVAILABILITY SCENARIO

In the Increased BFC Availability Scenario, we retain the dynamic location of supported units and the use of variable consumption rates for a 30-day operational scenario to best approximate supported unit demands. In this scenario, we introduce a twenty-percent increase in the upper bound on the number of BFCs available for activation in each network. This provides an overall increase in capacity of twenty-percent and provides an operational buffer that was not available in previous scenarios. As a result of the increase in overall network capacity, we find that all networks meet all unit demands and the increased quantity of BFCs available for activation reduces Mean Objective values significantly despite an increase in the mean number of BFCs open for each network. The reduction in Mean Objective Function Value is attributed to the increased number of BFCs available within the network. In addition to meeting all demand which removes any penalty, on average the greater number of BFCs reduces the networks' barrel-nautical mile costs between BFC locations and supported units.

The buffer created in this scenario demonstrates that the observed performance gap between the smaller capacity networks and the larger capacity networks is reduced when a surplus capacity exists in the model. This effect can be seen in the relatively stable mean objective function values of the smallest two capacity networks, while the larger networks demonstrate significant decreases in Mean Objective Function Values with only modest increases in the number of BFCs required to meet demand. The Mean Objective Function Value for the 25,000-barrel capacity network from this scenario is 83,737,364.9 with an average number of 43.28 BFCs opened. This represents a 17.0 percent increase in performance with a modest 7.50 percent increase in BFCs required from the previous Dynamic Supported Unit Demand Scenario Mean Objective Function Value of 100,922,943.2 with an average number of 40.00 BFCs opened. We observe a similar trend of improvement in the 20,000-barrel capacity network as well. This is an important observation from the sensitivity analysis of the optimization model, because a network with 44 or 58 BFCs respectively is arguably easier to manage than a network with 202 BFCs across the range of acquisition, operations and sustainment, and command and control.

Table 11. Increased BFC Availability Scenario Results Summary

Scenario Results Summary						
BFC Capacity	BFC Qty	Mean BFC Open	Mean Objective Value	Objective Value StdDev	Mean Delivered (bbl)	Mean Unmet Demand (bbl)
5000	240	201.1	75773477.9	10333025.86	980591.71	0
10000	120	102.05	80709592.7	10400191.14	981680.28	0
12500	96	83.93	78563325.5	10357474.46	980092.74	0
20000	60	57.3	81267095.3	12573551.71	980332.77	0
25000	48	43.28	83737364.9	11755821.02	981865.69	0

The boxplots contained in Figure 17 provide a visual representation of the output data from the scenario. The boxplots clearly show that there is significant overlap of the interquartile ranges of each of the networks. Furthermore, we observe a departure from the strict positive correlation between larger capacity BFCs and higher objective function values as shown by the 12,500-barrel capacity BFC network and the remarkably similar performance between then the 10,000 and 20,000-barrel capacity networks.

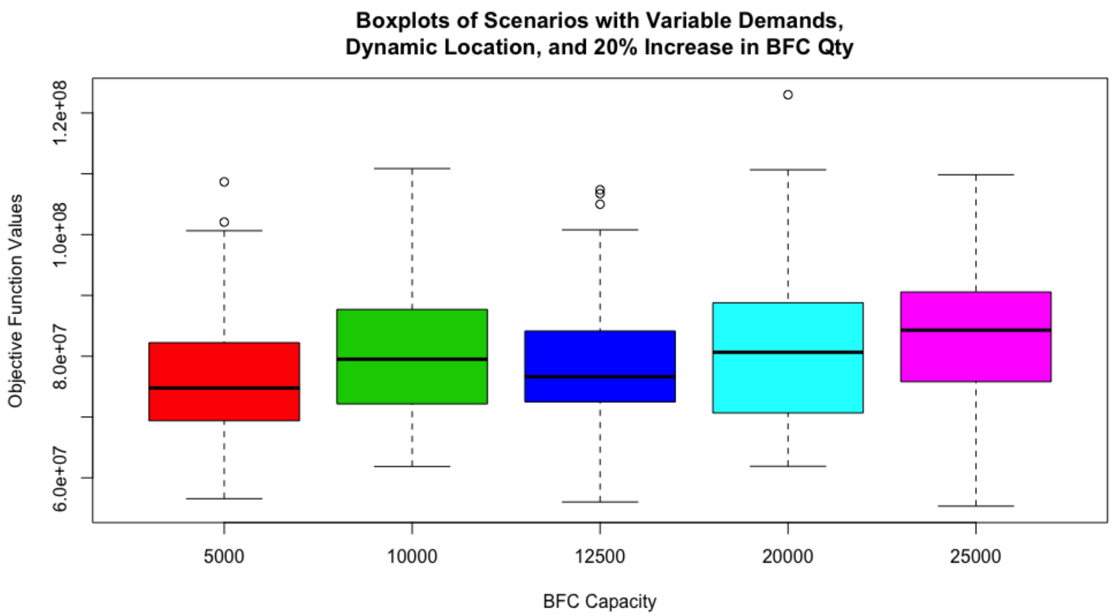

Figure 17. Boxplots of Results for the Increased BFC Availability Scenario

This scenario revealed the importance of building excess capacity into a network when we anticipate variability in the location and consumption rates of supported units. Adding a possible twenty-percent additional capacity into each network, we observed a decrease in mean objective function values for all system despite the necessity to open a higher number of BFCs. In the context of this study, paying a higher initial cost in order to ensure unobstructed logistics support results in desirable overall network performance. Ultimately, the objective of introducing the BFC concept is to reduce the likelihood of operational pauses due to logistics shortfalls for units within the AOR.

J. ANALYSIS OF INCREASED SUPPORTED UNIT DEMAND SCENARIO

The final scenario considered in the study returns to the original BFC networks in terms of capacities and upper bound on quantity of BFCs that can be opened in each model run. The Increased Supported Unit Demand Scenario introduces a twenty-percent increase in the mean consumption rate of each supported unit. This increase in mean consumption rate is combined with variability in consumption rates at each time step which results in an increase of twenty-percent in the expected value of demands in each run compared to previous runs. The objective of this analysis is to analyze network behavior under conditions in which BFC network capacity is consistently exceeded.

During the Increased Supported Unit Demand Scenario, the study seeks to find trends in the mean objective function values of each network, analyze the scale of unmet demands in each network, and analyze model outputs regarding the impact of unmet demands on individual supported units. Table 12 provides a summary of results from the scenario which reveals that the mean objective values of each network are essentially indistinguishable when the mean delivered barrels of fuel are capped at the upper bound of the networks and the mean unmet demands are remarkably similar. An interesting outcome is that five networks with differing capacities and available BFCs were penalized nearly equally despite previous results in which smaller capacity networks were able to reduce supporting-supported distances to yield lower mean objective function values. In this scenario, the presence of high penalty rates overshadowed the advantages of smaller capacity networks observed in previous scenarios.

Table 12. Increased Supported Unit Demand Scenario Results Summary

Scenario Results Summary						
BFC Capacity	BFC Qty	Mean BFC Open	Mean Objective Value	Objective Value StdDev	Mean Delivered (bbl)	Mean Unmet Demand (bbl)
5000	200	200	1028135418	96212672.3	1000000	179260.5
10000	100	100	1034915657	106256088.5	1000000	179479.4
12500	80	80	1037210817	100419907.8	1000000	179797.9
20000	50	50	1021820937	115123660.6	1000000	175658.8
25000	40	40	1022119145	107245841.5	1000000	176088.1

Boxplots of the outputs are provided in Figure 18. The figure clearly demonstrates the impact of unmet demands on the performance of each network in terms of increasing objective function values and equalizing performance between the different networks.

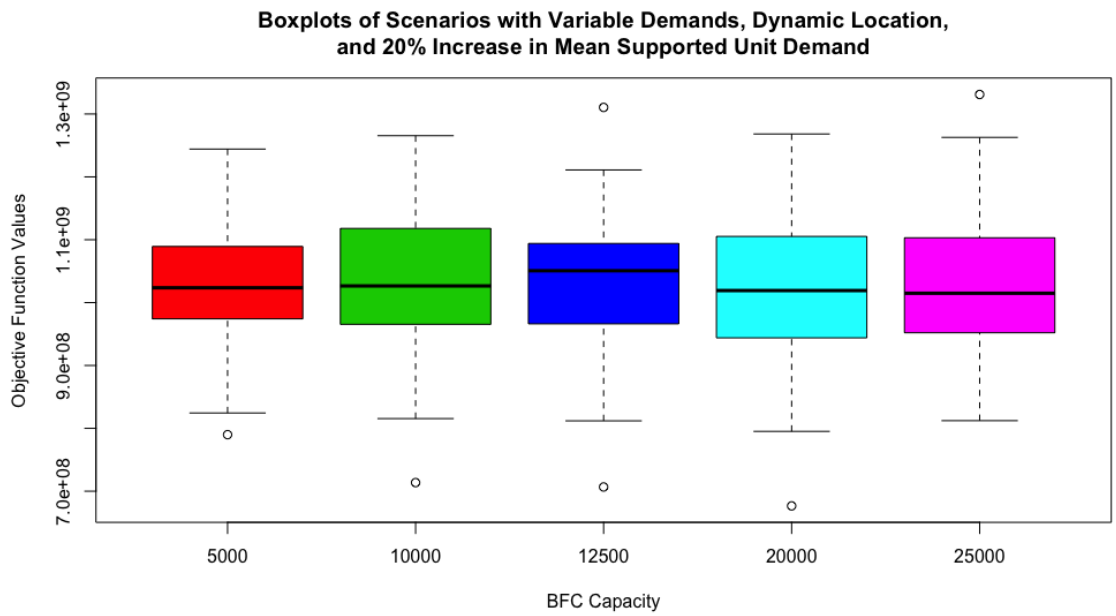

Figure 18. Boxplots of Results for the Increased Supported Unit Demand Scenario

The next logical step in the study is to analyze the unit shortfalls to find trends in the unmet demands within each network. Table 13 provides an overview of the average number of units of each type with unmet demands across all networks and all runs. The results show that on average seven DDGs have unmet demands and all forty EABs have unmet demands. These are important findings for the validity of the model as developed. The CG units with their high penalty and high demand are more likely to receive fuel in the network in order to minimize penalties. DDGs have a lower penalty and lower demand than the CGs; however, their demands and penalties as developed are higher than the EABs and thus only approximately thirty-five percent of DDGs on each run had fuel shortfalls. The combination of lower fuel capacities, lower consumption rates, and lower penalties resulted in every EAB having fuel shortfalls in every one of the five hundred scenario runs.

Additionally, because EABs are ground-based units, they pose a difficult distance problem for delivery relative to the DDGs and CGs that operate in SLOCs closest to possible BFC locations.

Table 13. Average Supported Unit Unmet Demands

Average Number of Units with Unmet Demands Per Scenario Run Given a 20% Increase in Mean Demands			
BFC Capacity	CG	DDG	EAB
10000	0.0	7.0	40.0
12500	0.0	7.1	40.0
20000	0.0	7.0	40.0
25000	0.0	7.1	40.0
5000	0.0	7.0	40.0

The Increased Supported unit demand Scenario uncovered two important aspects of the optimization model: first that when network capacities are consistently exceeded the maximum network capacity matters more than BFC quantity or capacity; and second that as formulated units with lower demands and lower penalties with be most likely to face fuel shortfalls when network capacity is exceeded. Both of these findings are important in understanding the method by which BFC networks are employed in a wartime or peacetime scenario to ensure that any one unit-type does not face critical gaps in logistics support.

V. SUMMARY AND CONCLUSIONS

A. SUMMARY OF RESULTS

The scenarios explored in this study were designed to evaluate the BFC concept around a central wartime scenario that permitted the use of several sub-scenarios to provide an opportunity for sensitivity analysis of the optimization model's generated networks. The use of a central scenario with several derivative demand and location-based variations on that scenario enabled the study to uncover important aspects of the BFC concept relating the central research questions of how to best employ a BFC network in a contested maritime environment.

The model results demonstrated that a network that distributes capacity to areas of high anticipated demands will generate consistently low mean objective function values so long as supported unit demands are met. This requires developing good estimates of logistics supportability prior to deploying a BFC network, and understanding the concept of operations for DMO and EABO that will be supported.

Furthermore, the model demonstrates that building excess capacity into the BFC network will result in better rates of return on performance gains than the amount of materiel investment required to build the required excess capacity. Essentially, paying a little more on the front end to build a larger, more resilient network will provide a greater return on investment than attempting to simply meet expected demands. Networks demonstrated up to seventeen percent gains in performance for less than an eight percent increase in the quantity of assets required.

The model did not explicitly explore the impact of mobile BFCs on network performance; however, the use of a thirty-day scenario provided insights into how movement can enhance network performance. If BFCs are strictly stationary, they become either one-time use or a secondary refueler must enter the WEZ in order to refill them. The use of a secondary refueler is contradictory to one of the motivations for the use of BFCs which was to permit high value CLF assets to remain safely outside of the First and Second Island chains to conduct shuttle operations as required. BFCs that are self-mobile, or can be towed by other unmanned or minimally manned surface craft can be used indefinitely provided they can ferry back to the seam between the high risk and low risk zones to conduct replenishment from larger tankers and then return to their assigned sector within the AOR. The use of mobile BFCs also means that fewer overall numbers of BFCs are required if they can conduct an intermediate resupply and return quickly enough to continue operations. A BFC rotation cycle can be generated in the areas of high demand in which BFCs are on station conducting resupply of USN vessels while other BFCs are transiting to and from intermediate resupply. This rotation cycle would ensure that a sufficient number of BFCs are always prepositioned in anticipation of supported unit demands while reducing the overall burden on acquisitions, operations, and support requirements.

An important finding from the model was that when demands exceed capacity within any network, system performance depends more on the overall capacity of the network rather than the characteristics of the individual network elements. This means that a network with less desirable platforms, but with a higher overall capacity will perform better than the network with the best possible platform composition with insufficient capacity.

Finally, the model uncovered that a shortcoming in the logic of using a min-cost max-flow problem is that units such as ground-based EABs are dominated by higher consuming USN vessels when the network must minimize penalties for unmet demand. To overcome this finding in the model, the penalty for unmet demands from lower consumers must be offset by higher proportional penalties, or placed on a sub-network that services only low consuming units such as USMC EABs.

B. RECOMMENDATIONS

The first recommendation in employing BFCs for optimally pre-positioning bulk fuel resources is to address the operational requirements and scheme of maneuver of the Marine Corps and Navy priority units. The use of distribution mapping in Chapter IV of the study was used demonstratively as a means of resolving uncertainty for key demand locations when a basic operational scheme of maneuver is known, but specific demand locations are not known. Logistics supports operations, and understanding the operational context for BFC employment is the first requirement in developing an effective network.

Minimally manned or unmanned BFCs should be mobile. BFCs should be capable of self-propulsion or be towable by other low-cost attritable technologies to the extent that they can relocate to address operational adjustments and conduct intermediate resupply for later use and to reduce the exposure of strategic level logistics assets to precision guided munitions within the First and Second Island Chains. Networks comprised of mobile BFCs are more operationally flexible and require fewer individual assets to fulfill the same overall level of demand.

BFC capacity should be influenced by the capacity and demands of their supported units. In the study, the 5,000-barrel capacity BFC network required more than three individual BFCs to refill an empty CG. This means that three redundant assets were required in the same location possibly at the same time to resupply a single supported unit. This should be avoided because it makes RAS more cumbersome and exposes both supporting and supported units to greater threats while they are limited in maneuver for greater periods of time. To this end, a homogenous BFC network should be comprised of BFCs that are capable of refueling any supported unit with a single asset with additional capacity left over to conduct additional resupplies while on station or while transiting to or from an intermediate supply location. To this end, the study would recommend BFCs capable of at least 20,000-barrel storage capacity for use in support of DMO. An alternative BFC network would be one comprised of different sized BFCs built for specific purposes. A network may contain larger BFCs to service USN vessels and aviation units, and smaller BFCs to refuel units with lower consumption rates such as company-sized EABs.

C. AREAS FOR FUTURE RESEARCH

There are many areas for future research that will yield fruitful results in the area of optimal pre-positioning of bulk fuel resources.

There are many promising bulk fuel storage and delivery technologies such as those explored by NSWC Carderock (2019). This study was intentionally broad in order to develop a general understanding of the capabilities and limitations of the BFC concept without allowing current materiel solutions to influence the inputs or outputs of the study. Having developed a basic framework for the study of BFC employment, a natural transition would be the study of how current and future technologies can meet or exceed the baseline of performance developed in this study.

This study did not research the impact of mixed composition BFC networks relative to homogenous BFC networks. The final scenario in which supported unit demands were increased beyond network capacities revealed a shortcoming in viewing all BFCs and all units as homogenous assets. A study that examines the impact of a network comprised of multiple sizes of BFCs each with their own prioritized list of supported unit-types would address this shortcoming. Furthermore, BFC networks with various platforms and sizes may prove to be more resilient and more responsive than the networks explored in this study.

This study only briefly examined the impact of movement on BFC network effectiveness. The importance of studying the contribution of mobile BFCs cannot be overstated as minimally manned or unmanned logistics platform are critical in supporting the operational requirements set forth in Design 2.0 and the CPG.

A final area for further research is to explore the specific connectors that will link BFCs with their supported units both at sea and over the shore. Hebert (2019) explored the impact of ship to shore fuel delivery in support of Marine Corps EABs and a similar approach should be employed to investigate connectors needed to permit BFCs to conduct RAS in support of USN vessels and logistics over the shore in support of USMC ground-based units.

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