2020-06

LOGISTICS IN CONTESTED ENVIRONMENTS

Bengigi, Elad; Chan, Jun Liang; Chan, Vincent C.; Dougherty, Sean R.; Er, Ivan Y.; Garcia, Roberto J.; Lemenager, Kylen D.; Lim, Gabriel G.; Lowery, Matthew T.; Marks, Johnathan D....

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/65507

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING ANALYSIS CAPSTONE REPORT

LOGISTICS IN CONTESTED ENVIRONMENTS

by

Sean R. Dougherty, Roberto J. Garcia, Kylen D. Lemenager,
Bradley S. Nye, Joseph Rego, Benjamin E. Sandridge,
and Michael G. Shofner

June 2020

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2020	**3. REPORT TYPE AND DATES COVERED** Systems Engineering Analysis Capstone Report	
4. TITLE AND SUBTITLE LOGISTICS IN CONTESTED ENVIRONMENTS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Sean R. Dougherty, Roberto J. Garcia, Kylen D. Lemenager, Bradley S. Nye, Joseph Rego, Benjamin E. Sandridge, and Michael G. Shofner			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Director, Warfare Integration (OPNAV N9I), Washington, DC 22202			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This report examines the transport and delivery of logistics in contested environments within the context of great-power competition (GPC). Across the Department of Defense (DOD), it is believed that GPC will strain our current supply lines beyond their capacity to maintain required warfighting capability. Current DOD efforts are underway to determine an appropriate range of platforms, platform quantities, and delivery tactics to meet the projected logistics demand in future conflicts. This report explores the effectiveness of various platforms and delivery methods through analysis in developed survivability, circulation, and network optimization models. Among other factors, platforms are discriminated by their radar cross-section (RCS), noise level, speed, cargo capacity, and self-defense capability. To maximize supply delivered and minimize the cost of losses, the results of this analysis indicate preference for utilization of well-defended convoys on supply routes where bulk supply is appropriate and smaller, and widely dispersed assets on shorter, more contested routes with less demand. Sensitivity analysis on these results indicates system survivability can be improved by applying RCS and noise-reduction measures to logistics assets.

14. SUBJECT TERMS logistics, contested, great-power competition			**15. NUMBER OF PAGES** 289
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING ANALYSIS

and

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2020

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ABSTRACT

This report examines the transport and delivery of logistics in contested environments within the context of great-power competition (GPC). Across the Department of Defense (DOD), it is believed that GPC will strain our current supply lines beyond their capacity to maintain required warfighting capability. Current DOD efforts are underway to determine an appropriate range of platforms, platform quantities, and delivery tactics to meet the projected logistics demand in future conflicts. This report explores the effectiveness of various platforms and delivery methods through analysis in developed survivability, circulation, and network optimization models. Among other factors, platforms are discriminated by their radar cross-section (RCS), noise level, speed, cargo capacity, and self-defense capability. To maximize supply delivered and minimize the cost of losses, the results of this analysis indicate preference for utilization of well-defended convoys on supply routes where bulk supply is appropriate and smaller, and widely dispersed assets on shorter, more contested routes with less demand. Sensitivity analysis on these results indicates system survivability can be improved by applying RCS and noise-reduction measures to logistics assets.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	anti-access/area-denial
AEM/S	advanced enclosed mast/sensor
AIS	Automated Identification System
AO(s)	area(s) of operations
AOA	analysis of alternatives
ASBM(s)	anti-ship ballistic missile(s)
ASCM(s)	anti-ship cruise missile(s)
ASuW	anti-surface warfare
ASW	anti-submarine warfare
CE	contested environment
CF	coverage factor
CG(s)	guided-missile cruiser(s)
CIWS	close-in weapon system
CLF	combat logistics force
COMMS	communications
CONOPS	concept(s) of operations
CNO	Chief of Naval Operations
CNR	carrier-to-noise ratio
COI(s)	critical operational issue(s)
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CSBA	Center for Strategic and Budgetary Assessments
CSIS	Center for Strategic and International Studies
DAU	Defense Acquisition University
DDG(s)	guided-missile destroyer(s)
DI	directivity index
DMO	distributed maritime operations
DOD	Department of Defense
DON	Department of the Navy

DOT	Department of Transportation
DR(s)	data requirement(s)
DT	detection threshold
EAB(s)	expeditionary advanced base(s)
EABO	expeditionary advanced base operations
ELINT	electronic intelligence
ELS	expeditionary logistics system
EO	electro-optical
EPF	expeditionary fast transport
ESB	expeditionary sea base
ESD	expeditionary transfer dock
EW	electronic warfare
FFBD	functional flow block diagram
FFG(s)	guided-missile frigate(s)
FLIR	forward-looking infrared
FOV	field of view
FRAGO	fragmentary order
FSS	frequency selective surface
GPC	great power competition
IDEF	integrated definition
IFOV	instantaneous field of view
IPR	in-progress review
ISR	intelligence, surveillance, reconnaissance
JCS	Joint Chiefs of Staff
JHSV(s)	joint high-speed vessel(s)
LCS(s)	littoral combat ship(s)
LCU	landing craft utility
LHA(s)	landing helicopter assault ship(s)
LHD(s)	landing helicopter dock ship(s)
LOCE	littoral operations in a contested environment

LPD(s)	amphibious transport dock ship(s)
LSD(s)	dock landing ship(s)
MARAD	Maritime Administration
MET(s)	mission essential task(s)
MOE(s)	measure(s) of effectiveness
MOLA(s)	marine operations logistics asset(s)
MOP(s)	measure(s) of performance
MOS(s)	measure(s) of suitability
NATO	North Atlantic Treaty Organization
NDS	National Defense Strategy
NL	(background) noise level
NMS	National Military Strategy
NPS	Naval Postgraduate School
NSS	National Security Strategy
ONI	Office of Naval Intelligence
OOB	order of battle
OSV(s)	offshore support vessel(s)
OTHR	over-the-horizon radar
PLAN	Peoples Liberation Army Navy
POM	program objective memorandum
PLAN	People’s Liberation Army Navy
PRC	People’s Republic of China
RAM	radar absorbing material
RAS	radar absorbing structure
RCS	radar cross-section
ROMO	range of military operations
SAR	synthetic aperture radar
SE	systems engineering
SEA	systems engineering analysis
SEA29	Systems Engineering Analysis Cohort 29

SIT	simple initial threat
SL	source level
SLOC(s)	sea line(s) of communication
SM-2	standard missile 2
SME(s)	subject matter expert(s)
SOA	speed of advance
SOI	system of interest
SOR(s)	system operational requirement(s)
SSBN(s)	nuclear-powered ballistic missile submarine(s)
SSDS	Ship Self-Defense System
SSGN(s)	nuclear-powered guided-missile submarine(s)
SSK(s)	conventionally powered attack submarine(s)
SSN(s)	nuclear-powered attack submarine(s)
T-AO	fleet replenishment oiler
T-AOE	fast combat support ship
T-AK	maritime prepositioning ship
T-AKE	dry cargo/ammunition ship
T-AKR	maritime prepositioning ship (roll-on/roll-off)
TL	transmission loss
TSSE	Total Ship Systems Engineering
UCAV(s)	unmanned combat aerial vehicle(s)
UNREP	underway replenishment
UNTL	Universal Naval Task List
USV(s)	unmanned surface vehicle(s)
UUV(s)	unmanned undersea vehicle(s)
VLS	vertical launch system
WEZ(s)	weapons engagement zone(s)
WIC	Warfare Innovation Continuum
WWII	World War Two
XLUUV	extra-large unmanned underwater vehicle

EXECUTIVE SUMMARY

A. BOTTOM LINE UPFRONT

With the rise of great-power competition and emerging anti-access area denial capabilities over the last decade, the United States military has adopted strategies which include distributed maritime operations and expeditionary advances base operations. While these concepts maintain conventional warfighting advantages against peer adversaries like China and Russia, they place increased demands on logistics support infrastructure which currently lacks the capacity and resiliency necessary to sustain a protracted campaign.

Logistics during a fight against a peer adversary will be quite a daunting task. Most supply carriers will attrite before they make a second delivery. Our recommended strategy is to utilize well-defended convoy operations on any supply route where bulk supply is appropriate. When smaller deliveries are necessary, assets must be widely dispersed to minimize the chance that they are detected and engaged. To keep up with high attrition rates, future logistics systems must be inexpensive, rapidly replaceable, and either unmanned or minimally manned to reduce the loss of life. Finally, as championed by Captain Wayne Hughes in his book *Fleet Tactics and Naval Operations*, we must "attack effectively first" (2018, 17). In doing so, we can greatly improve our odds by degrading enemy capabilities before they have an opportunity to target our logistics system.

B. PROBLEM STATEMENT

The tasking statement for this work was assigned by Director, Warfare Integration (OPNAV N9I), the project sponsor, and by the Naval Postgraduate School Chair of Systems Engineering Analysis. Their broad scope tasking was refined using a Systems Engineering Waterfall method, incorporating background research, stakeholder analysis, functional analysis to generate the following problem statement:

Design a cost effective, deployable, and resilient unmanned and manned system of systems to provide logistics in contested environments by near-peer competitors in the 2030–2035 timeframe.

- Consider system ***<u>delivery rates</u>*** of dry stores, fuel, and ammunition at sea and to forward operating areas ashore.

- Where possible, include ***<u>joint contributions</u>*** in the system of systems.

- Develop ***<u>alternative architectures</u>*** and their operational employment concepts.

- Investigate current ***<u>commercially available</u>*** lift and technologies for rapid acquisition as one alternative.

By near pear competitors we specifically mean the pacing threats of China and Russia. The fictional scenario, "The Global War of 2030—Two Years In," was generated to support the 2019–2020 Naval Postgraduate School Warfare Innovation Continuum and served as the reference mission for our logistics system. System delivery rates were addressed via measures of effectiveness and performance that we were utilized to compare one architecture to another. Lastly, many architectural variations and associated concepts of operations were evaluated, with final recommendations including elements from each of them, arranged in such a way to emphasize strengths and mitigate the weaknesses of each component.

C. METHODOLOGY

To compare the performance of one logistics system to another, a Monte-Carlo simulation-based circulation model was the primary analysis tool. Systems were differentiated by their radar cross section, acoustic signature, size, carrying capacity, self-defense capability, unit cost, and speed. As many of these attributes were not readily available through unclassified sources, sub-models were employed to estimate the interaction between logistics carriers and threat assets. The model estimated the probability that a logistics asset was detected on each route, performed engagement analysis, and ultimately generated the expected number of deliveries and tonnage throughput before the asset was attrited.

Finally, route specific outcomes were aggregated through a network model that can determine maximum supply flow, identify the most critical ports and routes, and efficiently assign specific assets to individual routes. Analysis via the network model will continue in subsequent thesis work by Ensign Christian Sorensen, and preliminary outcomes are incorporated in the conclusions and recommendation of this work.

D. KEY RESULTS

1. Expected Number of Deliveries

The most concerning conclusion we came to was that almost all vessels completed less than one round trip and only about one delivery. Adding defensive layers in conjunction with convoy operations offered the most significant potential improvement. One subset of analysis compared the Expeditionary Logistics System (ELS) Mothership, ELS Marine Operations Logistics Assets (MOLA), Orca Extra Large Unmanned Undersea Vehicle (XLUUV), Maritime Prepositioning Ship (T-AK), and Maritime Prepositioning Ship roll on/roll off (T-AKR). The ELS concept was proposed by fellow students in a Naval Postgraduate School Total Ship Systems Engineering Capstone project. They suggested using a high-capacity mothership to transport bulk supply outside the contested environment. The mothership then distributes supplies across the contested environment to the warfighter via an embarked fleet of small delivery platforms, or MOLAs. The Orca extra-large unmanned undersea vehicle (XLUUV) is a Boeing design which can carries relatively small volumes of cargo underwater, snorkeling only to recharge batteries. A subset of the results, illustrating the expected number successfully deliveries for these platforms on a route from Yokosuka to Okinawa, follows in Figure 1.

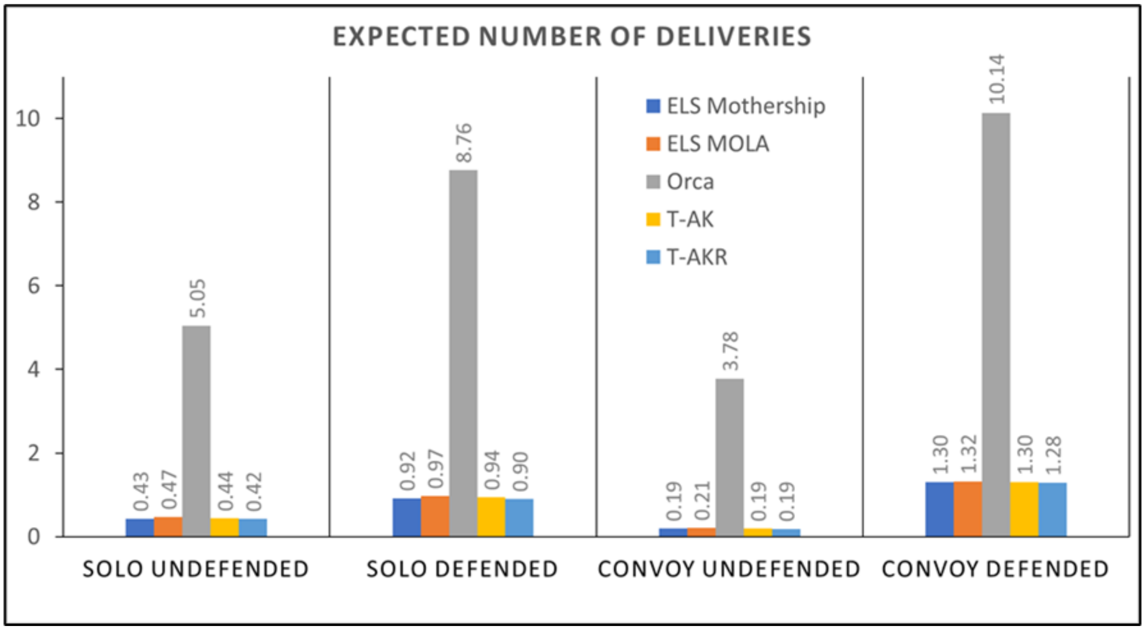

Figure 1. Expected Number of Deliveries (Yokosuka to Okinawa)

This is a daunting outcome that alone proves the need for upgrade of the logistics capabilities of the U.S. Navy. It was clear that undefended vessels delivered less cargo tonnage than they lost and that defended convoys delivered the most tonnage per vessel.

While most surface vessels, whether with a small observable signature like the ELS MOLA or a large signature such as a T-AKR, demonstrated comparable survivability rates, the Orca XLUUV stood out as a clearly more survivable asset. As it operated in the underwater domain, it almost completely avoided ASBM and ASCM threat layers, except for time spent snorkeling. It was also clear that some vessels stood out with less than average survivability, such as the JHSV and T-AOE. The dominating attribute which decreased their performance was their large acoustic signature. Survivability alone, however, was an incomplete metric because it did not translate directly into mission accomplishment because the most survivable assets were also the slowest and lowest capacity.

2. Cost of Losses per Ton Delivered

To analyze the cost of losses, we divided the cost of losses values by tonnage delivered to create a measure of performance (MOP) that related risk to reward. The risk was the monetary losses likely to occur on each transit. The reward was the tonnage delivered. The vessels that performed the highest under this MOP were the Offshore Support Vessel (OSV), ELS Mothership, Expeditionary Transfer Dock (ESD), and Expeditionary Sea Base (ESB). A subset of the results in Figure 2 illustrate their performance on a route from Yokosuka to Busan.

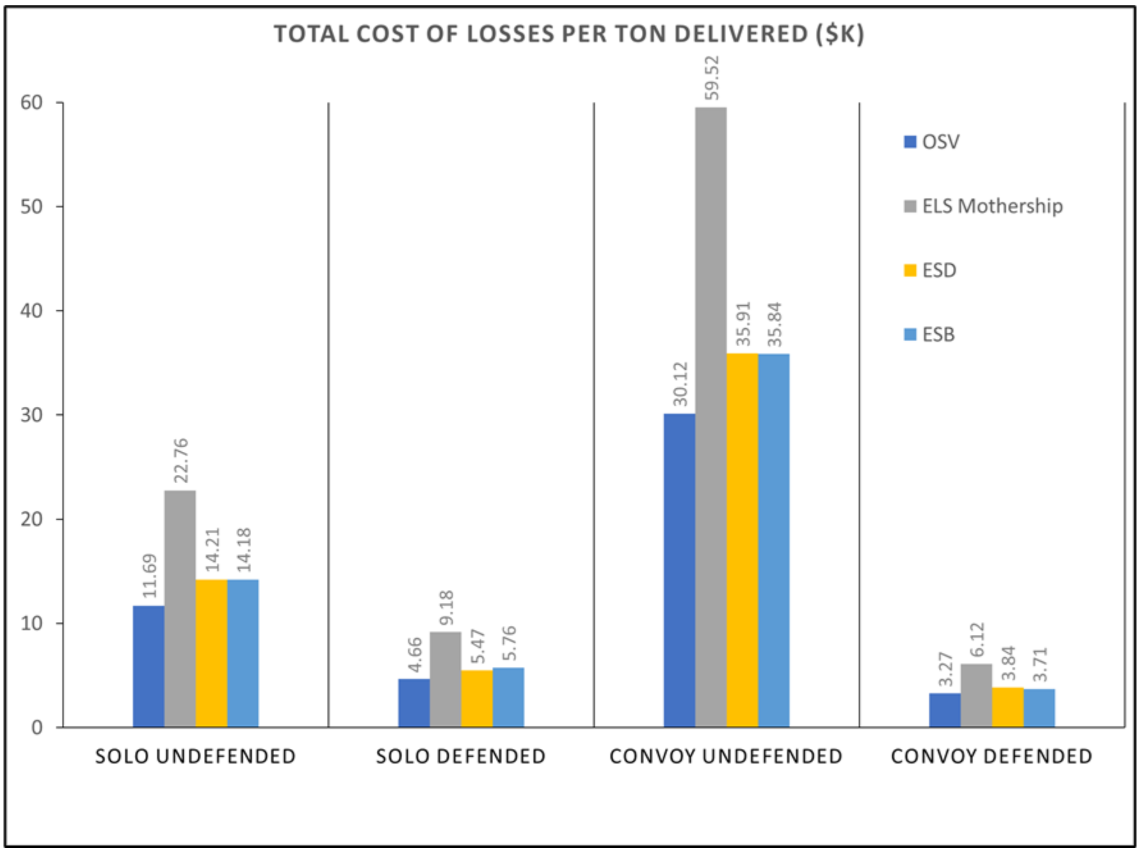

Figure 2. Best Performers in MOP: Total Cost of Losses per Ton Delivered (Yokuska to Busan)

The vessels with the lowest performance in this MOP were the Joint High-Speed Vessel (JHSV), Expeditionary Fast Transport (EPF), Littoral Combat Ship (LCS), Amphibious Transport Dock (LPD), and T-AK. This is contrary to the established notion that distributed logistics are the answer for distributed operations and should be examined. Figure 3 illustrates their performance on a route from Yokosuka to Busan, and it is critical that the scale on the y-axis is significantly different from Figure 2.

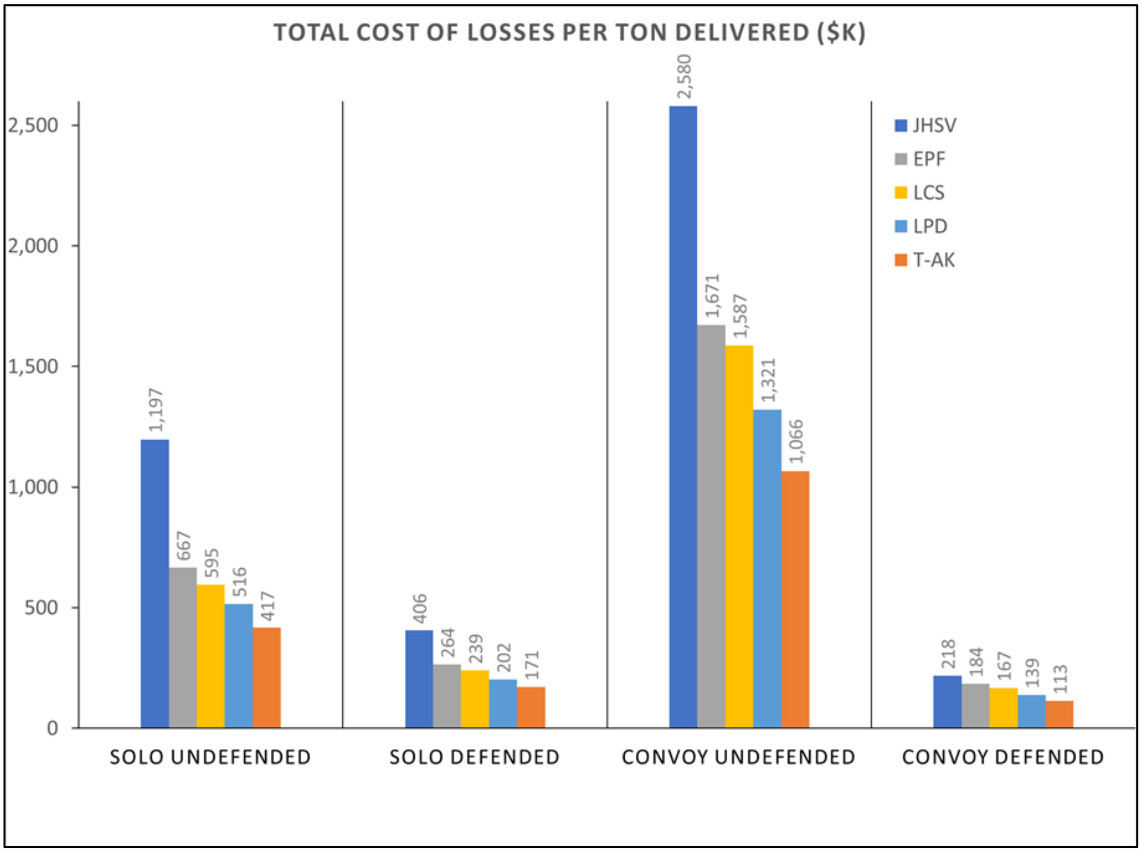

Figure 3. Worst Performers in MOP: Total Cost of Losses per Ton Delivered (Yokuska to Busan)

The OSV, ELS Mothership, ESD, and ESB performed well for this metric because they are relatively cheap and have a large cargo capacity relative to their size. Their low prices come from their lack of complexity as generic cargo carriers that are not overly inundated with excess systems.

These results do not exclusively conclude that using gross tonnage vessels in convoy configurations is the answer to logistics in a contested environment. Though not as well as the OSV, ELS Mothership, and ESD and ESB, other vessels performed fairly under this metric. This metric is very cost focused. If the main goal is to minimize cost and the fact that a certain level of loss may occur is accepted, then it is highly recommended that these options are explored and implemented. However, there are other factors that were not analyzed that should also be examined. These include speed of delivery and agility of assets. Large cargo vessels that can get the most delivered with the least amount of monetary losses are ineffective if they cannot deliver on time or in the correct manner.

3. Sensitivity Analysis

Sensitivity analysis was performed on the effects of reducing radar cross section and/or acoustic signature. The outcomes indicate that a 0.10 to 0.20 percent survivability increase can be harvested on a one-way transit through modest reductions to either of these signatures. When improvements were applied in combination, one or the other domain was dominant, and no synergy was observed.

E. CONCLUSION

The course of action that we recommend pursuing are the Offshore Support Vessel Concept, the ELS Concept, and Traditional Logistics Utilizing ESD and ESB. For the OSV Concept and the ELS Concept the high value unit can be the ESD, ESB, or ELS Mothership. Contrary to what was initially proposed, the performance of these large vessels in terms of losses per ton delivered, allows them to enter the contested environment. The distributed logistics asset could then occur later in the supply chain. For the ELS concept, the MOLA should attempt to emulate OSV and/or Orca XLUUV characteristics as much as possible. No matter what course of action is chosen, added defense of these vessels is highly beneficial and highly recommend. This could come in the form of upgrading onboard defenses or providing some sort of defensive escort. Lastly, RCS and noise reduction should be done on all vessels as practical. This is especially important to vessels projected to be traveling alone. In consideration of cost, it is beneficial to determine which reduction would have the greater impact to survivability and apply that reduction alone.

Reference

Hughes, Wayne P., Jr., and Robert P. Girrier. 2018. *Fleet Tactics and Naval Operations*. Annapolis, MD: Naval Institute Press.

ACKNOWLEDGMENTS

The Systems Engineering Analysis Cohort 29 capstone team would like to thank our project advisors, Dr. Papoulias and Dr. Atkinson, who were there with support, guidance, and insight during every step of our capstone project.

In memory of the late CAPT Wayne P. Hughes, USN (Ret), we express our utmost gratitude and respect for his service to our nation, enduring contributions to the field of military operations research, and dedication to the education of his students.

We would be remiss if we did not also give our gratitude to the faculty and staff in the Systems Engineering and Operations Research Departments for the countless hours spent imparting their knowledge and wisdom. While all the staff had a role in getting us to where we are today, several members deserve our special thanks and gratitude:

- Matt Boensel
- CDR Matthew Geiser, USN
- Dr. Andy Hernandez.
- Jeffrey Kline
- Greg Miller
- Dr. Javier Salmerón
- Mark Stevens

Our team extends a special thanks to Abby McConnell in the Graduate Writing Center for the many hours spent coaching us and helping us to refine this report.

Finally, we say thank you to our families for the love and support they gave over the past two years. Their patience and understanding have empowered us, and will continue to empower us, to achieve the things we never dreamed possible.

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I. INTRODUCTION

The senior leaders of the United States have issued the Navy's top-level security and defense goals through the:

- *National Security Strategy* (NSS)
- *National Defense Strategy* (NDS)
- *National Military Strategy* (NMS)
- *A Design for Maintaining Maritime Superiority*, *Version 2.0*
- *Commandant's Planning Guidance*

These documents describe a shift in America's focus from nearly two decades of regional conflict and counterinsurgency in the Middle East to the growing global threat posed by peer adversaries—namely China and Russia. As these adversaries grow their economies and military capabilities, and cooperate to challenge America's national power, the world finds itself entering an era of great-power competition (GPC; Berger 2019; DOD 2018; JCS 2018a; Richardson 2018; White House 2017). In this environment, the basic assumption from past conflicts that our "bases are sanctuaries" is no longer true (Priebe et al. 2019, ix). Our enemies can precisely track and target our forces from much greater distances than in the past with increasing ability. Additionally, where the U.S. has customarily operated anywhere and everywhere that international law permits, our adversaries are continually improving anti-access and area-denial capabilities which threatens that ability as well. The long-established global balance of power is beginning to tilt as adversaries seek to challenge the U.S. as the world's military leader.

With the threat of GPC looming and America's military capability advantage shrinking, the Navy's mission remains to "be ready to conduct prompt and sustained combat incident to operations at sea" (Richardson 2018, 1). To this end, the Navy recognized the need to update both the fleet and the tactics by which the fleet operates to remain relevant in the future threat environment. In recent years, this has meant an increasing focus on developing and deploying a distributed force. This effort seeks to move away from traditional fleet architectures that mass combat power in few, highly capable capital assets. A concept of distributed operations does the opposite, distributing capability and risk amongst a greater number of assets employed across a much larger geographical area. This concept challenges enemy targeting capabilities and changes the enemy's cost-benefit calculus in our favor. The overall effect is a resilient combat capability that maintains the U.S. military advantage.

A distributed fleet, however, comes with a larger logistics footprint—more units in more places with the same or greater demand as in the traditional architecture. Designed for post–Cold War peacetime efficiency, our current logistics force is *just* capable of meeting the logistics demand of a traditional fleet architecture. A shift to distributed combat fleet architecture will exceed the current logistics force capacity unless the Navy implements corresponding changes to its support architecture as well. Additionally, in an environment of global conflict, attrition of logistics assets should also be anticipated. The current fleet of combat logistics force (CLF) has too few ships and lacks the necessary survivability to endure a protracted conflict with a peer or near-peer enemy (Walton, Boone, and Schramm 2019).

The Center for Strategic and Budgetary Assessments proposed a particular logistics fleet architecture they felt would meet the demands of GPC. Their assessment recommended specific types and quantities but assumed an attrition rate over the course of a global conflict. One of their recommendations was that future analysis should seek to model attrition to yield more accurate results for force planning (Walton, Boone, and Schramm 2019). Our research sought to make an analysis-based recommendation for a logistics fleet architecture that accounts for attrition, considers the impact of self-defense capability and escorted convoy protection, and determines supply system capacity through network optimization modeling. The following report details our efforts and culminates with our proposed logistics system.

A. PROJECT BACKGROUND

Our project was led by the 29th cohort of Systems Engineering Analysis (SEA29) students at the Naval Postgraduate School (NPS) was assigned to conduct this capstone project in partial fulfillment of graduation requirements. The purpose of this project was to demonstrate to the faculty an integrated, iterative, multidisciplinary, and analytical approach to problem solving that exercised the fundamental tenets of systems engineering and operations research.

1. Warfare Innovation Continuum

The NPS Warfare Innovation Continuum (WIC) is an annual campus-wide endeavor that aligns efforts in classrooms, capstone projects, thesis work, research, wargames, and workshop events towards a relevant and timely real-world defense problem. The complete WIC event flow and timeline is illustrated in Figure 1.

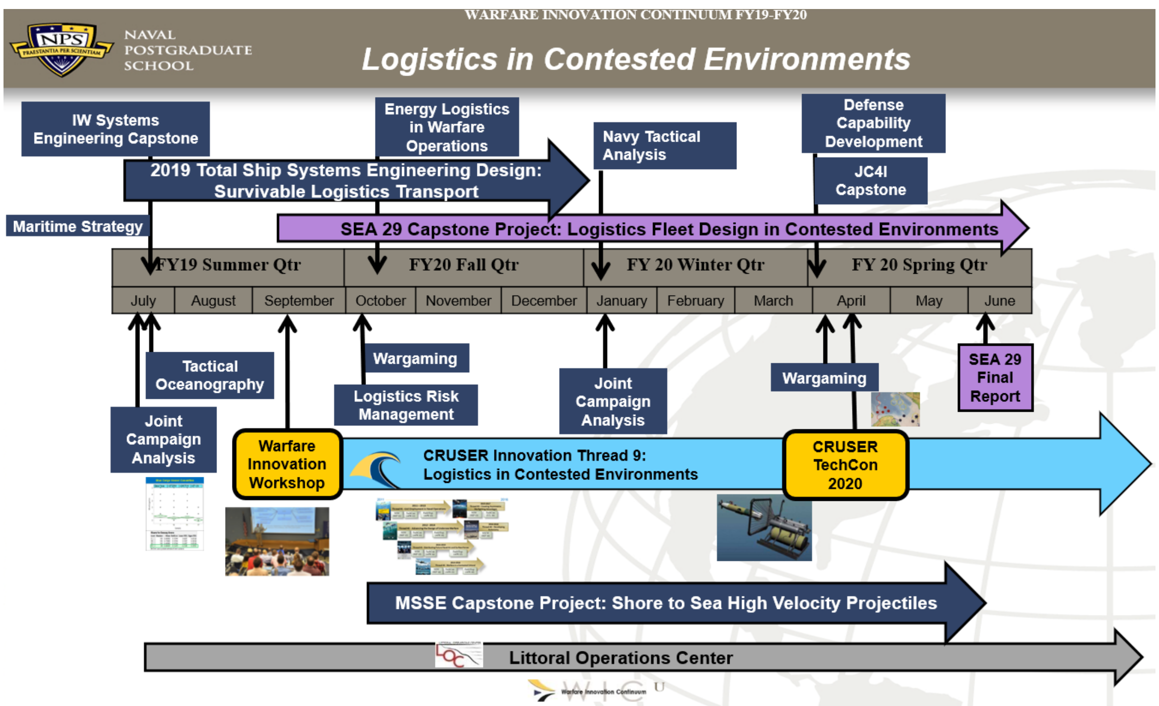


Figure 1. 2019–2020 Warfare Innovation Continuum Event Flow. Source: Jeffrey Kline, unpublished brief (2019).

The theme of the 2019 WIC was “Logistics in Contested Environments.” The WIC Innovation Workshop, an event orchestrated by the Consortium for Robotics and Unmanned Systems Education and Research (CRUSER), brings together the innovative minds of naval officers from NPS, the fleet, and other Department of Defense (DOD) commands as well as early career engineers from the civilian sector. The workshop served as a primer for this integrated capstone project, another thread of the WIC, where the Systems Engineering Analysis cohort leads a companion research and analysis effort in support of the annual theme.

2. Tasking Statement

The official tasking statement from the Chair of Systems Engineering Analysis to this student group was as follows:

> Design a cost effective, deployable and resilient unmanned and manned system of systems employed to provide logistics in contested environments by near-peer competitors in the 2030–2035 timeframe Consider system delivery rates of dry stores, fuel, and ammunition at sea and to forward operating areas ashore; system vulnerability, survivability, and reliability; and costs. Where possible, include joint contributions in the system of systems. Develop alternative architectures and their operational employment concepts. Investigate current commercially available lift and technologies for rapid acquisition as one alternative. Consider both Pacific and Atlantic operating areas. (Jeffrey Kline, email to authors, September 1, 2019)

B. PROJECT TEAM COMPOSITION

Our team was composed of 18 students representing curricula across campus and serving in diverse warfare disciplines within the United States, Singapore, and Israeli armed forces. We were able to leverage our diverse knowledge and operational experience to provide valuable insight when scoping the problem and completing analysis. Our team’s composition and background are shown in Table 1.

Table 1. SEA29 Project Team Composition

Name	***Country***	***Service***	***Job Specialty***
Aldin Sim	Singapore	Army	Combat Engineer
Benjamin Sandridge	United States	Navy	Surface Warfare
Bradley Nye	United States	Navy	Surface Warfare
Chan Jun Liang	Singapore	Civilian	Web Developer
Christian Sorenson	United States	Navy	Submarine Warfare
Derek Tay	Singapore	Army	Combat Engineer
Elad Bengigi	Israel	Army	Operations Research
Gabriel Lim Guang Nian	Singapore	Air Force	Engineer
Ivan Er	Singapore	Army	Armor Officer
Johnathan Marks	United States	Navy	Engineering Duty Officer
Joseph Rego	United States	Navy	Submarine Warfare
Kylen Lemenager	United States	Navy	Surface Warfare
Matthew Lowery	United States	Marine Corps	Artillery
Michael Shofner	United States	Navy	Surface Warfare
Roberto Garcia	United States	Navy	Surface Warfare
Sean Dougherty	United States	Navy	Aviation
Sean Yang	Singapore	Air Force	Aviation
Vincent Chan Chi Meng	Singapore	Navy	Surface Warfare

To organize the team’s efforts, three project groups were formed: systems engineering (SE), technical systems, and modeling and simulation. Dividing the efforts among the three groups enabled the team to better leverage each members’ individual knowledge and interests to efficiently complete project tasks. Our SE team focused on defining the problem, analyzing the need, and developing the system’s operational and functional requirements. The technical systems team conducted an analysis of alternative communications architectures to gain insight on how the system could combat a communications-denied environment. Additionally, this team researched technical input values for use in the modelling and simulation efforts. These values included data such as platform radar cross-section, defensive capability, and armament. Lastly, the modeling and simulation team developed a survivability and network optimization model to analytically determine which architectures would be most viable in contested environments. The team then conducted an analysis of alternative architectures to propose a final recommended architecture for the Navy to consider. Table 2 details the makeup of each of the project task groups:

Table 2. SEA29 Task Organization Chart

Advisors	Fotis A. Papoulias Michael P. Atkinson
Group Lead	Sean Dougherty
Chief Editor	Benjamin Sandridge
Systems Engineering Team	Roberto Garcia (lead) Jonathan Marks Benjamin Sandridge Aldin Sim
Technical Systems Analysis Team	Kylen Lemenager (lead) Matthew Lowry Vincent Chan Chi Meng Elad Bengigi Derek Tay
Modeling and Simulation Team	Joseph Rego (lead) Bradley Nye Sean Yang Michael Shofner Christian Sorenson Ivan Er Chan Jun Liang Gabriel Lim Guang Nian

C. LITERATURE REVIEW

Among the first tasks accomplished by our team, we conducted a review of works with similar subject matter and focus to better understand the problem space. The goal of this review was to assess current initiatives, parallel research efforts, and historical cases to determine how to frame the problems that the Navy faces while performing logistics in contested environments. We also wanted to identify areas where our research could add new insights and value to the existing research efforts in this subject area.

1. Current Initiatives

The Chief of Naval Operations (CNO), Admiral Michael Gilday, released a fragmentary order (FRAGO) in December 2019 to serve as an update to the Navy's *A Design for Maritime Superiority, Version 2.0* which was released in December 2018. The FRAGO shares his vision of the current and future fleet and predicted future threat environment. He highlights the concept of GPC as discussed in the NSS and the NDS and calls the fleet to focus on "warfighting, warfighters, and the future Navy" (1). In a section of the FRAGO titled "Future Navy," Gilday (2019) specifically discusses the need to "make naval logistics more agile and resilient" (7). He lays out a vision which includes the ability to revive, repair, rearm, resupply, and refuel a fleet operating under the distributed maritime operations (DMO) concept. This vision would seek to support his desired end state of "a Navy fully prepared to fight and win" by "maximizing the benefits of expeditionary advanced base operations (EABO) and littoral operations in a contested environment (LOCE)" (Gilday 2019, 6). To this end, Gilday (2019) states, "We will develop and field affordable, lethal, numerous, and connected capabilities" (6).

In addition, a 2020 report by the Congressional Research Service seeks to provide justification for operating in a distributed fleet architecture. The report states that the Navy's current architecture concentrates risk in few, large, and expensive assets. This architecture is becoming increasingly vulnerable to China's rapidly advancing capabilities in anti-access/area-denial (A2/AD). Posing a particular threat are China's "anti-ship missiles and their supporting detection and targeting systems" (O'Rourke 2020, 19). O'Rourke (2020) offers that shifting to a distributed architecture would:

1. Complicate the enemy's ability to target the fleet.
2. Distribute risk across a larger number of less expensive, more risk-worthy platforms.
3. Allow for the use of unmanned surface vehicles (USV) and unmanned undersea vehicles (UUV) in highly contested areas where combat capability is required, but risk is too high for a manned vessel to operate.

4. Increase the ability of the fleet to rapidly adapt to a changing threat environment.

The author goes on to state that Department of the Navy (DON) leaders appear more willing to support a distributed architecture than in the past because of an emerging belief that it will be operationally necessary, more affordable, and is now technically feasible.

For similar reasons, the Commandant and the CNO cosigned the EABO concept in February 2019. The goal of EABO is to move away from the large, concentrated, vulnerable, and expensive logistics and basing infrastructure that U.S. adversaries can easily target. The naval force will seek to develop a smaller, more distributed infrastructure that can operate within the enemy's weapon ranges without incurring disproportionate risk (O'Rourke 2020).

2. Related Research

A 2019 report titled *Sustaining the Fight: Resilient Maritime Logistics for a New Era* released by the Center for Strategic and Budgetary Assessments (CSBA) focused on the same topic of the SEA29 tasking statement: the U.S. ability to perform logistics in the context of GPC. In summary, the authors found the current logistics force to be inadequate to support major military operations against either China or Russia. Further exacerbating this problem, the Navy's 30-year shipbuilding plan calls for a decreased percentage of spending for procurement of logistics assets. Under this plan, the already inadequate logistics force will be even less capable of supplying a proportionally larger fleet (Walton, Boone, and Schramm 2019).

The report identifies that since the 1990s, the expeditionary logistics capabilities of the fleet have been largely retired, and an overreliance on vulnerable shore-based supply depots has followed. Adversaries of the United States are becoming increasingly sophisticated and are challenging the nation's military in ways that were not planned for when the current fleet was being shaped in years past.

Five key assumptions were identified that the authors claim will better reflect the current and future threat environment and should be considered when shaping the future logistics force:

1. Distant and contested basing
2. Global conflict
3. Forward deterrence and rapid response
4. Protracted conflict
5. High attrition planning. (Walton, Boone, and Schramm 2019, i–ii)

CSBA's modeling under these assumptions led them to identify "major gaps in logistics capacity that would hinder the fleet's ability to employ its preferred concepts at scale during conflict" (Walton, Boone, Schramm 2019, ii). Their proposed solution involves:

- employing mature technologies
- modifications to current assets
- chartering assets
- providing stipends to industry
- new construction

These solutions would fill the capacity shortfalls and provide the Navy with a logistics fleet that enhances combat capability and revitalizes the decaying U.S. maritime sector of industry (Walton, Boone, and Schramm 2019).

The key takeaway from the report regarding the U.S. ability to refuel the force involved creating a mixed fleet of assets to increase total fuel capacity and redundancy in the logistics system. Specifically, the authors recommended that the navy "go big, go small, go fast, and go different" (Walton, Boone, and Schramm 2019, iv). "Go big" refers to the use of U.S. flagged tankers to serve as prepositioned intermediate fuel depots. "Go small" refers to the use of offshore support vessels (OSV), widely used in the oil platform industry, as small refueling platforms. "Go fast" refers to accelerating the procurement of fleet oilers. "Go different" refers to development of risk-worthy unmanned or minimally manned systems to deliver fuel in highly contested environments.

For cargo and munitions distribution, the authors recommend that the Navy shift to a "scalable and distributed approach" (Walton, Boone, and Schramm 2019, iv). Their recommended approach would involve:

- wider use of distributed aviation logistics
- procuring higher efficiency roll-on/roll-off resupply ships that would transfer cargo underway to other logistics ships
- increasing stocks of spare parts
- increasing the fabrication ability onboard ships
- developing abilities to reload munitions both at anchor and underway

3. Historical Analysis

Although U.S. leadership is concerned that we face potential great-power competition and future challenges in performing logistics in contested environments, it would not be the first time America has risen to this challenge. World War Two (WWII), the last truly global conflict, serves as a historical case study on how the U.S. achieved success in logistics in the past. While technology has vastly changed how warfare is waged today as compared to WWII, one significant commonality remains—logistics forces must operate within a contested environment to supply and maintain combat efforts. We would be remiss if we did not review this history to determine what still applies in today's complex environment.

In 1946, shortly after WWII ended, a report titled *Antisubmarine Warfare in World War II* was released by the Navy Department's Operations Evaluation Group. Originally a confidential analysis, the report was declassified in 1959 and contains insights derived from operational data on defending individual logistics ships and the effects of convoy and escorts. The authors, Sternhell and Thorndike (1946), reported two factors which they found affected a submarine's approach on a ship traveling individually: the ship's speed and employment of zigzag maneuvers.

Regarding a ship's speed, Sternhell and Thorndike (1946) stated:

there are three important speed classes.

> 1. High-speed ships—sufficiently fast that the submarine cannot track or overtake them. The sinkings are low and not greatly dependent upon speed, though the additional speed of the ship clearly makes the submarine's problem increasingly difficult.
> 2. Low-speed ships—so slow that the submarine can track and overtake without difficulty. Sinkings are approximately ten times as great as in the high-speed case and are not critically dependent on speed.
> 3. Intermediate-speed ships—for which there is an abrupt transition from conditions of class 2 to class 1 and whose losses depend strongly on speed. (96–97)

Next, the authors addressed the maneuvering characteristics of an individual ship.

> By making fairly radical turns at irregular intervals, the ships can make it more difficult for the submarine to approach to a good firing position and to secure good torpedo-firing data. The net result is that the submarine will tend to be forced to fire from a poorer position with poorer accuracy and will therefore have less chance of securing a hit. (Sternhell and Thorndike 1946, 98)

They conclude that both factors can be considered and applied to reduce the number of ships sunk by enemy submarines. However, they also noted that the effect was limited and "the most successful defensive measure has been the use of escorted convoys" (Sternhell and Thorndike 1946, 99).

The authors then provided their insights on utilization of convoys and escorts. They claimed the greatest advantaged derived from convoy was the concentration of defensive capability it provides, since it would be infeasible to escort all ships individually. Secondarily, convoy reduces the number of opportunities for a submarine to encounter a unit "since the convoy becomes the unit instead of the individual ship" (Sternhell and Thorndike 1946, 100). They state:

> A convoy of 15 or more ships is apparently large enough that the number of ships sunk per U-boat attack does not depend on convoy size. Such would not be the case for smaller convoys, where we would expect increased size to be associated with an increase in number (though not in fraction) of ships sunk... it appears that large convoys are much the safest for the individual ships, since the *fraction* of convoyed ships sunk decreases markedly with increasing convoy size... The effect of each additional escort is to reduce the ships sunk by about 0.075 ship, that is, to reduce the U-boat's chance of

> penetrating the screen by about 6 per cent. (Sternhell and Thorndike 1946, 106–108)

Next the authors discuss considerations on the limitations of convoy. They note that convoying slows down cargo transport in two ways:

1. Ships spend more time in port due to port congestion and convoy assembly time.
2. Ships spend more time at sea due to decreased transit speeds of convoys over individual ships.

If ships are instead routed independently, their transit speed will increase, but more ships will be sunk, and fewer ships will be available over time. The authors note that when comparing convoys to individual shipping by considering total cargo delivered, independently routed ships are more efficient for up to about six or seven months, when, due to losses of individual ships, the convoy would have delivered more cargo (Sternhell and Thorndike 1946).

The key takeaway, then, is that convoy can be an effective means of protecting ships, but only when the threat is serious enough to justify cargo delays and the expected duration of conflict is sufficiently long for the benefits to outweigh the costs. If justification exists based on threat and duration, then large convoys should be used (Sternhell and Thorndike 1946).

Another historical analysis on the use of convoy during WWII can be found in the second chapter of *The Pleasures of Counting* by T.W. Körner (1996). This work further elaborates on some of the topics of Sternhell and Thorndike's insights and additionally offers counterpoints to some historical arguments against convoy.

One such argument against convoys refuted by Körner (1996) is that a "convoy would provide an easier target for a submarine" (28). Instead, he offers that:

> The ocean is so large and a convoy occupies so little space in it that a convoy is almost as hard to find as a single ship... Attacking an escorted convoy is more dangerous and more difficult than attacking a single ship. Even if a U-boat manages to get into a position to attack it will normally only sink one or two ships... In the worst case when the U-boat manages to make repeated

> attacks it carries only a limited number of torpedoes and can sink only a limited number of ships. (28)

Defending the use of convoys against the argument that "a convoy can only travel as fast as its slowest ship," Körner (1996) made a similar point to that made in Sternhell and Thorndike's work:

> The statistics of the two World Wars show that a ship is safer in a convoy even if the convoy's speed is substantially lower than that achievable by the ship on its own. A faster ship sailing alone will, of course, deliver more tonnage per month, but only until it is sunk. (27)

One final defense for convoys against the argument that they caused "delays involved in unloading" is offered:

> It turned out that it was the *unpredictability* of arrival of independently routed ships which disrupted the (relatively) smooth running of the ports and the railway systems which served them. The high probability that convoys would arrive and leave on schedule was a remedy for, and not a cause of, port congestion. (Körner 1996, 27)

Taken together, the analyses presented by Sternhell and Thorndike (1946) and Körner (1996) on the use of escorted convoys offer compelling evidence for their effectiveness at protecting shipping against enemy attack during WWII. Additionally, Körner (1996) argues for convoy's potential to improve port efficiency, which could improve the overall logistics system throughput.

4. Our Contribution

After consulting the literature, we chose to approach the problem of logistics in contested environments with the intent of proposing an analysis-based recommendation for a logistics architecture. We determined our analysis would be based on a model that accounts for logistics asset attrition, considers the possibility of adding self-defense capability to logistics assets, and revisits the concept of escorted convoy in the context of present-day weaponry, defenses, tracking, and targeting systems. Our analysis would also attempt to utilize network optimization to match specific logistics architecture components to arcs within the network to gain insight on where specific asset types are best utilized to maximize system throughput.

D. OUTLINE

This report details our research, modeling, and analysis efforts and provides our insights and recommendations regarding logistics in contested environments. The sequence in which we present the information mirrors the systems engineering waterfall process steps to define and bound the problem, determine candidate system architectures, develop a representative model, and analytically compare the candidate architectures to arrive at a recommended system capable of meeting mission demands.

Chapter II of the report provides a detailed description of the systems engineering process our team utilized in the conduct of this research. It shares stakeholder and subject matter expert insights, provides relevant context, and bounds the scope of effort. Finally, it analyzes system requirements and functions, culminating in several candidate logistics architectures to serve as inputs to our analytical model.

Next, Chapter III explains our approach to modeling, lists our assumptions, and details each of the model components and how they interact. The theory behind each of the modeling components is discussed to convey the reasons for their inclusion. Equations utilized within the model are listed and their utility explained.

Chapter IV provides you with the outputs of our model and initial insights derived from the analysis. Initial results are presented along with sensitivity analyses. The effects of logistics vessel type and corresponding characteristics, self-defense capability, escorted convoy, and port capacity are demonstrated.

Finally, Chapter V contains our recommended solution for a logistics architecture and highlights key insights and findings. Amplifying information regarding specific modeling input values and a brief communication system analysis can be found in in the appendices.

II. SYSTEMS ENGINEERING

A. PROCESS OVERVIEW

Through the systems engineering analysis (SEA) curriculum, we were taught different definitions and models of SE which were directly applied to this research. Though there are many SE definitions, our team applied the following from Blanchard and Fabrycky (2011) to this research:

> An approach to translate operational needs and requirements into operationally suitable blocks of systems. The approach shall consist of a top-down, iterative process of requirements analysis, functional analysis and allocation, design synthesis and verification, and system analysis and control. Systems engineering shall permeate design, manufacturing, test and evaluation, and support of the product. Systems engineering principles shall influence the balance between performance, risk, cost, and schedule. (18)

All SE definitions include the major concepts of a top-down, iterative, and interdisciplinary approach. In this way, systems thinking enables us to look at the wholeness of a system or system of systems and how it interacts with its environment to optimally perform its operational functions to meet the stakeholder needs.

In addition, there are many models utilized to represent the SE processes. Blanchard and Fabrycky (2011) include three processes in their textbook, *Systems Engineering and Analysis*: Waterfall, Spiral, and "V" Model, which were analyzed by our SE team to choose the process that was best for us to follow given our nine-month time constraint. The model we chose mirrors that of the Waterfall model, as shown in Figure 2.

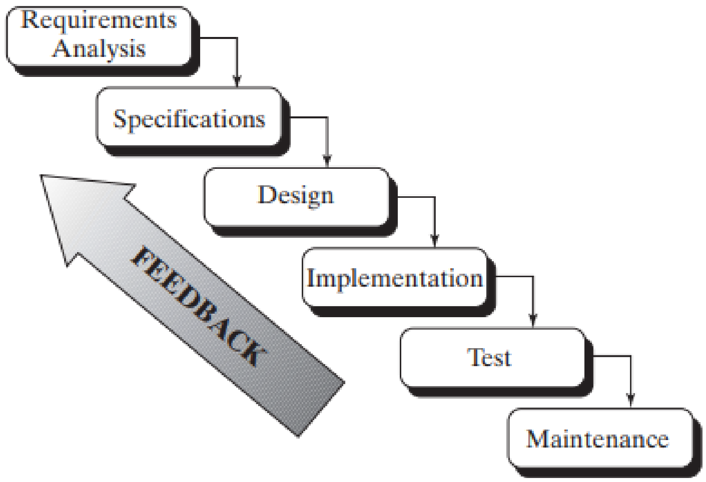


Figure 2. Waterfall Model. Source: Blanchard and Fabrycky (2011, 36).

We chose this model because of its ability to show traceability and our capability to iterate through these phases of the process model. However, we condensed and modified Figure 2 to tailor it for our capstone project, as shown in Figure 3. Due to the nature of our work, the waterfall model ended at the “Design” phase, this was because our final deliverable would encompass multiple concepts of operations (CONOPS) of old and new logistics capable platforms to employ in a contested environment. These CONOPS then served as inputs to an analytic model which was utilized to conduct an analysis of alternative solutions and recommend a final architecture based on the results.

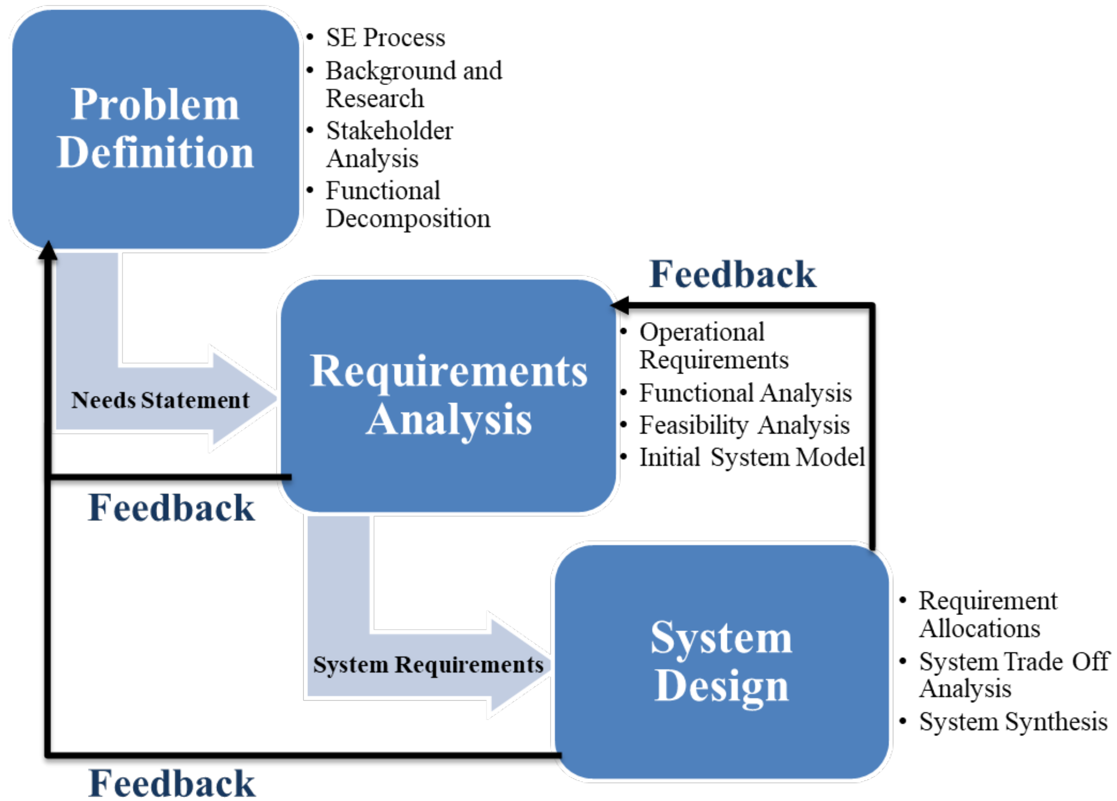


Figure 3. SEA29 Tailored Waterfall Model

The three phases of our tailored waterfall model were divided into three quarterly efforts with multiple feedback loops which provided opportunities to adjust work completed in previous phases. This demonstrates the iterative nature of the SE process.

1. Problem Definition

Phase one included developing a process model, conducting background research on logistics in contested environments, and forming focus groups to foster organization of effort, conversation, and idea sharing. Discussions within these groups enabled us to scope the problem, incorporate real-life operational experiences, and start formulating questions and candidates for a stakeholder analysis. The stakeholder analysis was a pivotal part of developing a need statement. The stakeholder analysis included several interviews with subject matter experts on campus, industry personnel, senior military officers, and government contractors. This process enabled us to further scope the problem and understand the capability gap the Navy faces. Phase one concluded with a defined needs statement where we brainstormed and, via functional decomposition, developed appropriate functions the system must accomplish to fulfill the Navy's need.

2. Requirements Analysis

The next phase involved developing operational requirements, conducting a functional analysis, developing several candidate logistics architectures, and developing an analytical modeling process to analyze the candidate systems. During this phase, we also conducted our first In-Progress Review (IPR) to explain the status of this project to our stakeholders and receive their feedback. When the status of the project was briefed at the first IPR, our stakeholders had the opportunity to pose questions, provide direction, and deliver other relevant feedback which we were able to use in refining system requirements. The operational requirements would later be used to define the mission, performance and physical parameters, operational deployment/distribution, operational life cycle, utilization requirements, effectiveness factors, and environmental factors (Blanchard and Fabrycky 2011).

Following requirements definition is a functional analysis. A functional analysis, as defined by Blanchard and Fabrycky (2011), "is an iterative process of translating system requirements into detailed design criteria and the subsequent identification of the resources required for system operation and support" (86). For us, this process was accomplished by analyzing our previous functional decomposition and ensuring there was traceability between requirements and functions. These efforts further refined the scope of the project and helped to define the attributes of the model we developed.

3. System Design

Finally, the last step of our process model was designing the system. This phase included a finalization of the model with an analysis of the results and recommended architectures. In developing adequate recommendations, a trade-off analysis was conducted. This compared different architectures according to their performance parameters along with their feasibility and overall effectiveness. The sensitivity analysis contained within the trade-off analysis also gave stakeholders the ability to evaluate our research to compare how our assumptions and decision criteria affected the results.

The following sections will provide details on each of the SE process steps our team completed during this research, beginning with problem definition.

B. PROBLEM DEFINITION

One of the great challenges and most important stages in the systems engineering process is problem definition. While the tasking statement represents an initial attempt to define the project scope, focus, and outcomes, the voice and concerns of all concerned stakeholders must be considered when diagnosing the true nature of the problem. The temptation to hastily address the given problem should be deferred until certain that the *right problem* is being solved. Stakeholder analysis, therefore, is an integral step in that problem definition.

For our project, the SEA29 tasking statement included a listing of on and off campus subject matter experts to serve as a starting point. We conducted research outreach and panel interviews (utilizing NPS Institutional Review Board approved questions) to gain perspective on the problem and to identify their interests as stakeholders. Based on those discussions, these individuals, and the organizations they represent, were divided further into "stakeholders" and "subject matter experts" (SMEs). In general, the stakeholders involved had a vested interest in the outcome and recommendations of the project, whereas subject matter experts served the project through the information they were able to provide themselves or through their professional networks.

1. Stakeholders

- VADM Ricky Williamson, USN, Deputy Chief of Naval Operations for Fleet Readiness and Logistics (OPNAV N4)
- RADM Daniel Fillion, USN, Director, Warfare Integration (OPNAV N9I)
- Mr. Paul Lluy, Assistant Deputy Chief of Naval Operations for Warfare Systems (OPNAV N9B)

- CAPT (Ret) Jeffrey Kline, OPNAV N9I Chair, Systems Engineering Analysis
- CAPT Eric Morgan, USN, OPNAV N4iL – Logistics Analytics Branch (LAB)
- CDR (Ret) Matthew Boensel, OPNAV N9I Chair, Systems Engineering Analysis
- Dr. Michael Atkinson, Operations Research Advisor
- Dr. Fotis Papoulias, Systems Engineering Advisor
- SEA29 Student Cohort

2. Subject Matter Experts

- RADM (Ret) Winford "Jerry" Ellis, NPS Undersea Warfare Chair
- RDML (Ret) Richard Williams, NPS Mine Warfare Chair
- CAPT Charles "Chuck" Good, NPS Surface Warfare Chair
- CAPT Edward McCabe, USN, NPS Air Warfare Chair
- Dr. Wayne Porter, CAPT (Ret), USN, Director, NPS Littoral Operations Center
- COL Randolph Pugh, USMC, NPS Senior Marine Representative
- Dr. Aruna Apte, NPS Graduate School of Defense Management
- Dr. Kenneth Doerr, NPS Graduate School of Defense Management
- CDR Matthew Geiser, USN, Operation Research Faculty
- CDR (Ret) Harrison Schramm, USN, Center for Strategic and Budgetary Assessments

- Lisa DeVine, Leidos
- Frank Leban, Naval Surface Warfare Center
- Dan Tubbs, Boeing, Echo Voyager Program Manager

3. Needs Analysis

The primitive needs of each stakeholder determined over the course of our discussions and outreach were compiled and are listed in Table 3.

Table 3. Primitive Stakeholder Needs

Stakeholder	***Primitive Needs***
OPNAV Leadership VADM Williams RADM Fillion Mr. Paul Lluy CAPT Morgan	• Insight, analysis, and recommendations for logistics systems, architectures, and concepts of operations • Recommendations to close capability gaps with identification of tradeoffs
NPS SEA Chair(s) CAPT (Ret) Kline CDR (Ret) Boensel	• Completion of graduation requirements • Relevant recommendations to OPNAV N9I
Capstone Advisors Dr. Atkinson Dr. Papoulias	• Completion of graduation requirements • Relevant recommendations to OPNAV N9I • Challenging and rewarding academic experience
SEA29 Cohort	• Completion of graduation requirements • Application of critical thinking and reinforcement of curricula skills

The stakeholders and SMEs collectively provided insight, concerns, and common themes that served as background information, shaped the problem, and enabled us to appropriately scope our efforts. Highlights from those discussions were broken into five main categories: general guidance, scoping considerations, economic considerations, threat environment considerations, solution centered suggestions. Following are the highlights captured during stakeholder analysis:

a. General Guidance

- Distributed Maritime Operations, as defined in *A Design for Maritime Operations, Version 2.0* by the Chief of Naval Operations (2018) will serve as a guidance for the concept of operations that may be employed against peer competitors.

- General Berger’s *Commandant’s Planning Guidance* builds upon and reinforces the concept of operations from the perspective of the United States Marine Corps (2019).

- Work from previous related NPS capstone and thesis efforts, such as the Total Ship Systems Engineering (TSSE) group, should be leveraged and incorporated.

b. Economic Considerations

- The time horizon of 2030–2035 enables project recommendations to feed and support program objective memorandum (POM) cycles and technological advances.

- Cost remains a large concern as budget constraints and national debt will always be considerations.

- Industrial base capability and buildup is a legitimate concern to the logistics problem.

- Consideration should be given to alternate ownership constructs for supply assets. Can capability be contracted? Must assets be purchased new or can they be repurposed?

c. Scoping Considerations

- Autonomous and unmanned systems are not desired capabilities in their own right. The capability, speed, and risk reduction they offer are what may make them valuable.

- Fuel logistics are the highest priority supply concern.

- A focus on physical delivery systems and their protection in a contested environment will be the most relevant area of focus.

- Communications and information support systems will be crucial to the success of logistics delivery in a contested environment but is not the best area of focus for this student group.

d. Threat Environment Considerations

- Reconnaissance, surveillance, and tracking systems advances are making it easier for peer competitors to follow movements, even in the ocean expanses.

- Long-range missiles have changed the landscape such that nearly everywhere can be considered contested.

- Underwater assets will still be threatened, even though the undersea domain remains the best place to hide.

- Risk tolerance will increase as conflict escalates through the range of military operations (ROMO).

e. Solution Centered Suggestions

- Inventory awareness and capability for the transfer of cargo from one carrier to another will enable lateral and backwards supply chain flows that can increase the resilience in the system.

- Stockpiles, whether overt or covert may be utilized to improve supply system resilience.

- Worldwide commerce may persist even during a peer competitor conflict. It may be possible to hide in plain sight or utilize commercial routes.

- Predictive ("push") versus reactive ("pull") logistics may be used to improve mission readiness and will require data collection and analysis efforts.

- Finding ways to reduce the demand signal could be as fruitful as finding ways to increase capacity and survivability.

The insights gained through stakeholder and needs analysis were then utilized to assist in the next step of the SE process: bounding the problem space.

C. BOUNDING THE PROBLEM SPACE

Military logistics is a broad subject that includes transportation of traditional warfighting materiel such as food rations, fuel, and ammunition (class I, III, and V supplies, respectively), but also extends to categories like training, data transfer, medical, mortuary affairs, and many others. The complex interrelationship between logistics as an enabler to military operations, and military operations as an enabler for logistics transport, is exacerbated by great uncertainty about precisely where in the ROMO a future conflict might emerge. The rapidly evolving capabilities of our near-peer state competition blurs the image further. As such, the limitations in time and available manpower dictated a narrowing in scope to create a more manageable problem set.

We realized early on the need to bound, scope, and provide context to the problem space. The Naval Postgraduate School scenario "The Global War 2030—Two Years In" (summarized in a subsequent section) was developed to provide context during the WIC and defined the scale of war within the ROMO. We adopted that scenario in our efforts to serve as context when making assumptions and conducting analysis.

To further clarify the term, "near-peer competitors" refers specifically to the pacing threats represented by China and Russia. While a China campaign is expected to be geographically limited to the Pacific Ocean operating area, a campaign against Russia is assumed to take place only in the Atlantic Ocean operating area and Western Europe. Thus, the project evaluated the relevant differences that are generated by the variations in operating environments and physical distances inherent in the respective geographic regions.

Dry stores, fuel, and ammunition were assumed to represent the bulk of material to be conveyed to the front lines in support of warfighting operations. Consumption and delivery rates for these classes of supply were considered in the establishment of measures of performance (MOPs) and measures of effectiveness (MOEs) which were utilized to compare one architecture to another. We considered production and packaging of resources to be outside the scope of this research—it was assumed that resources needed by the warfighter were available in the logistics system.

We expected this analysis effort to generate insight regarding the operational strengths and weaknesses inherent to existing logistics carriers, to include joint capabilities, commercially available lift technologies, and conceptual technologies. This effort endeavored to recommend an architecture that would likely include elements from each category, arranged in such a way to exploit the strengths and to mitigate the weaknesses of each component.

Based on the context provided in the "Global War 2030—Two Years In" scenario and the assumptions we made to scope the problem space, we then revisited the tasking statement to ensure we focused our efforts in the appropriate places.

1. Focused Problem Statement

After accounting for stakeholder concerns, input from subject matter experts, and a literature review including national strategic directives, we distilled the tasking statement into the following problem statement (emphasis added to the original):

> Design a cost effective, deployable, and resilient unmanned and manned system of systems to provide logistics in contested environments by near-peer competitors in the 2030–2035 timeframe.
>
> - Consider system ***delivery rates*** of dry stores, fuel, and ammunition at sea and to forward operating areas ashore.
> - Where possible, include ***joint contributions*** in the system of systems.
> - Develop ***alternative architectures*** and their operational employment concepts.
> - Investigate current ***commercially available*** lift and technologies for rapid acquisition as one alternative. (Jeffrey Kline, personal communication, September 1, 2019)

2. Scenario: "The Global War 2030—Two Years In"

We adopted the scenario developed by Professor Jeffrey Kline for both our Joint Campaign Analysis coursework and the 2019 WIC held at the Naval Postgraduate School for the basis of our project's context; it is called "Global War 2030—Two Years In." It is a notional representation of great-power competition in the 2030–2032 timeframe. We coupled the given scenario with real-world, open-source capabilities data found on the internet to create a realistic backstory for our project efforts. Based off the details of the scenario and in consideration of our time constraints, we chose to focus our efforts on only the Pacific area of operations. We felt this region presented the greater challenge to logistics due to the long lines of communication. It also allowed us greater opportunity to leverage the expertise of our Singaporean team members, who are also concerned with the growing threat posed by China. The following scenario detailing Russian and Chinese disposition is fictional but plausible, given their history and current capabilities.

a. China in the Year 2030

In 2030, China has become the world's leading economy. Although her economic growth began to slow in 2020, she strengthened trade infrastructure between Asia and

Europe under the "Belt and Road" initiative and continued her political, fiscal, economic, and military expansionism. Due to a strong energy trade (China's dependence on the Trans-Siberian pipeline on oil) and common desire to challenge the United States national power, relationship between Russia and China are flourishing. Further economic ties were generated by a series of trade agreements that began in 2023 (Jeffrey Kline, class notes, July 8, 2019).

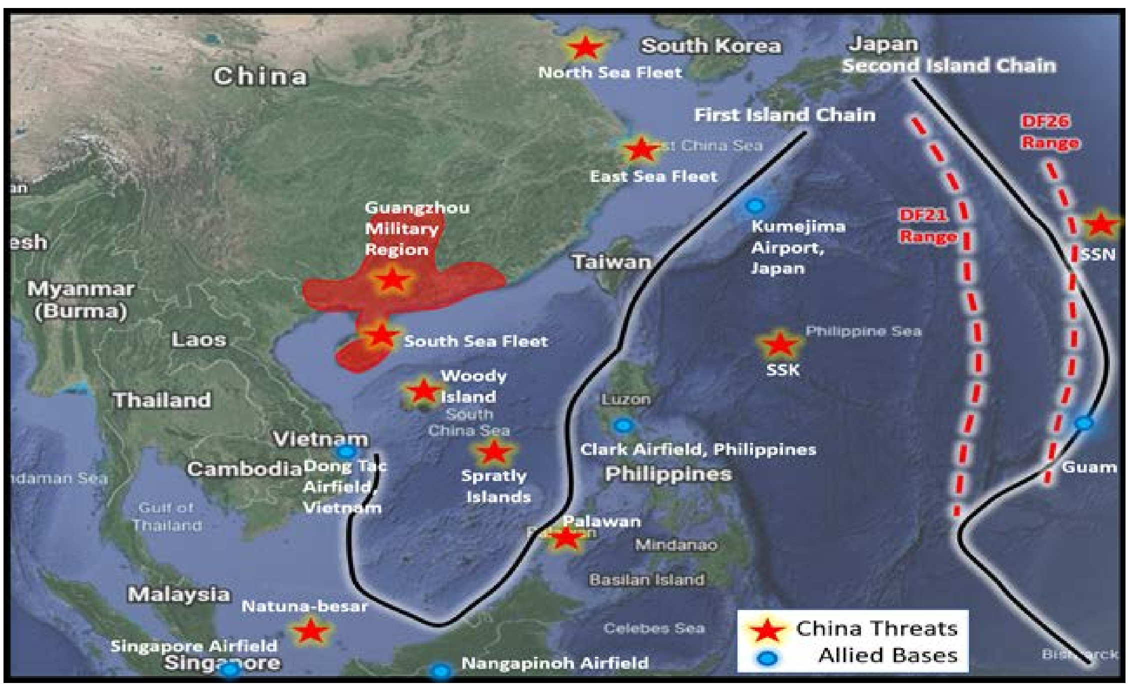
China has occupied several of the Spratly islands terra-formed through dredging in 2015 with military installations. They have situated their military assets such as fighter squadrons, unmanned combat aerial vehicles (UCAV), surface-to-air installations (S-500), anti-cruise missile mobile sites, electronic surveillance and communication sites, and ship support facilities. This has been strongly protested by Philippines and the United States (Jeffrey Kline, class notes, July 8, 2019).

Tensions between China and its neighboring East and Southeast Asia countries began to build in 2027, which revolved around territorial disputes and small-armed conflicts. These tensions eventually escalated into war in 2030. The following five examples list the events that occurred from 2027 and led to global war in 2030.

- In 2027, due to defaulted Chinese loans (for various trade infrastructure) by several countries along the "Belt and Silk" road, China forcefully occupied critical facilities and placed Chinese companies to manage and operate them. This led to violent civil protests of Chinese workers in Malaysia, Pakistan, Djibouti, Vietnam, and Indonesia.
- In 2029, China claimed that either Vietnam, Indonesia or the Philippines were responsible for the explosion of its deep-sea exploration ship 100 nautical miles North of Natuna Besar. China mobilized their South China Seas Fleet and demanded restoration from all three countries, or they would "secure" their seas. They also threatened to assume governorship of the island of Natuna Besar, Indonesia in compensation for the attack on their deep-sea exploration ship.
- A month later, the Chinese sank a patrolling Vietnamese ship using a land-based surface to surface missile. China announced all traffic through the South China Sea would henceforth be subject to inspection and control by Chinese forces.
- A Philippine helicopter fired on a Peoples Liberation Army Navy (PLAN) Type 56 corvette conducting gunnery exercises four miles from Palawan Island. In response, China also threatened invasion of Palawan.

- During an inspection of Chinese flagships in the Indian Ocean by the United States, a U.S. guided missile destroyer (DDG) was torpedoed by an unknown submarine. War was declared by all participants. North Korea allied itself with China. (Jeffrey Kline, class notes, July 8, 2019)

These events led to war in the early 2030 with China's rapid and successful occupation of Natuna Besar, Indonesia and Palawan, Philippines. It quickly evolved to a maritime war of attrition with China's sea control threatened by allied submarines inside the first island chain, and allied sea control threatened by PLAN submarines, ballistic missiles, and cruise missiles around and outside the first island chain. Although under threat of ballistic missile attack, allied expeditionary airfields are operating in the area of operations from Dong Tac, Vietnam; Kumejima Airport in Japan; Clark airfield in the Philippines; Singapore; Nangapinoh airfield, Borneo, Indonesia (Jeffrey Kline, class notes, July 8, 2019). Figure 4 shows the military context of the Pacific Theater.



Original map obtained from Google Earth, 2020.

Figure 4. Military Context of the Pacific and Indian Oceans

In addition to adopting the Global War 2030 scenario, we also conducted research on China's military capabilities and assets. This allowed us to assess the potential risks it poses to delivering logistics in a contested environment. There are a few key assumptions and key issues that would have to be focused on:

- China would most likely employ indirect strategy of attacking U.S. logistics and avoid "force on force" confrontation.

- China possess numerous ISR (intelligence, surveillance, reconnaissance), and strike capabilities covering the South China Sea, and beyond, which affords her extensive detection ranges.

- The survivability of individual U.S. logistics assets will depend on signature, exposure time, and countermeasures.

In the following subsections, we give an overview of various Chinese threats U.S. forces are likely to encounter within the contested environment.

(1) Satellites

China's Yaogan satellites are a series of reconnaissance satellites that are equipped with different sensors (electronic intelligence (ELINT), synthetic aperture radar (SAR) and optical) for area surveillance. A simulation conducted by the National Institute of Advanced Studies, Bangalore, India, presented the results of the coverage pattern for identifying, locating and tracking a ship from the Pacific Ocean, showed in Figure 5. The results demonstrated the robustness of the constellation of satellites that can be used to detect and track U.S. logistics ships in the area of operations (AO). It is assumed that the Chinese satellite surveillance capability will be leveraged to provide weapon cueing for anti-ship ballistic missiles and anti-ship cruise missiles launched from shore installations.

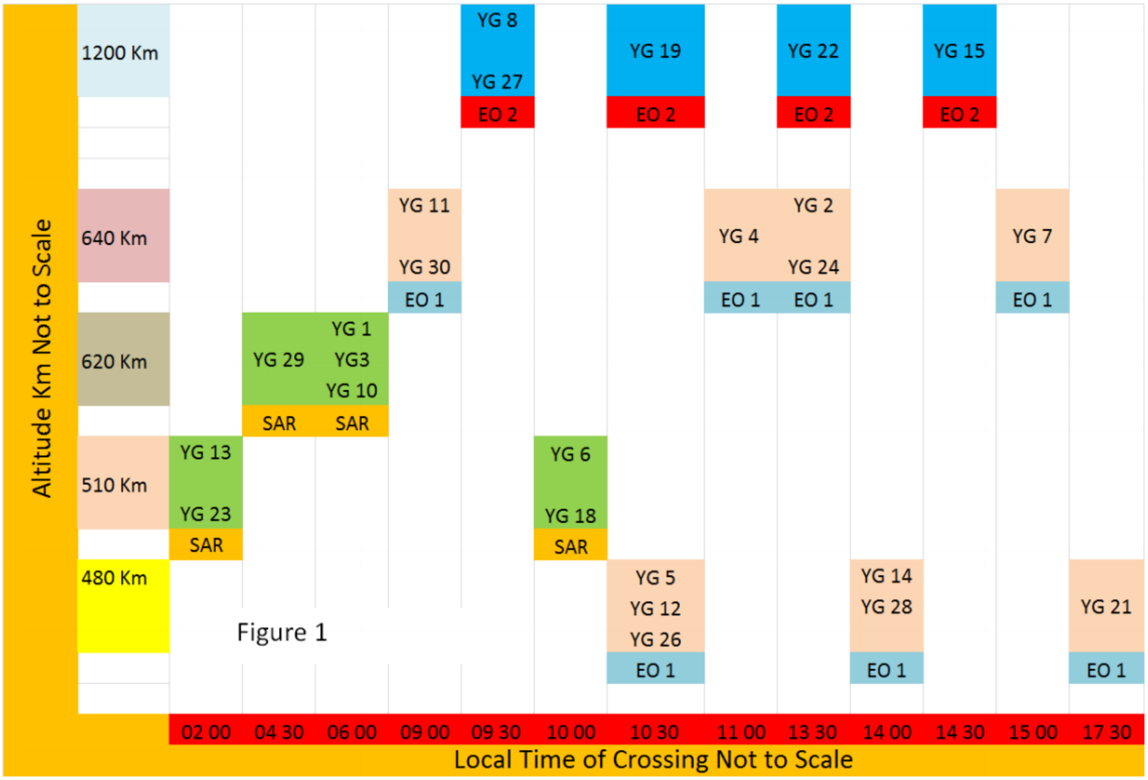


Figure 5. Equatorial Crossing Times for Chinese SAR Satellites. Source: Chandrashekar and Perumal (2016, 14).

(2) Unmanned Aerial Vehicles

The Chinese unmanned aerial vehicle (UAV) and unmanned combat aerial vehicle (UCAV) arsenal includes high altitude, medium-to-long endurance capabilities which can conduct search and disruption operations during the logistics supply mission of U.S. force. These assets pose a great threat, with small radar cross-section (RCS) and can also be capable of operating in swarms, making it difficult to detect and counter. Some of the examples of the UAVs are shown in Table 4. These assets will provide additional search, track, and targeting capability to support Chinese weapon systems.

Table 4. Chinese UAV and UCAV Inventory. Adapted from Jeffrey Kline, class notes (2019).

Name	***Quantity***	***Type***	***Capabilities***	***Speed (kts)***	***Range (nm)***	***Altitude (ft)***
Soaring Dragon	160	High Altitude Long Endurance	ISR	470	4,700	57,000
Pterodactyl	100	Stealth Medium Altitude Long Endurance	ISR Strike	174	2,500	17,000
Zond UAV	224	High Altitude Medium Endurance	ISR Electronic Warfare (EW)	135	6,000	49,000
Zond UCAV	300	High Altitude Long Endurance	ISR EW Strike	135	6,000	49,000
Dark Sword	30	Supersonic	Strike Air-to-air	Unknown	Unknown	Unknown

(3) Aircraft

The Chinese aircraft assets, shown in Table 5, are capable of a variety of mission profiles, ranging from search to destroy. The greatest threat to the U.S. Force logistics would be aircraft capable of detection and delivering anti-ship cruise missiles (ASCM).

Table 5. Chinese Aircraft Inventory. Adapted from Jeffrey Kline, class notes (2019).

Name	***Numbers***	***Type***	***Capabilities***	***Speed***	***Range (km)***
Su-33 Flanker	200	Fighter	Anti-ship, air-to-air, bombs	Mach 2.2	3,000
FC-1 Fierce Dragon	100	Fighter	Anti-ship, air-to-air, bombs	Mach 1.8	1,352
J-10 Vigorous Dragon	300	Fighter	Air-to-air, Air-to-surface, Bombs	Mach 2.2	1,250
J-11 Aircraft	100	Fighter	Bombs, Rockets	Mach 2.1	3,530
J-20 Air Superiority Fighter	100	Fighter	Air-to-air, Bombs	Mach 2+	6,000
Y-8FQ MMA	60	Maritime Patrol	EP-3 Recon System, Sonar Buoy, depth charges, torpedoes, Submarine Detection	Mach 0.5	5,615
H-6K	20	Bomber	Forward-looking Infrared (FLIR), Search Radar Missile/Bombs	Mach 0.8	3,000
H-20	25	Bomber	Air-to-ground missiles, Bombs	Mach 0.95	12,000
TU-154 M/D	10	ISR	ELINT, SAR, Infrared, Television, Photography	Mach 0.75	6,598
Y-8XZ (Y-8 Variant)	20	AEW	EP-3 Recon System	Mach 0.5	5,615
Y-8/Y-9 (Y-8 variant)	80	Transport (troop lift)	90-equipped troop capacity	Mach 0.5	5,615
Y-20	20	Transport (Cargo)	66-ton capacity	Mach 0.75	4,500

(4) Anti-ship Missiles

Within the arsenal of ballistic missiles that the Chinese possess, the DF-21 and DF-26 pose the greatest threat to U.S. logistics as due to the capability for “conventional strikes against naval targets” (O’Rourke 2019, 4). If coupled with surveillance and targeting systems including satellites, UAVs and aircraft identified in the preceding sections, China might easily target not only naval logistics ship, but also combat aircraft carriers. Due to the missiles’ range and maneuverability, the ballistic missiles are difficult to counter and intercept. Figure 6 shows the arsenal of the Chinese ballistic missiles and their area of coverage.

Figure 6. Chinese Ballistic Missiles and Coverage Areas. Source: CSIS (2020).

(5) Naval Submarine Force

Submarines afford the Chinese the element of stealth and surprise and would be the most likely avenue of attack on U.S. logistics. Submarines also have the highest probability of avoiding U.S. combat forces, while potentially inflicting the greatest damage. Some of these include the conventionally powered submarines (SSK), the nuclear-powered submarines (SSN), and the nuclear-powered ballistic missile submarines (SSBN). These submarines can launch both torpedoes and anti-ship cruise missiles.

(6) Naval Surface Force

The Chinese possess multiple naval surface vessels such as guided-missile cruisers (CG), guided-missile destroyers, guided-missile frigates (FFG) and corvettes. A study by the Congressional Research Service states that China has “the region’s largest navy, with more than 300 surface combatants, submarines, amphibious ships, patrol craft, and specialized types" (O'Rourke 2019, 21). These assets will be a substantial threat to U.S. logistics if they are encountered at sea.

(7) Mines

China poses a significant threat to U.S. shipping in terms of mine warfare. They are most likely to utilize mines for denial. According to a Naval War College Review article written by Scott Truver (2012), China would also rely heavily on offensive mining in any scenario involving Taiwan. With a strong maritime militia consisting of fishing boats and other non-combatant vessels, China can deploy mines all over the Pacific Theater. According to Goldstein (2019), "laying 2,000 mines per day should be relatively easy for Chinese ships and aircraft" (par 6). The Chinese arsenal of mines consists of "over 50,000 mines [in] over 30 varieties of contact, magnetic, acoustic, water pressure and mixed reaction sea mines, remote control mines, rocket-rising and mobile mines" (Freedberg 2015, par 15). Freedberg's (2015) article later goes on to state that China could even possess 80,000 to 100,000 mines in all.

(8) Information and Electronic Warfare

In addition to traditional military assets, China also possesses the capability to conduct cyber warfare and deny, spoof, or hack U.S. logistic networks. This has the potential to disrupt the ability to replenish U.S Forces in the AO. The use of electronic warfare (EW) may allow China to deny the U.S. the use of communications for coordinating logistics. China may also have the EW capability to track U.S. logistics, making supply missions more vulnerable.

b. Russia in the Year 2030

By 2030, Russia has achieved a larger and more stable economy supported by the export of oil to Europe and China. With a more stable economy, the Russian military has accelerated modernization efforts yielding more capable missile programs and a larger, more modern submarine fleet. In the Black Sea region, Russia maintains control of Crimea since its annexation in 2014 and maintains forces on the Ukraine-Russia border. In the Baltic Sea region, annual military exercises are held as a show of force along the borders of their neighboring countries. In the Mediterranean Sea region, the partnership between Russia and Syria continues with a permanent naval group of 15 ships homeported at a naval facility in Tartus and continued use an airbase at Hmeymim (Jeffrey Kline, class notes, July 8, 2019).

By 2032, Russia has taken advantage of the ongoing engagement of the United States in the Pacific and increased its efforts in political interference using cyber warfare, social media, and insurgency. Inspired by Russian rhetoric of reclaiming traditional lands, and with a promise of Russian support, Serbia invaded Montenegro. Supported by Bosnia and Herzegovina and Croatia, Montenegro was able to halt the advance of Serbian forces after a week of fighting. As shown in Figure 7, a front was established along the Moraca River between Podgorica and Niksic (Jeffrey Kline, class notes, July 8, 2019).

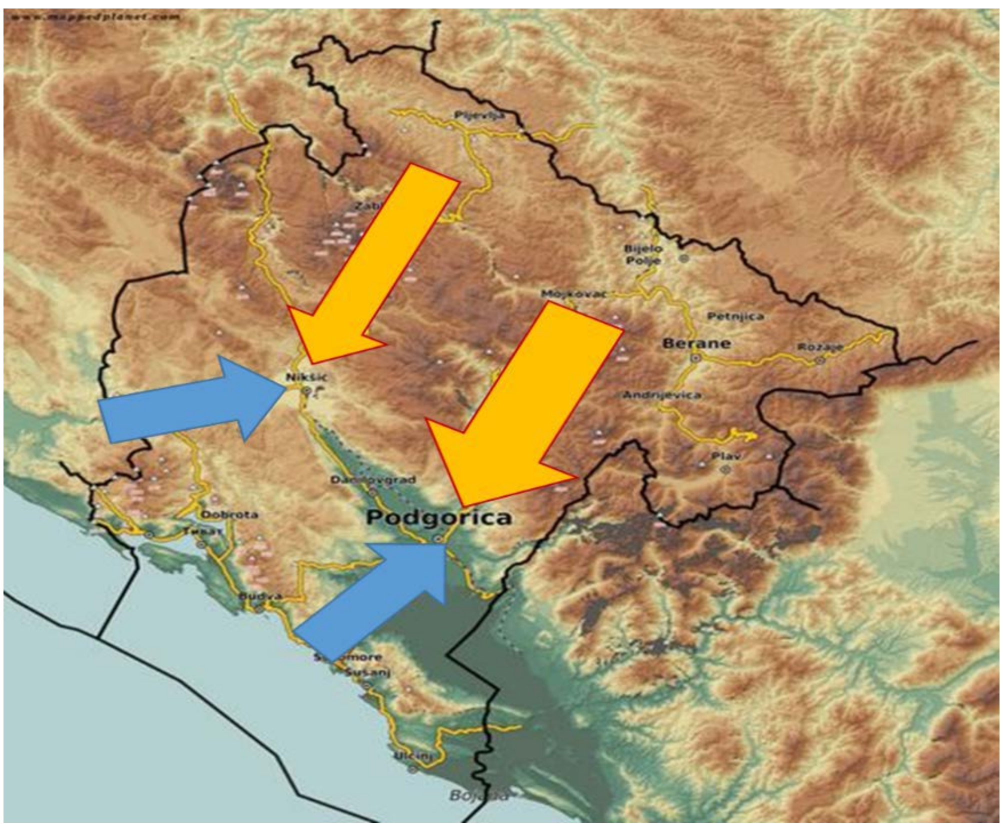


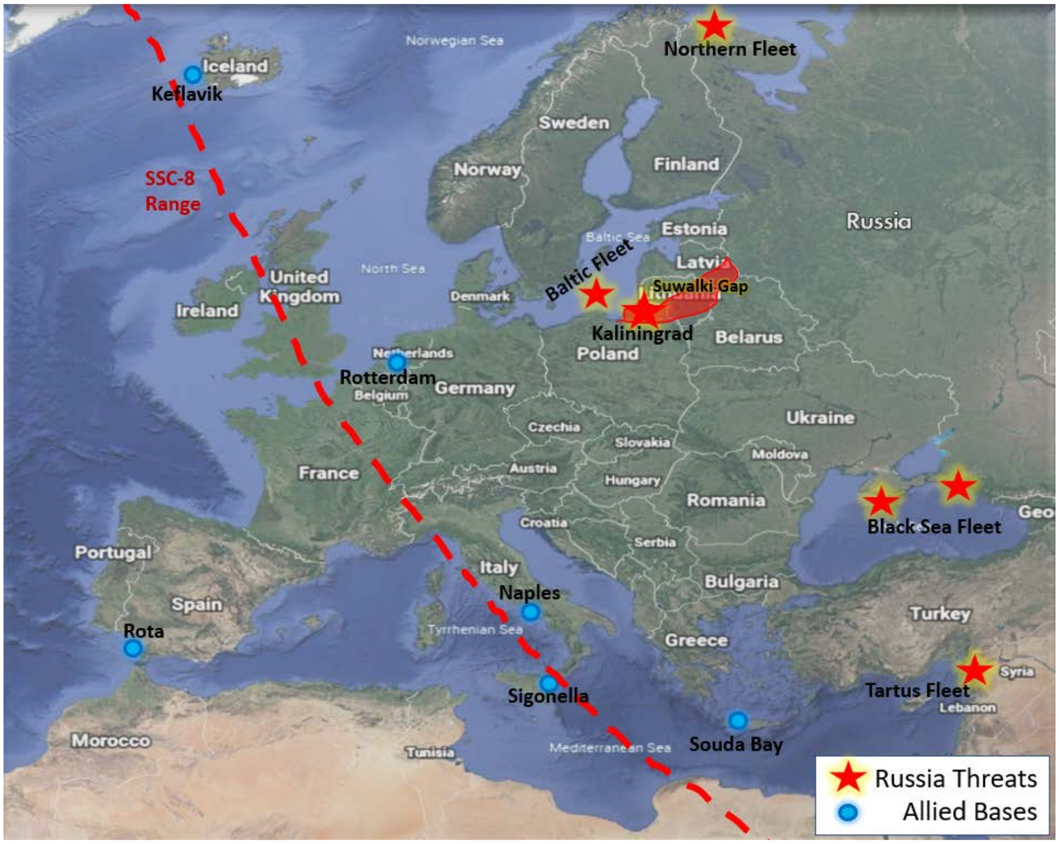
Figure 7. Serbian Invasion of Montenegro. Source: Jeffrey Kline, class notes (2019).

Committing to their promise of support, Russia sortied six ships from Tartus and two submarines in the Mediterranean to the Adriatic Sea to impose a quarantine on the flow of all military supplies. An additional 10 submarines from the fleet in the North Sea were also sortied to the Atlantic (Jeffrey Kline, class notes, July 8, 2019).

In addition to their interference in the Balkans, Russia instigated unrest in the Baltic states by claiming persecution of ethnic Russians in Latvia and Lithuania. Russian forces mobilized on the borders which prompted the North Atlantic Treaty Organization (NATO) rapid reaction force to deploy five thousand troops with artillery support to Latvia and Lithuania in response. Capitalizing on the civil unrest, Russia invaded Lithuania by moving troops through the Suwalki Gap between Belarus and Kaliningrad as shown in Figure 8 (Jeffrey Kline, class notes, July 8, 2019).

Figure 8. Russian Invasion of Lithuania. Source: Jeffrey Kline, class notes (2019).

Within 24 hours, Russian forces had defeated the forces of the NATO rapid reaction force and taken control of all Lithuanian lands south of Kaunas. The invasion of Lithuania prompted the invocation of NATO Article 5 (Jeffrey Kline, class notes, July 8, 2019). Figure 9 shows the military context of the Atlantic and Mediterranean Theater.



Original map obtained from Google Earth, 2020.

Figure 9. Military Context of the Atlantic Ocean and Mediterranean Sea

Like with the Chinese threats, our team also conducted open-source research on Russian military capabilities to assess the potential risks posed to the team's tasking of delivering logistics in a contested environment. In a study assessing Russia's armed forces, the RAND Corporation determined that the Russian Navy maintains effectiveness in three key mission areas: strategic deterrence, coastal defense, and short-term presence operations (Crane, Oliker, and Nichiporuk 2019). The study also determined that the Russian Navy lacks proficiency in other mission areas such as sea denial in the open ocean, sea control, and power projection and attributes this to a lack of large surface combatants capable of accomplishing these missions (Crane, Oliker, and Nichiporuk 2019). Among the three mission areas in which the Russian navy maintains effectiveness, our primary concern lies with their capabilities in coastal defense. These capabilities include threats such as small surface combatants, submarines, and aircraft which can be armed with anti-ship and anti-submarine missiles and torpedoes as well as shored-based coastal defense anti-ship cruise missiles. The following subsections provide an overview of various Russian threats U.S. forces are likely to encounter within the contested environment.

(1) Unmanned Aerial Vehicles

The Russian UAV threat present in this scenario is the Altius-M, which is a long-range, medium-altitude UAV with a maximum speed of 950 kilometers per hour and a flight time of up to 48 hours. The Altius-M employs a modular design with payloads capable of strike, reconnaissance, and electronic warfare (Jeffrey Kline, class notes, 2019). These capabilities pose a threat to U.S. Forces by providing Russia with capability for locating, tracking, and striking logistics assets.

(2) Aircraft

The Russian aircraft assets, shown in Table 6, are capable of a variety of mission profiles, ranging from search to destroy. The greatest threat to the U.S. Force logistics would be aircraft capable of detection and delivering anti-ship cruise missiles.

Table 6. Russian Aircraft Inventory. Adapted from Jeffrey Kline (class notes, 2019).

Name	***Numbers***	***Type***	***Capabilities***	***Speed***	***Range (km)***
An-30 Clank	13	ISR	Aerial cartography, Reconnaissance, Transport	Mach 0.44	2,630
Su-30M Flanker-G	25	Fighter	Air-to-air, Air-to-surface, Bombs	Mach 2	3,000
Su-35S Flanker-E	45	Fighter	Anti-ship, Air-to-air, Air-to-surface, Bombs	Mach 2.25	3,600
Su-57 Felon	35	Fighter	Anti-ship, Air-to-air, Air-to-surface	Mach 2	3,500
Tu-160 Blackjack	30	Strategic Bomber	Cruise missiles, Short-range nuclear missiles	Mach 2.05	12,300

(3) Anti-ship Missiles

Russia has developed a variety of ASCMs and anti-submarine missiles that are capable of being launched by surface combatants, submarines, aircraft, and coastal defense sites. Potential ASCM threats include the SS-N-22 SUNBURN (3M-80 MOSKIT), SS-N-25 SWITCHBLADE (3M-24 URAN), SS-N-26 STROBILE (3M-55 ONIKS), and SS-N-27 SIZZLER (3M-54 KALIBR). A potential anti-submarine missile threat is the 91R from the KALIBR weapons family. The basic characteristics for the export versions of these missiles are listed in Table 7, and it is assumed that Russian domestic variants are more capable (ONI 2015).

Table 7. Russian Anti-ship Cruise Missile Inventory. Adapted from ONI (2015).

Missile	***Type***	***Speed***	***Range (km)***
SS-N-22	Anti-ship	Mach 2+	120-240
SS-N-25	Anti-ship	Subsonic	130
SS-N-26	Anti-ship	Mach 2.5	300
SS-N-27	Anti-ship	Cruise: Subsonic Terminal: Supersonic	220
91R	Anti-submarine	Subsonic	Ship-launched: 40 Sub-launched: 50

(4) Naval Submarine Force

A lack of direct access to major ocean areas outside of the Pacific has led to submarines becoming the capital ships of the Russian navy (ONI 2015). Submarines afford Russia the element of stealth and surprise and would be the most likely avenue of attack on U.S. logistics. Submarines also possess the highest probability of avoiding U.S. combat forces, while potentially inflicting the greatest damage. The primary threats from their coastal defense capability include the *Kilo*-class and *Petersburg*-class diesel-electric SSKs and the nuclear-powered *Severodvinsk*-class multipurpose guided missile attack submarine (SSGN). Their strategic deterrence capability includes the *Dolgorukiy*-class SSBN. Like China, Russian submarines can also fire both torpedoes and anti-ship cruise missiles to threaten U.S. logistics assets.

(5) Naval Surface Force

With a higher priority placed on coastal defense, Russia has focused on developing smaller surface combatants capable of guarding key areas along their coastline and littoral areas (Crane, Oliker, and Nichiporuk 2019). The primary threats among their smaller surface combatants include the *Sviyazhsk*-class guided-missile patrol ship (PGG) and the *Gorshkov*-class, *Grigorovich*-class, and *Steregushchiy*-class FFGs. While Russia may be focusing on smaller surface combatants for their coastal defense capabilities, threats are still posed by their larger surface combatants. The primary threats here are the *Sovremenny*-class DDG and the nuclear-powered *Lider*-class CG.

(6) Mines

Russia stands to be the greatest threat with respect to mine warfare and has an estimated inventory of "upwards of 250,000" mines, according to Truver (2012). The mines could be employed offensively, defensively, or for denial operations. Russia possesses bottom, self-propelled, and moored mines that are sensitive to acoustic, magnetic, hydrodynamic (pressure), and electric signatures with operating radiuses of 50–60 meters (RusNavy n.d.). According to an article in The National Interest titled "Sunk Your Battleship: Russia is Developing Deadly Mines that Can Learn," Russia is developing "[artificial intelligence]-controlled mines that are self-learning and can adapt their behavior" (Peck 2019, par. 2). This will provide Russia the ability to create formations of mines deployed from various assets which are capable of selective-targeting—a serious threat to U.S. logistics ships.

(7) Information and Electronic Warfare

In addition to the traditional threats posed by Russia's armed forces, a RAND study identified other threats such as nonlinear warfare, noncontact warfare, and information warfare. These other threats support military operations by coordinating operations with the use of propaganda on social media platforms, electronic warfare, and cyber-attacks (Crane, Oliker, and Nichiporuk 2019). These threats have the potential to disrupt the ability to replenish U.S. Forces in the AO by denying the U.S. the use of communications for coordinating logistics and by making supply missions more vulnerable through tracking.

D. REQUIREMENTS DEVELOPMENT

Once we defined the problem, scoped the problem space, and determined the context our system would be operating within, the next step of the SE process called for developing the systems operational requirements. Developing operational requirements is essential to the SE process and in displaying traceability between the stakeholders needs, system form, functions, and components. To address a capability gap, a requirements analysis is conducted, involving extensive interviews with personnel who have vested interest, experience, and subject matter expertise on the topic. The Defense Acquisitions University (DAU) (2001) describes requirements definition as the primary focus of the SE process. Systems engineers must understand the primitive needs of the stakeholder to develop the requirements for an appropriate and effective system (2001, 35).

In the SE process and our work, the development of functional and performance requirements involves translating from the customers' requirements (DAU 2001). A customer requirement, as defined by DAU (2001), is a "statement of facts and assumptions that define the expectation of the system in terms of mission objectives, environment, constraints, MOEs and MOSs" (35). These requirements are then defined by the following categories: mission definition, performance and physical parameters, operational deployment or distribution, operational life cycle (horizon), utilization requirements, effectiveness factors, and environmental factors (Blanchard and Fabrycky 2011). We transformed the critical operational issues (COIs) into system operational requirements (SORs) using this method to ensure the proper requirements were developed.

1. Mission Definition

The primary purpose of the proposed system is to provide logistics to the warfighter in a contested environment. The term warfighter is general in nature; however, it describes the marine on the beach, the sailor on a ship, the airmen controlling drones, and the pilot flying fighters. It also describes allies in theatre. This system needs to be scalable in a manner that it can be used in different theatres of war against near-peer competitors. Due to the scalability of the system, it could also effectively supply logistics in an uncontested environment. It could enable the DOD to diversify its logistics fleet to meet the warfighter demand. Currently, the logistics fleet is incapable of supplying the requisite logistics to its warfighters in a time of a global war (Walton, Boone, and Schramm 2019). Therefore, our proposed system shall provide a method to transport and deliver mission essential cargo (such as class I, III, and V supplies) within a contested environment.

2. Critical Operational Issues

Another aspect of the process which involves stakeholders is the development of COIs. By identifying the COIs, we were able to narrow the scope of the project and understand what SORs a proposed logistics architecture would need to meet. Defense Acquisition University (n.d.) defines COIs as "key operational effectiveness or suitability issues that must be examined in operational test and evaluation to determine the system's capability to perform its mission." They are normally expressed in the format of a question and decomposed into MOEs and measures of suitability (MOSs). An MOE is a quantifiable metric used to evaluate a system in its intended environment (DAU n.d.).

Once the systems MOEs are determined, each is then further decomposed into one or more measures of performance (MOPs). An MOP, as DAU (n.d.) defines, is a "quantifiable metric regarding a particular performance parameter." After one creates viable MOPs, data requirements (DRs) are developed, which are the metrics used as input values for their respective MOP. We developed the following COIs:

- COI 1: Is the system capable of deploying to a contested environment (transport from supply nodes to the contested environment)?
- COI 2: Do the system connectors support transfer of goods from one carrier to another and from carrier to warfighters?
- COI 3: How available is the system?
- COI 4: How cost effective is the system delivering goods in a contested environment?
- COI 5: How survivable is the system?

3. Performance and Physical Parameters

The system of systems generated in this study will be scalable to address a wide range of potential conflict scenarios. As such, the amount of supply demanded and other parameters (such as sea state, altitude, range, and hours of operation) were represented as "X" values. We understood that different AOs and conflict scenarios will drive more specific values. This effort was consistent with the iterative SE process and a desire to remain solution neutral while defining the requirements. The following are the SORs we developed for performance and physical parameters:

SOR. 1: The system shall have probability of survival greater than XX.

- **The probability of detection shall be less than X**. The probability of detection influences a platform's *susceptibility* which is its ability to avoid the effects of a threat (Ball 2013). Lower probability of detection contributes to a lower susceptibility, which is desired to enhance system survivability.

- **The noise level of the system shall be X dB**. This refers to the acoustic noise generated by the unit when in its normal mode of operation. Higher noise levels lead to a greater probability of detection, which is unfavorable.

- **The velocity of units in the system shall be X knots**. The speed at which a platform can operate impacts its susceptibility by means of its time spent in a threat environment and its ability to evade a threat, if detected.

- **The system shall survive a sea state greater than six, as defined by the World Meteorological Organization**. In addition to man-made threats, the system must also withstand the effects of its operating environment. Sea state includes wave height and swell height.

- **The system shall have a defense mechanism**. Defense may refer to the system's ability to reduce its susceptibility, its vulnerability, or both.

SOR. 2: The system of systems shall deploy in a contested environment.

- **The system shall have a range of X nm**. The range of the system is the distance over which it may operate. The system should be capable of all its demand nodes with at least one supply node.

- **The system shall remain operational in seas greater than sea-state four, as defined by the World Meteorological Organization**. This varies from the sub–requirement under SOR1 in that the system must not only survive in sea state four, but also continue performing its primary mission.

- **The system shall operate at X altitude**. Aerial components of the system, if any, must operate at some distance above the surface of the Earth, which may impact its susceptibility.

- **The system shall operate at X meter below the waterline**. Submersible components of the system, if any, must operate at some distance below the surface of the sea, which may impact its susceptibility.

SOR. 3: The system shall be able to store required goods. The system must be capable of delivering enough supply to meet the demand signal of the warfighter. Capacity of each unit in the system and the overall system capacity will both affect this requirement.

- **The system shall be capable of storing X tons of munitions**.

- **The system shall be capable of storing X tons of dry goods**.

- **The system shall be cable of storing X barrels of fuel**.

4. Operational Deployment Parameters

For the purposes of this analysis, the system will be required to deploy in the Pacific and Atlantic AOs. The system will be capable of using different domains (air, surface, sub-surface, and land) assets to deliver logistics. The system will be expected to transit from high seas to territorial seas and international airspace into national airspace as shown in Figure 10.

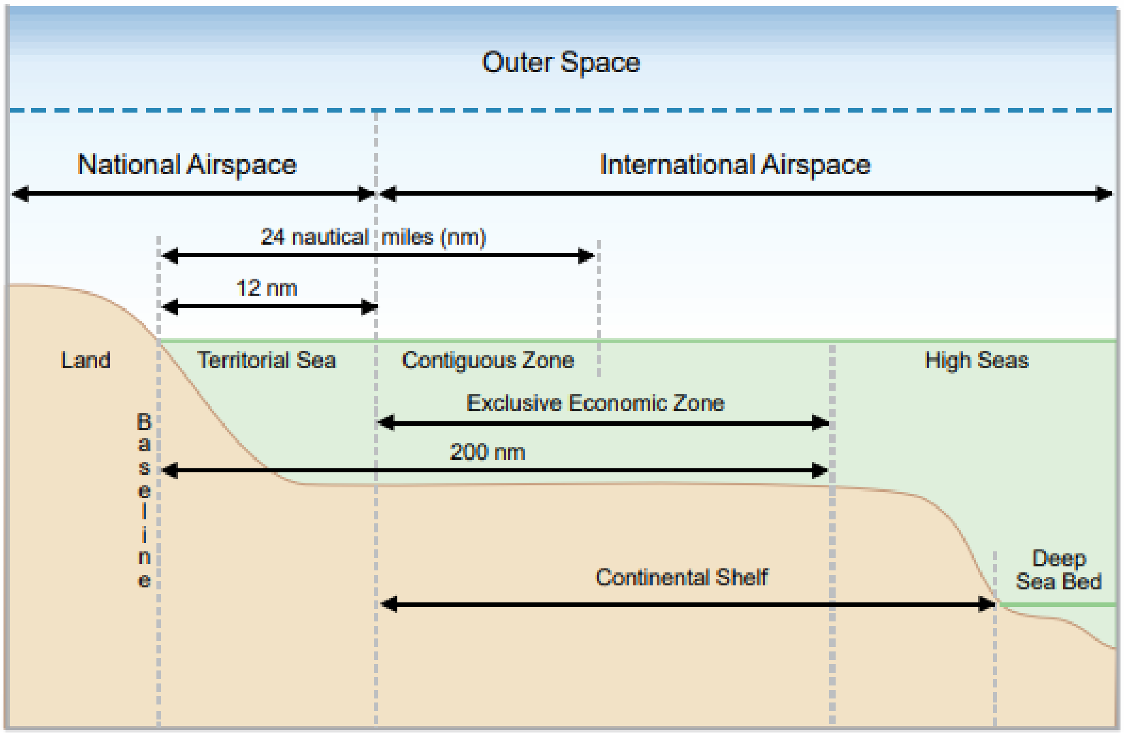


Figure 10. Legal Boundaries of the Oceans and Airspace. Source: JCS (2018b, I-6).

The system will also operate and deliver its logistics in the littorals. The *Joint Intelligence Preparation of the Operational Environment* defines littorals as an area that is made up of two segments of the operational environment:

1. Seaward: the area from the open ocean to the shore, which must be controlled to support operations ashore.
2. Landward: the area inland from the shore that can be supported and defended directly from the sea. (JCS 2014, GL-6)

SOR. 4: The system shall operate in and above littoral waters.

- **The system shall operate at X altitude**. This operating environment of the littorals may dictate an operating altitude for aerial assets that differs from its altitude in other environments.

- **The system shall have a draft of X meters**. The draft of a vessel is the distance between the waterline and the lowest part of the vessels keel beneath the waterline. Vessels are unable to safely navigate in waters shallower than their draft (plus a safety factor to account for tidal range).

SOR. 5: The system shall offload/onload goods.

- **The system shall transfer X tons of goods per day**. This is the rate at which the system is capable of loading or unloading dry cargo to/from the delivery or transfer units of the system.

- **The system shall transfer X gallons of fuel per day**. This is the rate at which the system is capable of loading or unloading fuel to/from the delivery or transfer units of the system.

Table 8 summarizes our efforts to decompose the COIs into SORs, MOEs, MOPs, and DRs. These metrics and data requirements helped our team to measure the effectiveness of our logistics system.

Table 8. Measuring System Success

COIs	***SORs***	***MOEs***	***MOPs***	***DRs***
1. Survivability	1.1 The system shall have Probability of Survivability greater than. XX	1.1.1 Probability of survival 1.2.1 Percent degradation due to wave heights	1.1.1.1 Probability of detection 1.1.1.2 Noise level 1.1.1.3 Speed 1.1.1.4 Threat detection range 1.1.1.5 Missile load-out 1.1.1.6 Rate of Fire 1.2.1.1 Sea State	1.1.1.1.1 Radar cross-section 1.1.1.2.1 Source noise level 1.1.1.2.2 Transmission losses 1.1.1.2.3 Background noise level 1.1.1.2.4 Directivity index 1.1.1.2.5 Detection threshold 1.1.1.3.1 Start location 1.1.1.3.2 End location 1.1.1.4.1 Sweep width 1.1.1.5.1 Missile capacity 1.1.1.6.1 Time between fires 1.2.1.1.1 Wave height

COIs	***SORs***	***MOEs***	***MOPs***	***DRs***
2. Deployability	2.1 The system shall operate in contested littorals 2.2 The system shall store required goods	2.1.1Platform range 2.1.2 Percent degradation due to wave heights 2.2.1 Storage	2.1.1.1 Vehicle speed 2.1.1.2 Fuel efficiency 2.1.1.3 Fuel capacity 2.1.2.1 Operational sea state 2.2.1.1 Storage Capacity	2.1.1.1.1 Start location 2.1.1.1.2 End location 2.1.1.1.3 Start time 2.1.1.1.4 End time 2.1.1.2.1 Distance 2.1.1.3.1 Fuel consumption rate 2.1.1.3.1 Usable fuel capacity 2.1.2.1 Wave height 2.2.1.1.1 Capacity of dry goods (tons) 2.2.1.1.2 Capacity of munitions (tons) 2.2.1.1.3 Capacity of fuel (barrels)
3. Distribution	3.1 The system shall operate in littoral waters	3.1.1 Platform range	3.1.1.1 distance 3.1.1.2 Speed	3.1.1.1.1 Depth 3.1.1.1.2 Altitude

COIs	***SORs***	***MOEs***	***MOPs***	***DRs***
	3.2 The system shall offload/onload goods	3.2.1 Transfer cargo	3.2.1.1 Amount transferred 3.2.1.2 Percent of successful transfers	3.1.1.2.1 Start location 3.1.1.2.2 End location 3.1.1.2.3 Start time 3.1.1.2.4 End time 3.2.1.1.1 Tons of goods per day 3.2.1.1.2 Barrels of fuel per day 3.2.1.2.1 Number of successful transfers 3.2.1.2.2 Number of failed transfers
4. Availability	4.1 The system shall have an availability greater than XX 4.2 The system shall have a reliability greater than XX	4.1.1 Operational Availability (A_O) 4.2.1 Reliability	4.1.1.1 Mean time between maintenance 4.1.1.2 Mean downtime 4.2.1.2 Mean time between failure	4.1.1.1.1 Time between maintenance 4.1.1.2.1 Start time of maintenance 4.1.1.2.2 End time of maintenance 4.2.1.2.1 Hours of operation before critical failure

COIs	***SORs***	***MOEs***	***MOPs***	***DRs***
5. Cost Effectiveness	5.1 The per unit cost of the system shall be less than current logistics platforms. 5.2 The learning and production rates for the manufacturing of the system shall be lower than existing platform.	5.1.1 Cost 5.2.1 Learning curve	5.1.1.1 Fixed operation and maintenance cost 5.2.1.1 Slope of learning curve	5.1.1.1.1 System benefits 5.1.1.1.1.2 Life cycle cost 5.1.1.1.1.3 System effectiveness 5.2.1.1.1 Unit number 5.2.1.1.2 Theoretical cost of one unit

5. Communications Requirements

To create a resilient and reliable logistics architecture, two essential functions are demand signals and inventory awareness. Demand signals represent the need of the warfighter, the end user, who requires supplies to maintain mission readiness and to execute missions. This is commonly understood as “pull” logistics. These demands are currently passed from the warfighter to suppliers via information systems, relying primarily on satellite-based communications. Inventory awareness enables logisticians to identify the nearest storage location or asset carrying the demanded supplies, and route them to the warfighter in the most efficient manner. Inventory awareness relies on the capability to update stock usage and locations in real time. In a conflict, inventory awareness becomes even more critical because knowing that a shipment is destroyed, and its contents, will enable immediate initiation of subsequent delivery efforts. Inventory awareness, as much as demand signal transmission, also relies on real time information sharing.

In a multi-domain war of attrition with a peer competitor, communication systems are likely to contested and potentially denied entirely. One method to reduce the amount information sharing required is through conversion to “push” logistics systems where possible. In a push logistics system, utilization rates are analyzed, often with the help of artificial intelligence, to predict the needed supplies and proactively ship them to the warfighter. This has a secondary benefit of reduced administrative burden on logisticians in the field. While push logistics should be exploited to the maximum extent possible, it is unreasonable to assume that the fidelity would be high enough to eliminate the demand signal requirement entirely. Furthermore, push logistics are no substituted for inventory awareness.

For these reasons, any logistics architecture will require some form of a communications (COMMS) network to receive and transmit requisite demand signals between distant supply and demand nodes of the architecture. Though we focused most of its efforts on the transport and delivery functions of logistics, the COMMS component was determined vital and required further analysis. Our technology team developed an analysis on potential COMMS architectures that could support the system. The details and results of this analysis are listed in Appendix A.

E. FUNCTIONAL ANALYSIS

As described by Blanchard and Fabrycky (2011), a function is an operation that the system must perform to meet an objective. A functional analysis is used in the SE process due to its iterative nature, and how it facilitates a decomposition of system level requirements into functions the System of Interest (SOI) must perform to meet the stakeholders needs. This analysis is done during the conceptual phase to keep systems engineers unbiased and allow them to remain solution neutral. That is, in developing the system, one must identify a need, create requirements, allocate functions, and identify components and subcomponents that will perform specific tasks. To adequately accomplish and document a functional analysis, the use of diagrams and models is necessary. These include a functional hierarchy, Integrated Definition (IDEF), and Functional Flow Block Diagram (FFBD) modeling (Blanchard and Fabrycky 2011).

1. Top-Level Functions

The functional hierarchy prioritizes the function of the system. In scoping the tasking statement, we chose to analyze and model the transportation and delivery functions of logistics as shown in Figure 11.

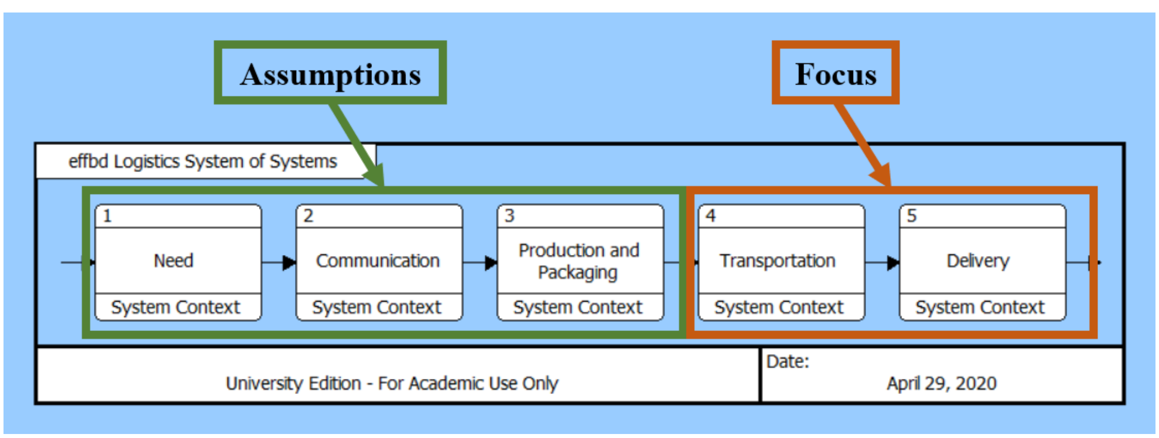


Figure 11. Logistics Functions

NEED: The logistics system will be required to recognize a need and generate a demand signal. That is, the systems must have a method for the warfighter to recognize a deficiency and requisition a specific part, sustenance, fuel, or other need. For the purposes of our analysis, we assumed that the infrastructure was already in place to enable the warfighter to input their needs into the system.

COMMUNICATION: As stated in the previous section, the system requires a supporting communications architecture. This architecture will need to be robust and enable the warfighter to communicate their needs. It must also enable the components of the proposed system to share information with each other, the supply depot, and warfighter. The ability of system components to effectively communicate with each other was considered vital, and an in-depth analysis can be found in Appendix A.

PRODUCTION AND PACKAGING: We also assumed that the system would be required to effectively produce and package parts for delivery via transport assets. We understood the U.S. will require a robust supply infrastructure buildup and that there will always be a finite supply of parts, munitions, fuel, and dry goods. For the purpose of this proposed system, these limitations were considered outside the scope and the analysis assumes that there would be a production and packaging component in place to supply the requisite goods.

TRANSPORTATION: The system will require a transportation function to store, transfer, and transit to the contested environment. We chose to focus on this top-level function and analyze several alternatives to develop a CONOPS and architecture that would adequately perform this function. The system will be transiting in a contested AO; therefore, the system will need to be robust and resilient.

DELIVERY: The system will need to be able to deliver cargo and fuel to both vessels at sea, units operating within contested littorals, and units ashore.

2. System Interfaces (IDEF0)

The Defense Acquisition University (2001) describes IDEF0 models to “show data flow, system control, and the functional flow of life cycle processes” (51). As shown in Figure 12, an IDEF model has inputs, controls, mechanisms, and outputs, wherein: an input is a form of data, object, or action that triggers the function, a control is a process, constraint, policy, or other method that further bounds the system, a mechanism is a method to facilitate the functions actions, and the output is the intended byproduct by which the function produced. The input, control, and output arrows could relate to other function showing an interconnection between top-level functions.

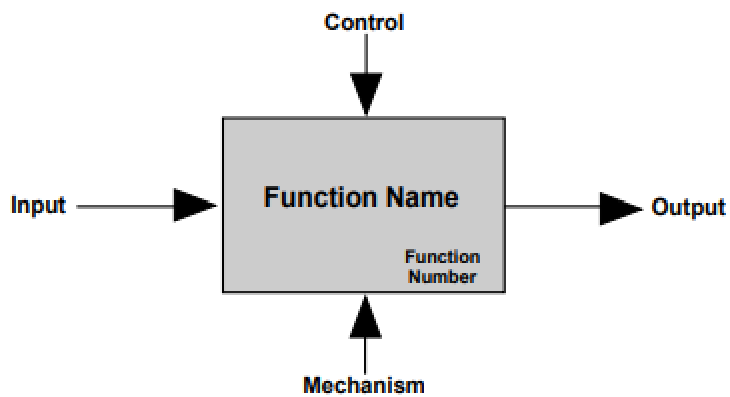


Figure 12. IDEF0 Box Format. Source: DAU (2001, 51).

To further bound the system, we created an IDEF0, as shown in Figure 13. Though the focus of the proposed system was centered on the transportation and delivery function, the IDEF0 shows the interconnection of all the top-level functions the system will be required to perform, along with exchange of information and constraints.

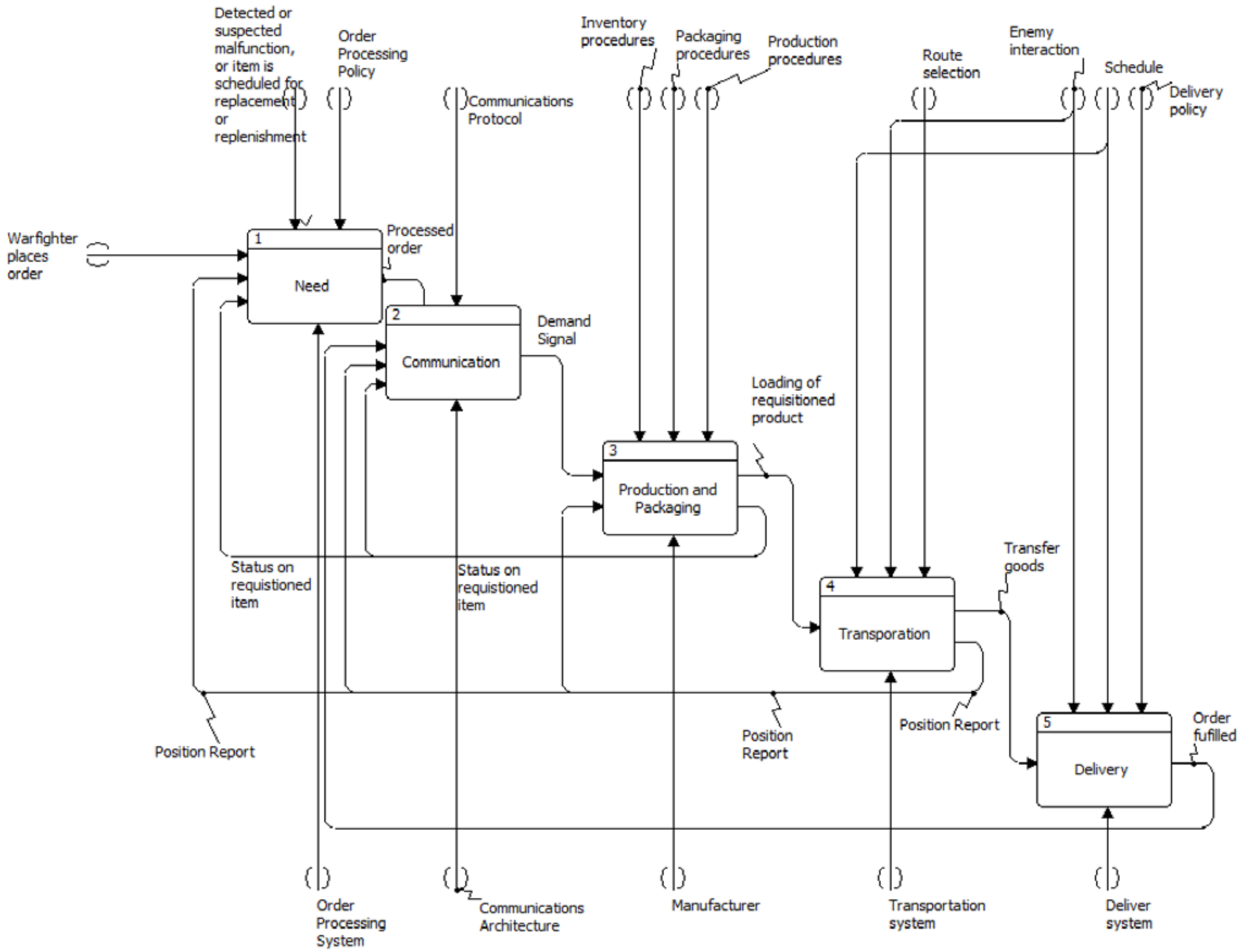


Figure 13. Proposed System IDEF0

3. Functional Decomposition

Decomposing the system level functions further, we decided to use the functions delineated by the *Universal Naval Task List (UNTL)*. The UNTL was developed by Navy, Marine, and Coast Guard leadership as an effort to standardize requirements for planning, executing, and planning joint missions while outlining mission essential tasks (MET) the services must complete (DON, 2007). For logistics, the DON defined 14 METs as shown in Figure 14. Each of the functions is further broken down into numerous subfunctions as well, giving a comprehensive description of the functions a successful logistics system must perform. We chose the following as critical top-level functions the system must accomplish in a contested environment to fulfill COIs 1–3: provide arms, provide fuel, provide transportation services, and supply the force.

NTA 4.0	Perform Logistics & Combat Services Support
4.1	**Provide Arms**
4.2	**Provide Fuel**
4.3	Repair & Maintain Equipment
4.4	Provide Personnel and Personnel Support
4.5	**Provide Transportation Service**
4.6	**Supply Force**
4.7	Perform Civil Military Engineering Support
4.8	Conduct Civil Affairs
4.9	Train Forces & Personnel
4.10	Perform Resource Management
4.11	Provide Operational Legal Advice
4.12	Provide Health Services
4.13	Conduct Recovery and Salvage
4.14	Provide Support Services

Figure 14. UNTL Top-Level Logistics Functions. Adapted from DON (2007b).

The UNTL further decomposes its logistics functions as shown in Figure 15. We agreed that the proposed system will be required to conduct the highlighted sub-functions to be effective for the warfighter.

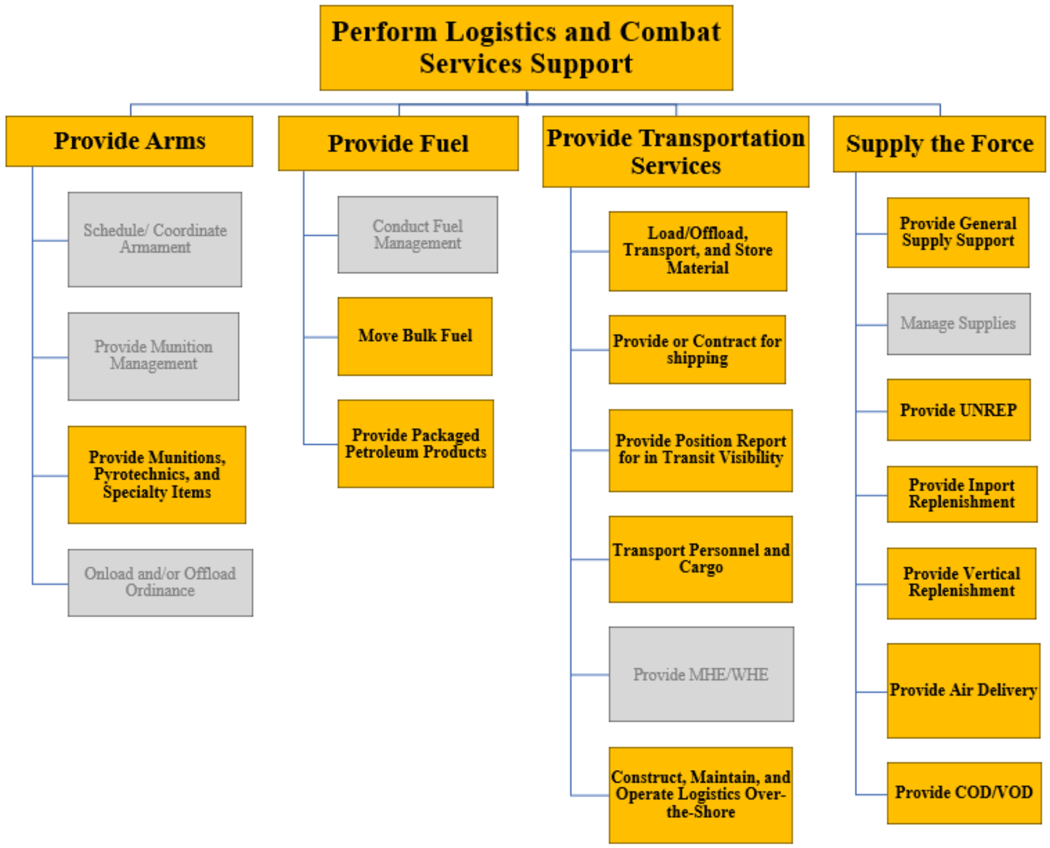


Figure 15. Logistics Sub-Function Hierarchy. Adapted from DON (2007b).

Upon completion of selecting the required functions, we developed a FFBD utilizing a systems architecture software called CORE 9. An FFBD demonstrates traceability from the top-level system functions down to subfunction level, as shown in Figure 16. It is important that all the elements of the SOI are depicted in the FFBD. DAU (2001) emphasizes that an FFBD is functionally oriented and solution neutral. This enables decision makers to remain unbiased regarding a solution—instead, prompting them to focus on what the system must do to fill the gap.

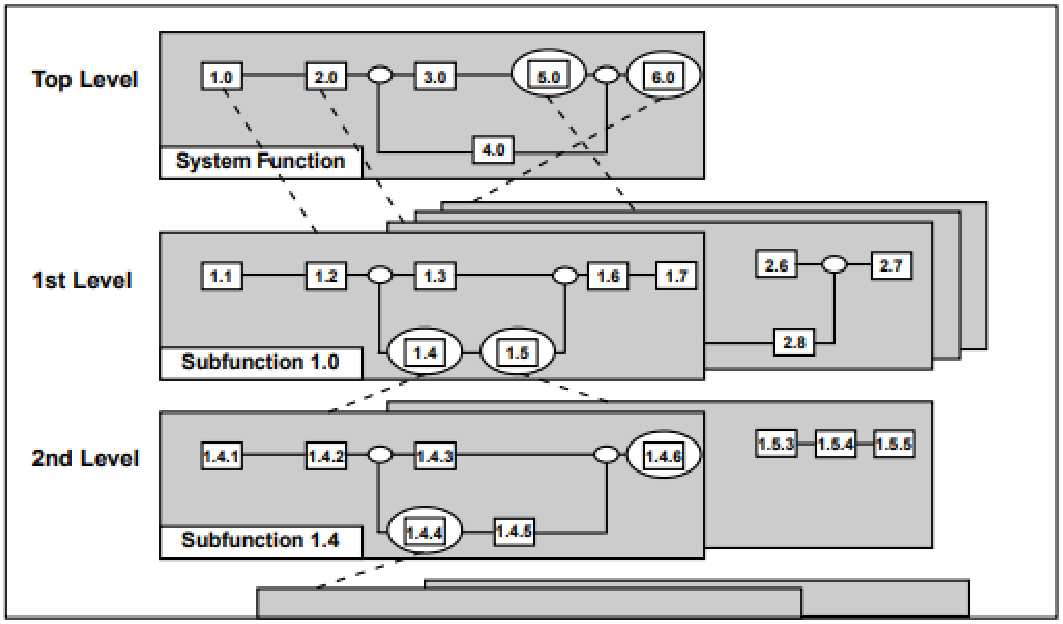


Figure 16. FFBD Traceability and Indenture. Source: DAU (2001, 49).

The complete FFBD for the proposed system is shown in Figure 17 The three parallel branches depict the proposed system and its interaction between the enemy and the warfighter. The proposed functions for the system also have associated COIs, as described in the previous chapter for traceability purposes.

1. Load Goods – (COI 2, COI 4, COI 5): The system must be able to load the required goods to the platform of choice. This could be through autonomous means, cranes, or personnel.

2. Store Material (COI 2, COI 4, COI 5): The system must be able to store the required cargo requested by the warfighter. The storage capacity and structure are important due to the type of cargo the system is required to transport such as fuel, munition, and dry goods. Transporting fuel and munitions carry certain restrictions, policies, and specific safety procedures. Therefore, the system must be able to accommodate these constraints.

3. Transit (COI 1, COI 2, COI 4, COI 5): The system must be able to transit in high seas, exclusive economic zones, and international airspaces. Due

to the scalability of the proposed system, it must be able to transit in different AOs. The purpose of this proposed system is to navigate and deliver goods to the warfighter in a contested environment. The interaction between the proposed system and the enemy is critical. As depicted in Figure 17, the enemy would be able track, locate, and potentially engage the proposed system.

4. Provide Delivery (COI 1, COI 3, COI 4, COI 5): The system must have a deliver method in the littoral and national airspace. The method of delivery could be manned or autonomous and have different domains such as air platform, surface, or sub-surface delivery methods.

5. Transfer required cargo (COI1, COI 3, COI 4, COI 5): Upon delivery, the system must have a method or mechanism to transfer the goods from the platform to the warfighter.

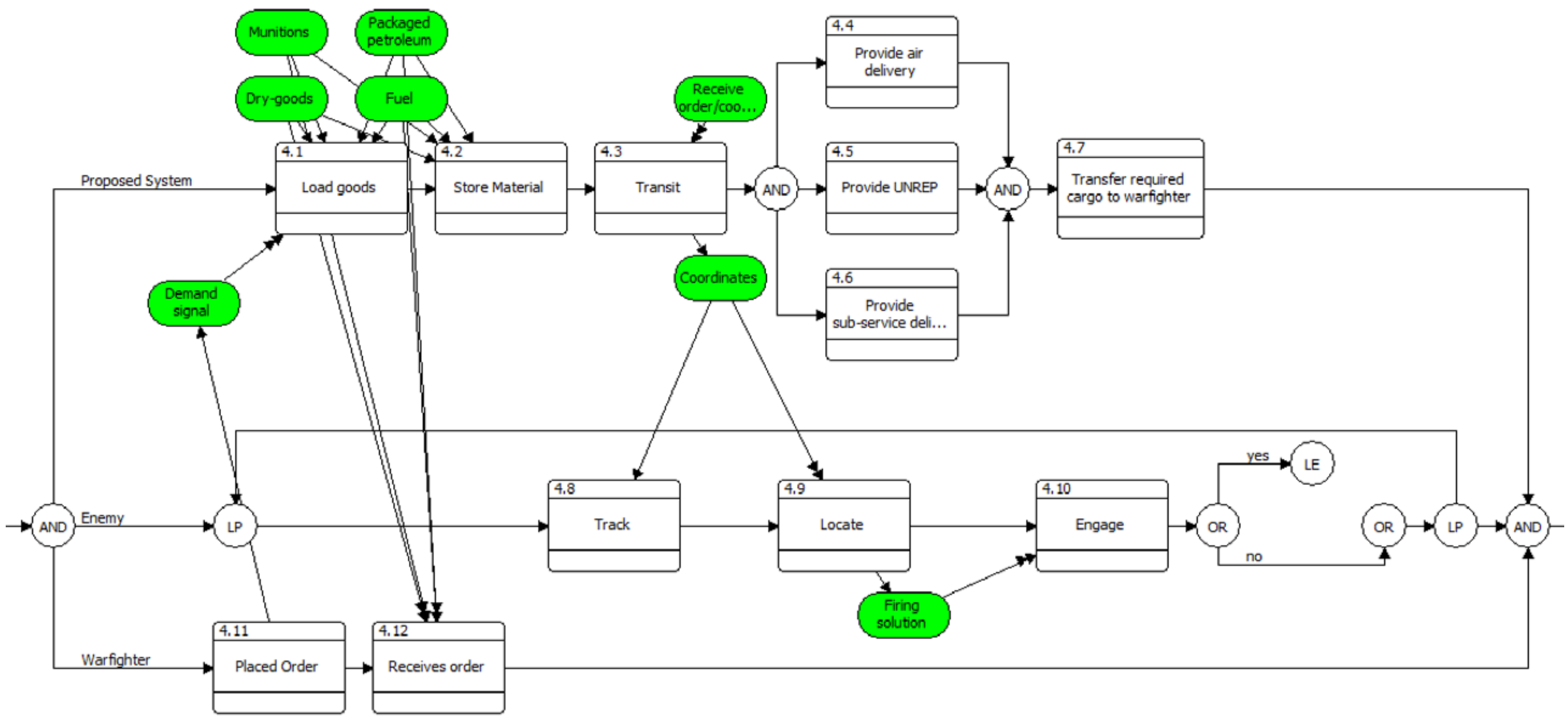


Figure 17. Decomposed FFBD

F. CANDIDATE LOGISTICS ARCHITECTURE ALTERNATIVES

After completing functional analysis, our next step was to translate system functions into form—the part of the SE process where the physical architecture of the system takes shape. We chose several architectures with the potential to accomplish the required system functions based on stakeholder discussion, participation in the 2019 WIC, and our own operational experiences. We analyzed each of the architectures in a process called "Analysis of Alternatives" (AOA). According to DAU (n.d.), an AOA "is initiated to examine potential materiel solutions with the goal of identifying the most promising option." We expected this process to yield insights into the advantages and disadvantages of each architecture so we could narrow our options down to the preferred solution. We also expected that the final solution of this process would likely be a blended solution of two or more potential architectures, which would allow the final architecture to leverage benefits and minimize drawbacks. This section serves to introduce each candidate architectures and our initial insights and assumptions about what they may provide to the solution space. The analysis conducted on the alternative architectures will be covered in a subsequent section of this document.

1. Traditional Logistics

First, as a basis for comparison, we analyzed the traditional logistics concept that the Navy already employs. Based on our operational experience, we know that in this architecture, a very few large, high-capacity, and high-value CLF ships operate inside and outside of contested environments (CE) to supply units in need of supplies, arms, and fuel. The CLF ships conduct underway replenishment (UNREP) with combatant ships and utilize embarked helicopter assets to deliver supplies ashore. Figure 18 illustrates the "Traditional Logistics" architecture—one that appears to be inherently non-distributed, and aggregates risk into a small number of expensive platforms which have no self-defense capability.

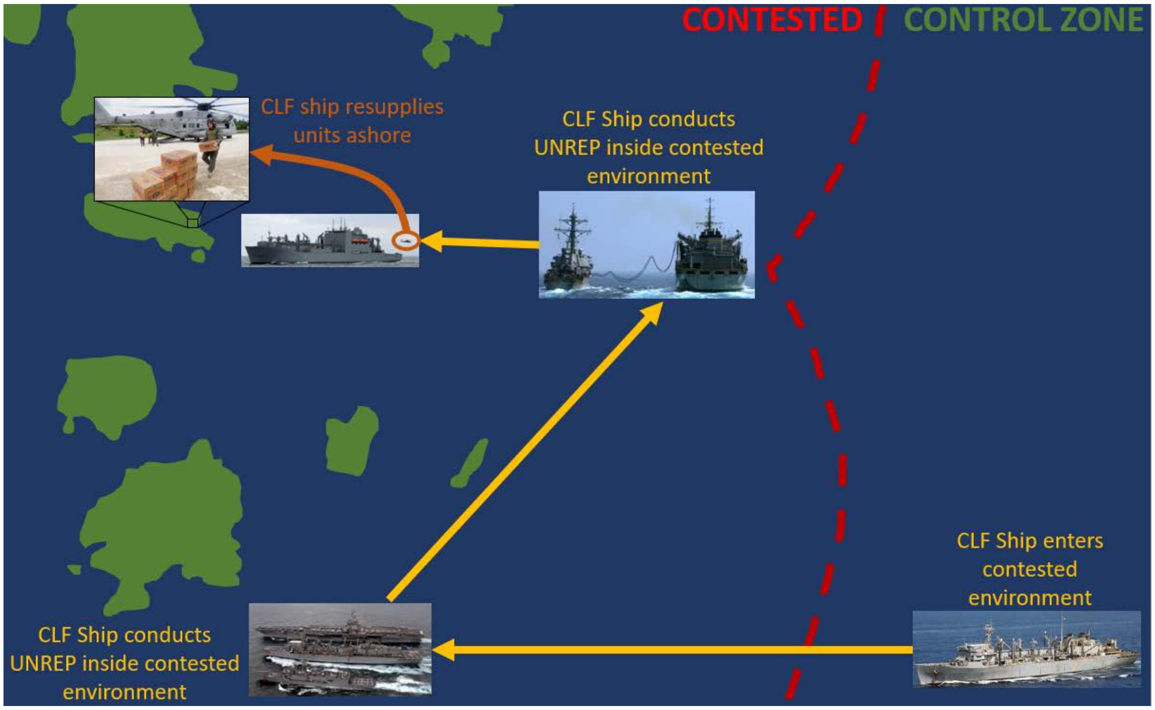


Figure 18. Traditional Logistics Architecture

2. SE Capstone: Expeditionary Logistics System

The next architecture we chose to analyze was one proposed by fellow NPS systems engineering students on the Total Ship Systems Engineering (TSSE) track. Within the 2019 WIC, they developed an Expeditionary Logistics System (ELS) as part of a ship design capstone project and proposed it as a replacement to the current CLF fleet ships. This architecture centers on a "mothership" that remains outside the CE and serves as an intermediate logistics node. The mothership receives bulk supply from large, merchant-size ships that circulate on long-haul shipping routes in the control zone. The mothership then distributes those supplies to the warfighter via an embarked fleet of small delivery platforms. The Total Ships Systems Engineering team named these small delivery vessels "Marine Operations Logistics Assets" (MOLAs). The MOLAs are both surface and subsurface and operate in a distributed manner within the CE (Alexander et al. 2020). Figure 19 illustrates the "ELS" architecture; initial assumptions about this architecture are that it distributes risk within the CE but still has a single point of failure in the mothership.

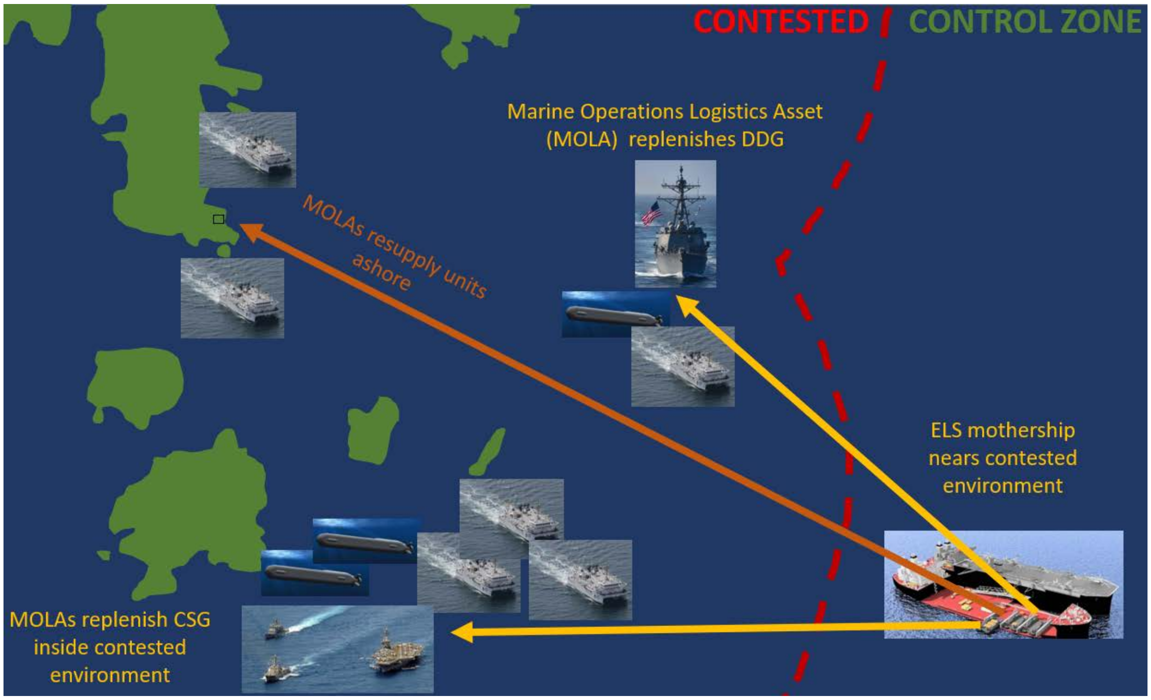


Figure 19. SE Capstone Architecture: Expeditionary Logistics System (ELS)

3. Alternative Use of Current Assets

A third architecture we chose explored the possibility of repurposing current fleet combat assets to serve in a logistics role, wherein repurposed warships would begin by rendezvousing with a CLF ship in the control zone to pick up bulk supply. Then, they would enter the CE in a distributed manner to supply units in need. Specific platforms we envisioned being employed in this architecture were:

- Landing Helicopter Assault Ships (LHA)
- Landing Helicopter Dock Ships (LHD)
- Amphibious Transport Dock Ships (LPD)
- Dock Landing Ships (LSD)
- Littoral Combat Ships (LCS)
- Joint High-Speed Vessels (JHSV)

Figure 20 illustrates the “Alternative Use of Current Assets” architecture, which has the potential for minimal joint contributions with use of joint aircraft and joint landing craft to complete “last tactical mile” deliveries ashore. This architecture appears to distribute risk inside the CE, delivery units have an inherent self-defense capability, and a single point of failure exists in the CLF ship that operates in the control zone. Other important points include that while the repurposed assets fill a supply role, they are less available in a combat capability, and a loss of one of these platforms results in losses to both combat and logistics capacities.

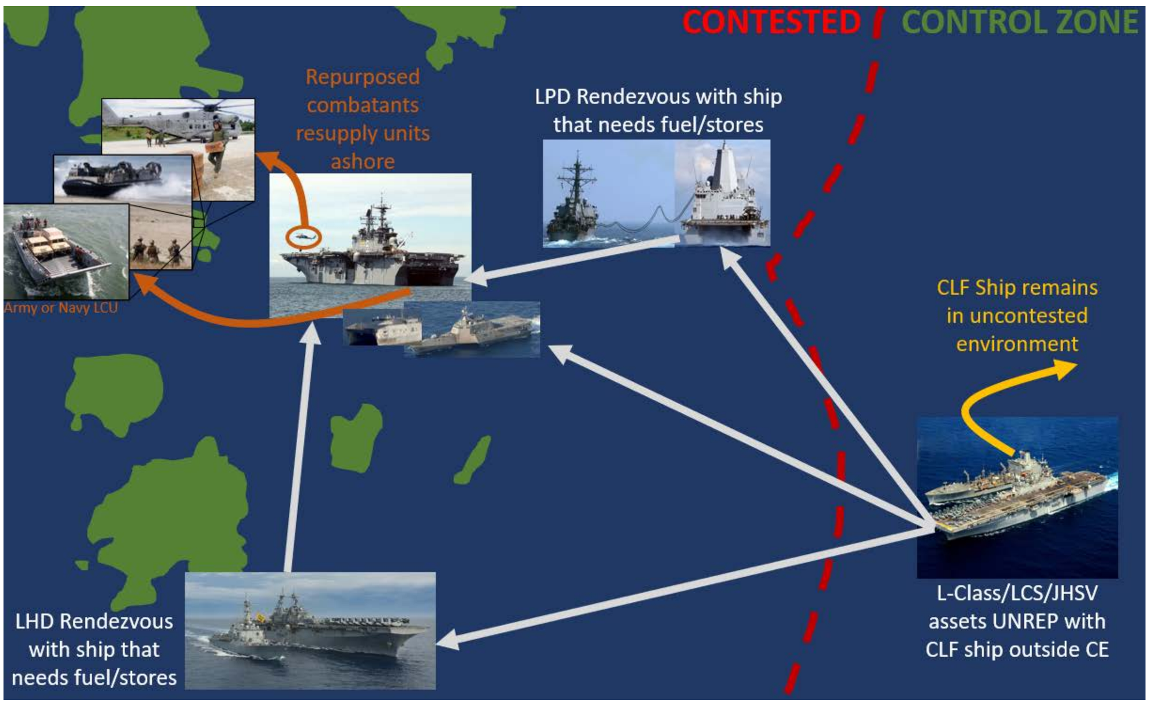


Figure 20. Alternative Use of Current Assets Architecture

4. Sea Train

A fourth architecture we considered was a “Sea Train” architecture, as illustrated in Figure 21, which is a novel concept discussed during the 2019 WIC (Englehorn 2019). A sea train consists of many small barge-like transports, each with their own propulsion capabilities; each that can form a line and physically couple together. During low-risk, long haul routes, the platforms leverage efficiency and speed by streamlining into a composite ship. Then, in the higher risk contested environments, the units disaggregate and utilize their own propulsion capabilities to deliver supplies. Surviving components reaggregate and make the return trip after their deliveries are complete. This architecture appears to be inherently distributed and therefore, eliminates the single point of failure seen in many of the other architectures, as any number of surviving sea train components can reaggregate and return to supply nodes. However, these units have no self-defense capability.

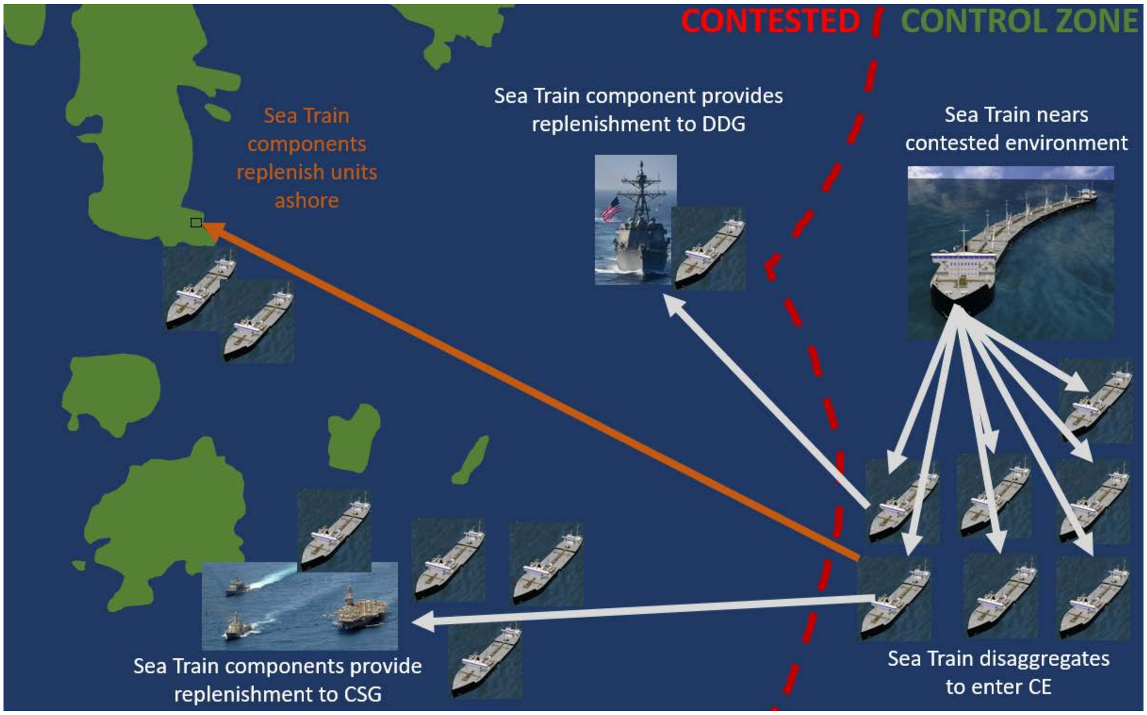


Figure 21. Sea Train Architecture

5. Offshore Support Vessels

Finally, we analyzed an architecture that includes the use of Offshore Support Vessels (OSV), illustrated in Figure 22. These vessels are current-day commercial assets employed in the supply and maintenance of oil platforms, which are readily attainable off-the-shelf and are relatively inexpensive given their capabilities. In this architecture, the OSVs would resupply with a CLF ship outside the CE, then proceed to make deliveries in a distributed fashion inside the CE to units in need. At first glance, this architecture, while distributed, lacks self-defense capabilities, and the CLF ship serves as a single point of failure.

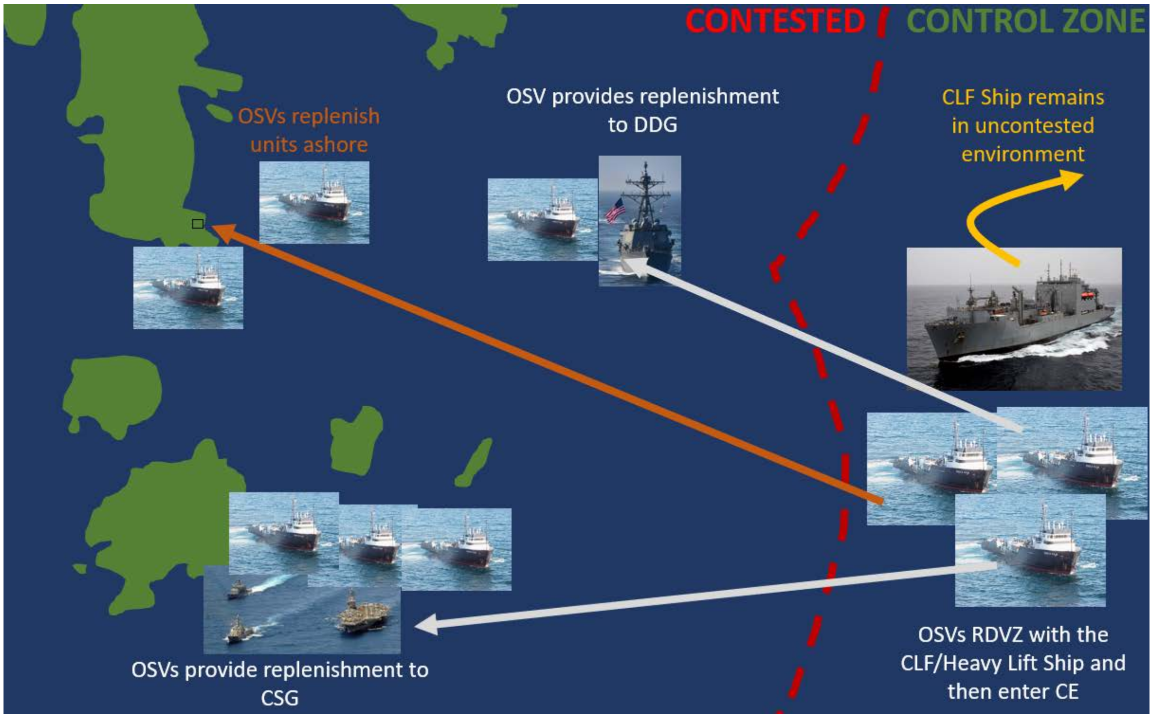


Figure 22. Offshore Support Vessel Architecture

After our initial analysis of the candidate architectures, they were included in our modeling efforts to gain further insights about their respective strengths and weaknesses. The modeling efforts took into consideration aspects of each architecture such as: vulnerability, susceptibility, speed, and capacity. The "Modeling" chapter of this report provides an in-depth discussion of the aforementioned analysis.

III. MODELING APPROACH

A. OVERVIEW

Logistics in a contested environment incorporates many factors, but the key issue is the ability for Blue Force (U.S. and her allies) to deliver supplies to the warfighter, end-users that are inherently located inside a hostile AO. Thus, to assess a delivery assets' ability to penetrate Red Force (China and Russia) threat-layers, a simple campaign model was selected: the circulation model. We developed a circulation model to analyze this problem because its purpose is to demonstrate statistical uncertainty in determining force effectiveness throughout a campaign (ORD 1999, 1a.1). As a result, the output provides a survivability assessment for Blue Force logistics assets engaged in a series of attacks by Red Forces.

In terms of survivability, for a Blue Force asset to be successful or survive a transit, it must avoid detection and/or defend itself from a Red Force attack; to simulate this, the model was broken down into two main parts. The first part is the probability of detection from the Red Force; the second part, is the probability that a Red Force engagement is successful, given a Blue Force is detected. The detection and engagement probabilities ultimately lead to the survivability of Blue Force logistics. The model incorporates many different threat-layers and sub-models, which will be discussed in detail in later chapters, seen in Figure 23. Each threat-layer within the circulation model yields its own probability of survival. We examine threat each layer separately and estimate the survival probability through various sub-models and analysis. This analysis was broken down into two separate efforts, probability of detection and engagement analysis, as shown in Figure 23.

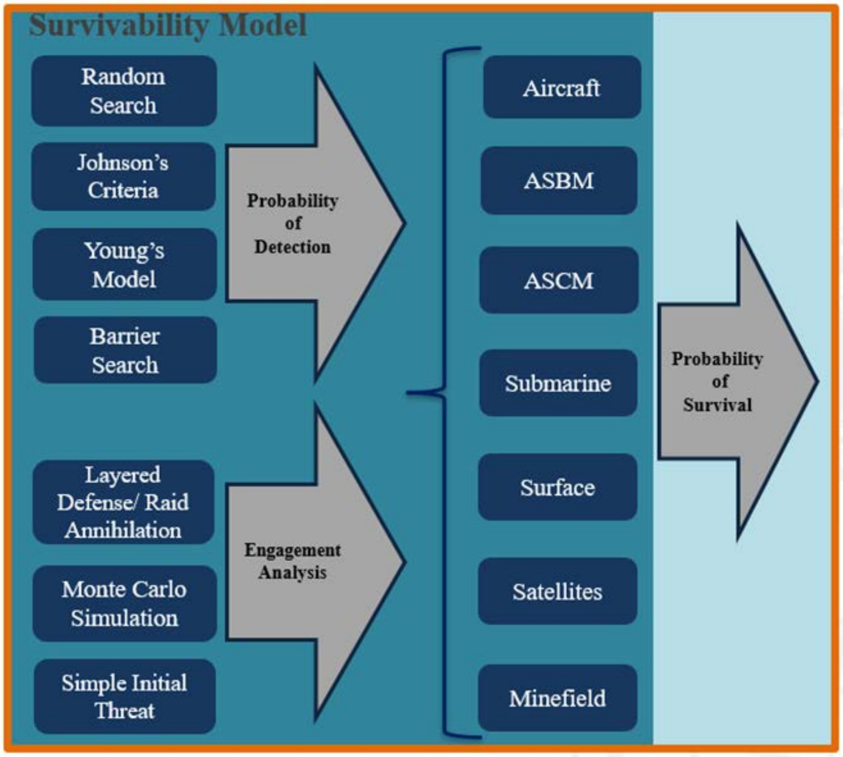


Figure 23. Overview of the Survivability Analysis with Generalized Inputs

Both the efforts behind the probability of detection and engagement analysis, previously described and shown in Figure 23, incorporate several other sub-models for the threat-layer analysis within the circulation model. These separate threat analyses and sub-models provide additional fidelity to quantitative and qualitative assumptions. To enhance the analysis of probability of detection, the additional sub-models employed were:

- random search
- Johnson's criteria
- Young's model
- barrier search

To further enhance the engagement analysis, the following additional sub-models were employed:

- Monte Carlo simulation
- simple initial threat (for mine warfare analysis)
- raid annihilation

These engagement analyses and probabilities of detection tools were applied to each of the threat categories and layers shown on the right side of Figure 23. Each category shown depends on a specific context and input sub-model and is further explained throughout this chapter. The types of threat-layers analyzed fell into these overarching categories:

- aircraft
- ASBMs
- ASCMs
- submarine (torpedoes and ASCMs)
- surface ships
- satellites
- minefields

Our modeling efforts then analyzed each respective threat to determine both the results of the probability of detection analysis and the engagement analysis. The results of both efforts were then aggregated to yield an overall probability of survival against each of the threat-layer categories. These threat-layer probabilities of survival then served as input values in the circulation model, as shown in Figure 24.

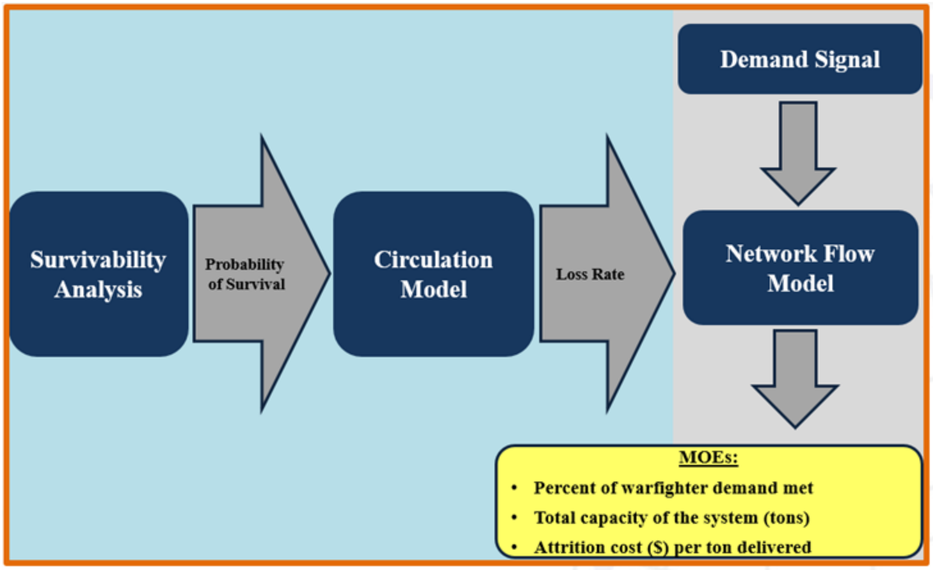
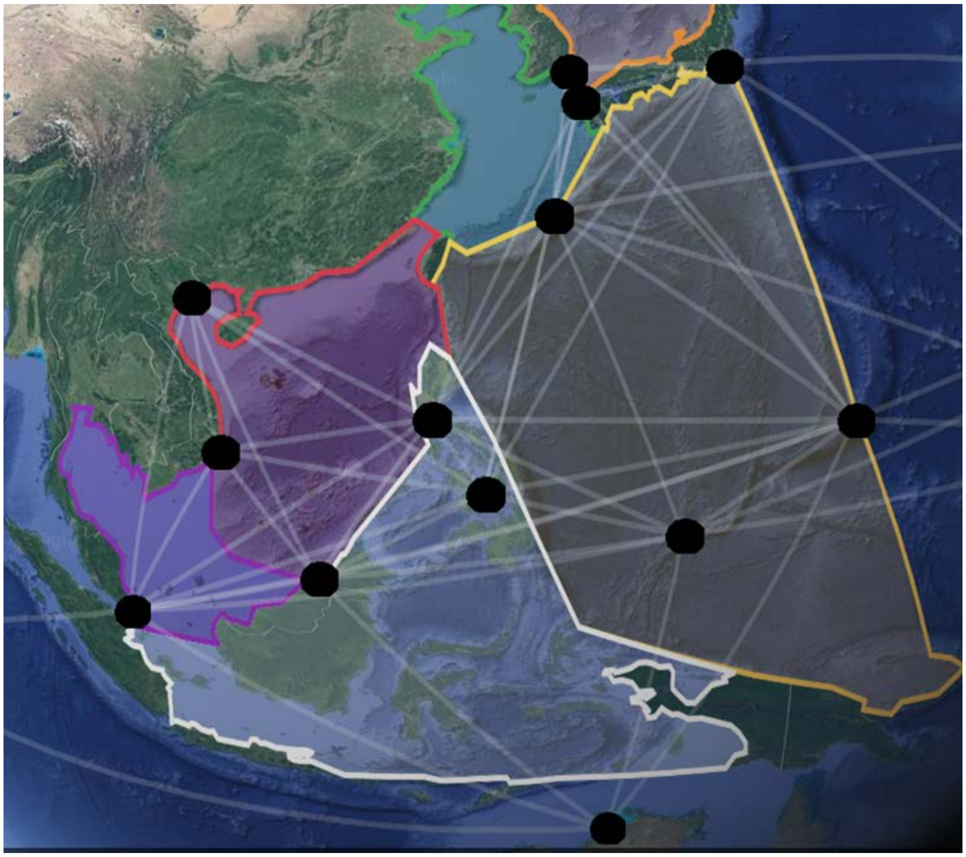


Figure 24. Overview of the Modelling and Simulation Approach Utilized

Together, each layer feeds into the overall loss rate of the specific Blue Force logistics asset being analyzed. The model results also enabled us to address our MOEs and MOPs which provide significant insight into the logistics system architecture and helped determine the susceptibility and vulnerabilities of each modeled asset. This not only provided insight into asset development, but also allowed for risk analysis of a logistics network along specified nodes and arcs.

To allow for risk analysis and mitigation through a contested AO, the outputs of the circulation model fed into a network flow model. The goal of the network flow model was to incorporate the demand signal of the warfighter, the capacity and processing ability of all the key ports within and between an AO, the capability of logistics carriers, and the cumulative suspected threats along a route into a single narrative. These three factors coupled together generated an optimal routing of logistics through a static network and helped in determining the resiliency and robustness of the logistics network by identifying critical hubs in the network arrangement. The results generated an optimized route that looked to mitigate risk and account for the supply and demand signal at each port within a specified network. An example of the static network is shown in Figure 25.



Original map obtained from Google Earth, 2020.

Figure 25. Network of Nodes and Arcs Optimized in the Network Flow Model

The black dots represent the various supply and demand nodes that the logistics assets will be traveling to and from. The white lines are the arcs, or the paths that the assets will travel between the nodes. Together, these nodes and arcs make the static network that was analyzed for results in the form of MOEs and MOPs. The survivability along these routes will inform the specific sensitivity analyses performed to support insights and recommendations to address the challenges of logistics in a contested environment. Combined, the MOEs, MOPs, sensitivity analysis generated from the circulation model, and the results of the network flow model provided tangible results. A list of system requirements and recommendations was then generated for future conflicts to solve logistics in a contested environment.

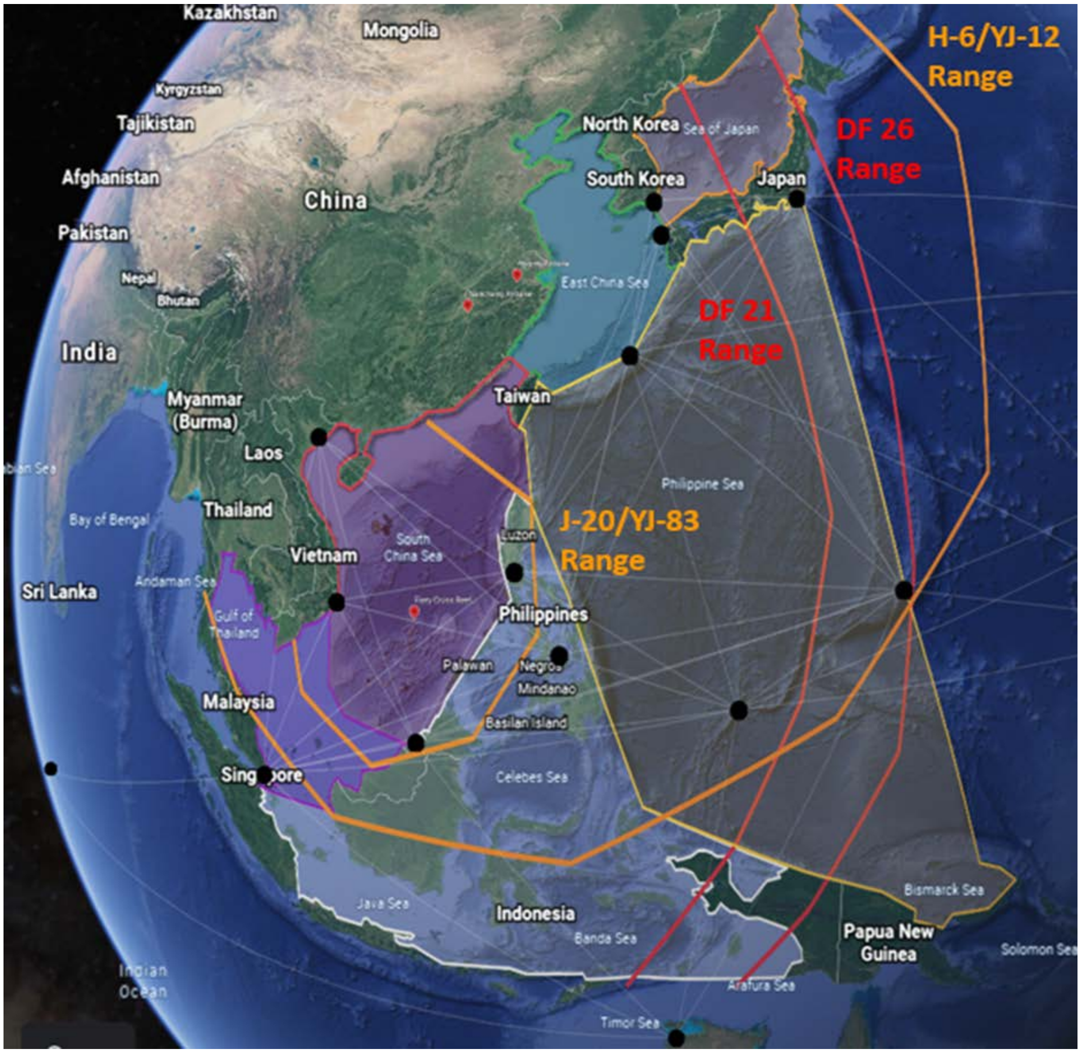
B. ASSUMPTIONS

All assumptions for the analyses previously discussed were purposely conservative in nature, to reflect the worst-case scenario, and are broken down into two categories: route design assumptions and threat assumptions. They are all general assumptions of the model based on People's Republic of China (PRC) and PLAN order of battle (OOB) (detailed in Appendix E) and technology, as well as Blue Force capability and technology:

1. Route Design Assumptions

- Pacific Theater is divided into discrete threat regions.
- Each threat region has an expected number of enemy combatants, organized by platform and operational availability.
- Arc length is based upon the most direct sea lane.
- Routes are determined based on allied nations, current logistics stores, and highly trafficked sea routes.
- Logistics assets will maintain a constant speed of advance along entire route.
- Threat rings are allocated to incorporate the air threat from ASCM, ASBM and aircraft.

The route design assumptions are additionally illustrated in Figure 26. Details on the development of Figure 26 are presented in Appendix D. Shown in this figure, are the assumptions used for the Pacific AO. Some of the nodes and arcs are depicted, as well as the specific breakdown of the various threat regions. Additionally, threat rings for the ASCM (orange half circles) and ASBM (red half-circles) threats are shown and identified on the map.



Original map obtained from Google Earth, 2020.

Figure 26. Visual Representation of the Route Design Assumptions

2. Threat Assumptions

- Threats are separated by class: ASCM (fired from surface ships, submarines, and aircraft), ASBM, mines, and submarines (torpedoes).
- If a Blue Force asset is detected by a Red Force platform, then the hostile asset will engage.
- Each engagement has a distinct range of salvo sizes.
- Minefields are assigned a set probability of occurring on a given route.
- Escorted convoys will counter incoming threats, with some probability of leakage still occurring.
- Logistics carriers have a staying power of one, meaning that if a weapon penetrates defenses this results in a kill.
- Red assets are not pre-alerted and have no information on the logistics route chosen by the Blue Force.

C. INPUT DATA

Specific modeling inputs are shown in Appendix B. The general types of inputs and their components utilized in our modeling efforts are summarized in Table 9.

Table 9. General Overview of Modeling Inputs

Category	***Considerations***
Threat Region	• Area • Enemy Distribution
Route Information	• Distance • Threat Exposure
Background Noise	• Sea State • Frequency of Concern • Civilian Activity (such as merchant and fishing vessels) • Contact Density
Blue Force Platform Characteristics	• Speed • RCS • Physical Size • Noise Level • Cargo Capacity • Salvo Size • Self-defense Capability • Countermeasures (electronic and acoustic) • Aegis (used with RAM, NSSM, SM-2) • Aircraft Defensive Layer • Deception Effectiveness
Red Force Platform Characteristics	• Speed • Armament • Salvo Size • Capability • Quantity • Type (submerged, surface, aircraft) • Over-the-Horizon Radar (OTHR) • Search Type (random, barrier)
Mines	• Mine Presence

D. SURVIVABILITY ANALYSIS

As previously mentioned, the survivability analysis was broken down into two parts: the probability of Blue Force detection and the probability of surviving an engagement given a Blue Force detection by a Red threat. The results ascertained from these analyses combine to estimate the one-way survivability. Since we expect that each logistics carrier will perform multiple deliveries, the one-way survivability feeds the circulation model that determines Blue Force survivability. Both the probability of detection and probability of engagement are broken down into separate analyses. In the following section, each category is explained in detail.

1. Probability of Detection

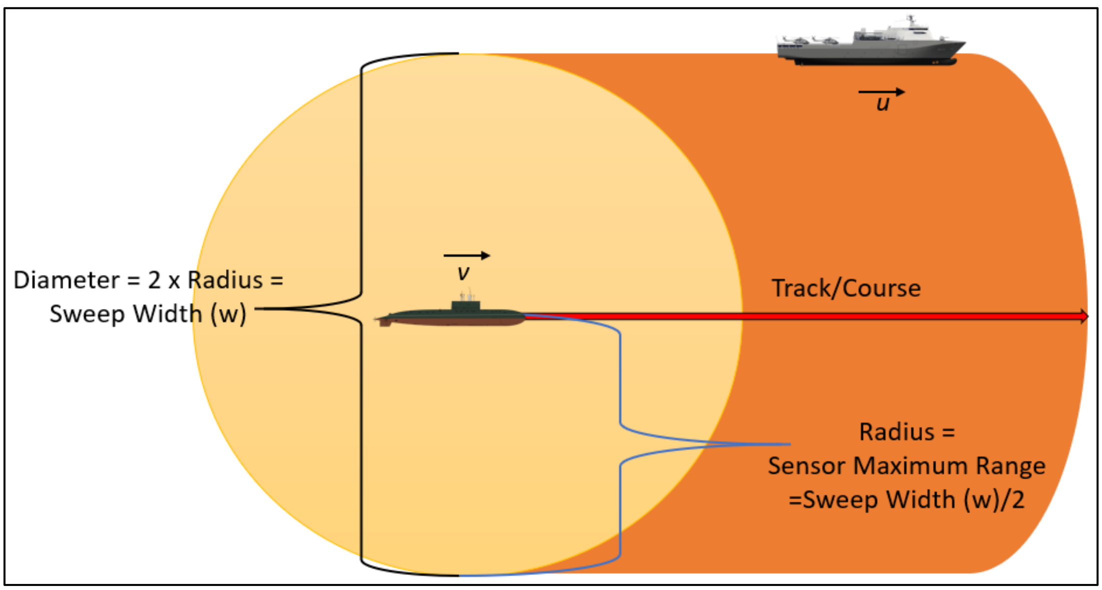
Using unclassified and open-source data, this section analyzes methods that estimated the probability of detection of the Red threat searching for the Blue Force. The following sections demonstrate the adaptations of random search theory that were applied for aircraft, submarine, and surface ship search. To bolster the random search theory and to tailor the equation for each Blue Force asset analyzed, the RCS and sound level were also incorporated into the analysis.

a. Random Search, Barrier Search, and Johnson's Criteria

Random search was selected as the basis for all search theory used in the probability of detection analysis for this model because it established a theoretical search where little information about a target is known in terms of its tactical employment and search plan (Wagner, Mylander, and Sanders 1999). As a result, with the little information that was available to us at the unclassified level, these inherent assumptions enabled us to generate tangible results. Thus, we generated a conservative estimate of the success probability of one asset being able to detect another within a specific coverage factor. The coverage factor, a facet of random search, is the ratio of the area within a sensor sweep width to that of a total search area (Wagner, Mylander, and Sanders 1999). To explain this further, the random search equation is shown in Equation 1,

$$F_d(t) = 1 - e^{\frac{-wvt}{A}}, \tag{1}$$

where $F_d(t)$ is the cumulative detection probability given search time, t is the time the Blue asset is in the search area, w, v, and A are the Red asset sweep width, search speed, and search area respectively (Wagner, Mylander, and Sanders 1999, 192). While there are multiple definitions for sweep width, w, this analysis treats this as the total distance perpendicular to the course of the searcher where a target can be detected. This concept is demonstrated by Figure 27, which shows a Red Force submarine searching for a Blue Force logistics asset.



This figure demonstrates sweep width as used in our model. Shown, a Red Force SSK searches for a Blue Force logistics ship. The orange and yellow regions represent the search area, with the yellow circular area representing the sweep width of the searcher moving along the track indicated by the red arrow.

Figure 27. Sweep Width Demonstration

The coverage factor (CF) for random search can then be represented by the ratio:

$$CF = \frac{wvt}{A}.$$

An understanding of the specific parameters within this relationship can yield better analysis with information. As stated in *Naval Operations Analysis*, "in the case where more is known about a target and a systemic means of searching is used, an equal amount of search effort should yield a higher probability of detection" (Wagner, Mylander, and Sanders 1999, 174). As a result, the specific signatures of the platform being analyzed were incorporated through RCS and sound level, to increase the effectiveness of the analysis against Blue Force logistics assets. In the following subsections, we describe how we apply random search models to enemy aircraft, submarines, and surface ships.

(1) Airborne Search (Radar and Electro-optical)

Aircraft-mounted sensor systems can be used to detect, track, and identify possible targets (Harney 2013). Harney goes on to state that in terms of an aircraft's radar system, pulses of radio signals are emitted and scattered off ships when they are in the path of the emitted energy. The reflected energy is then amplified and processed in the radar system to filter out the required echoes as part of its search and detection process. Likewise, Koretsky, Nicoll and Taylor (2013) note that these electro-optical sensors operate over a range of spectral bands, such as the visible and infrared regions, and provide imaging abilities in day, night, and low light conditions. This probability of detection determination, through random search, was demonstrated through the analysis of using these electro-optical sensors.

Utilizing the information gleaned from the aforementioned sources, it was possible to derive the probability of detecting Blue Force logistics assets using aircraft random search. This discussion is based on the Y-8, a PRC Maritime Patrol Aircraft with a range of 2970 nautical miles (5,500 km) and a maximum velocity of 346 knots (640 km/hr) (Pike 1999). It was assumed to perform a random search at a fixed speed within the area the U.S. logistics platform was transiting. The probability of successful detection was influenced by the size of the search area, the sensor capability of the Chinese Y-8 aircraft, the speed of the Chinese Y-8 aircraft, and the time spent within the search area (Harney 2013). The cumulative probability of detection as a function of time was found using the random search equation (Equation 1).

An example of this application is the scenario analyzed within the first island chain. The search area was bounded by the first island chain and the Chinese landmass with an estimated size of 3,644,000 square nautical miles. The Chinese OOB has a fleet of 60 Y-8 aircraft at an estimated 17% fleet availability given any point in time, equating to ten aircraft per search cycle. The search area of each aircraft was determined by dividing the search area with the number of aircraft, so in this case 3,644,000 nautical miles divided by ten aircraft. The velocity of the U.S. ships was negligible compared to the velocity of the Y-8 aircraft; therefore, the U.S. ships can be considered static and not require the application of relative velocity (Washburn 2014). The velocity of a Y-8 aircraft was estimated to be 295 knots (152 m/s). The time allocated to perform search and detect missions was limited to eight hours, given the risk involved in the open sea and the endurance of the Y-8 aircraft. As such, multiple Y-8 aircraft must be deployed around the clock for surveillance. This was then extended to determine the cumulative probability of detection over the duration of transit by the U.S. logistics platform. However, to determine the sweep width to apply to the random search by Red Force air asset, the RCS was analyzed and converted to a detection range.

(i) Search Sweep Width of Radar Based on RCS

The maximum detection range of aircraft is limited by the horizon and the maximum range of its sensors. The earth’s curvature creates a blind zone beyond the “horizon,” as illustrated in Figure 28.

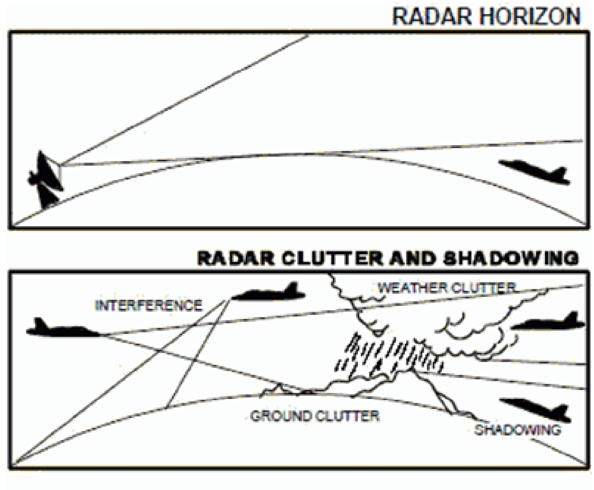


Figure 28. Illustration of Radar Horizon and Other Obscurants. Source: NAWC (1999).

A sensor can only detect a target if the target is above the horizon and if it is within the maximum range of the sensor (Ball 2003). Using Equation 2,

$$R_h(km) = 3.57\left(\sqrt{h_{searcher}(m)} + \sqrt{h_{target}(m)}\right), \quad (2)$$

it is possible to calculate the visual horizon, where 3.57 is a constant to determine the geometric distance to the horizon in kilometers, $h_{searcher}$ and h_{target} are the respective heights of the searcher and target above the surface of the earth in meters (Ball 2003, 479). This is purely for the visual horizon; a different but similar process is used for the electro-magnetic energy of a radar.

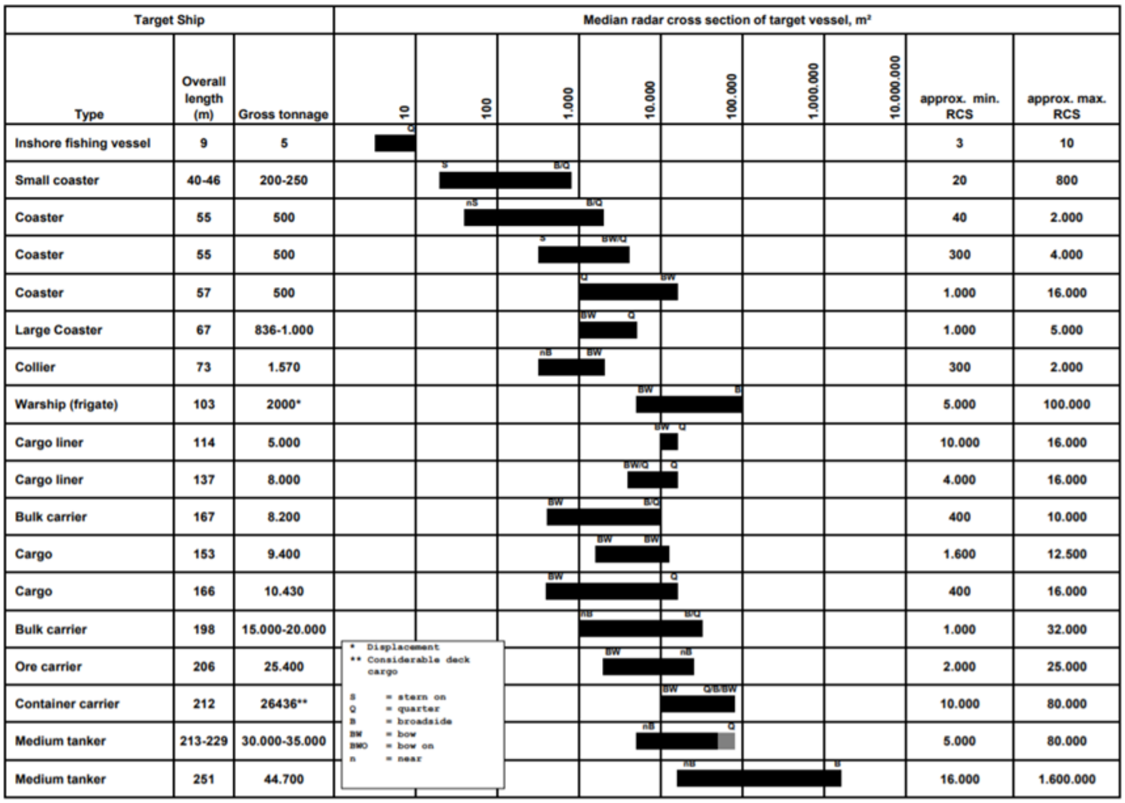
Like the visual horizon, there also exists a radar horizon. Due to their wavelengths, search radar waves bend more around the curvature of the earth due to atmospheric refraction and travel further than electromagnetic rays in the electro-optical (EO) spectrum (Payne 2010). Like the visual horizon, the radar horizon is governed by the height of the search aircraft and the height of the targets, which are U.S. logistics platforms in the context of this study. The radar equation used to estimate the radar horizon is like that used to calculate the visual horizon and can be seen in Equation 3,

$$R_h(km) = 4.12\left(\sqrt{h_{searcher}(m)} + \sqrt{h_{target}(m)}\right), \quad (3)$$

where 4.12 is a constant that accounts for the curvature of the earth and incorporates a conversion factor for meters to kilometers (Ball 2003). This equation is based on the geometry of the earth's curvature and approximations to account for the bending of radar waves. The higher the target or the searcher, the longer the radar horizon.

In considering altitude parameters, maritime patrol aircraft and UAVs typically operate at heights from 5,000 to 30,000 feet based on optimal endurance, sensor capabilities, and weather conditions. Modern sensors and digital processing have improved sensor capabilities, leading to higher-altitude operations that maximize detection horizons and sweep width. For the modelling process, an average search height of 10,000 feet (3,000 m) was used. This altitude is typical of turbofan and turboprop maritime patrol aircraft and unmanned aerial vehicles, balancing best endurance with the range and resolution of radar and electro-optic payloads. As an example, for a target height of 16.4 feet (5 m), this translates to a radar horizon of 126 nautical miles (234 km) and a visual horizon of 109 nautical miles (203 km). The mast heights of the navy ships studied in this project range from 3 to 46 meters in height.

Aside from the radar horizon, the radar cross section (RCS) of the target also affects the detection range. RCS is defined as the area of a platform that intercepts the incoming power from the electromagnetic waves of radar, and when scattered off this area, produces an echo or radar return. RCS relates to the physical size, shape, and construction material of the target. The larger the RCS, the more radar energy is reflected to the search radar. If the radar energy received by the radar is too low, the radar cannot distinguish the target signature from random noise (Payne 2010). We assumed that a modern airborne search radar can positively detect a large RCS target, such as a CLF fleet oiler (T-AO class) at a full radar horizon range. While detailed specifications of maritime radars were not available on open source, several sources support the statement that such large surface vessels can be detected at ranges of up to 400 km (IAI 2017; Kopp 2007). Referencing Figure 29, which shows estimated RCS for various ships, an approximate RCS can be determined for each Blue Force logistics asset. For example, the T-AO oilers are equivalent in size to a medium tanker which range from an RCS of 5,000 to 80,000 square meters. Consequently, we assumed an approximate average RCS size of 30,000 square meters to characterize a CLF oiler. Therefore, if a target has an RCS of 30,000 square meters, the probability of detection is 100% if it comes within the radar horizon of the search aircraft.



Target Ship			Median radar cross section of target vessel, m²	
Type	Overall length (m)	Gross tonnage	approx. min. RCS	approx. max. RCS
Inshore fishing vessel	9	5	3	10
Small coaster	40-46	200-250	20	800
Coaster	55	500	40	2.000
Coaster	55	500	300	4.000
Coaster	57	500	1.000	16.000
Large Coaster	67	836-1.000	1.000	5.000
Collier	73	1.570	300	2.000
Warship (frigate)	103	2000*	5.000	100.000
Cargo liner	114	5.000	10.000	16.000
Cargo liner	137	8.000	4.000	16.000
Bulk carrier	167	8.200	400	10.000
Cargo	153	9.400	1.600	12.500
Cargo	166	10.430	400	16.000
Bulk carrier	198	15.000-20.000	1.000	32.000
Ore carrier	206	25.400	2.000	25.000
Container carrier	212	26436**	10.000	80.000
Medium tanker	213-229	30.000-35.000	5.000	80.000
Medium tanker	251	44.700	16.000	1.600.000

Note: The medium tanker was assumed to be representative of a CLF oiler.

Figure 29. RCS of Various Ships. Source: Williams, Cramp, and Curtis (1978).

If the RCS of the target is smaller than the datum 30,000 m^2 RCS, we assumed that the detection range would decrease. To correct the detection range, we used Equation 4,

$$MaxRange(R) = \left[\frac{P_R G_R^{\,2} \lambda^2 \sigma}{(4\pi)^3 S} \right]^{1/4}, \tag{4}$$

where P_R is the power transmitted by the radar, G_R is the gain of the radar receiver antenna, σ is the RCS of the target, λ is the wavelength of the radar waves S is the minimum signal strength to distinguish a positive radar target from background noise (Ball 2003, 482).

On January 28, 2020 at NPS, Monterey, CA, Christopher Adams, Director of the Center for Survivability and Lethality at the Naval Postgraduate School, gave a lecture titled "Radar Fundamentals." Using notes from his lecture and Equation 4, RCS size and radar detection range are recognized to have a relationship that is based on the fourth power and a new radar detection range can be calculated from the datum radar performance as shown in Equation 5,

$$Radar\ Detection\ Range = \left(\frac{RCS}{RCS_{datum}} \right)^{0.25} \times Radar\ Horizon\ , \tag{5}$$

where RCS_{datum} is 30,000 m^2, RCS is the target RCS if less than 30,000 m^2, and *Radar Horizon* is the value calculated by Equation 2. Critically, this correction would only be made for targets with smaller RCS and not larger RCS targets. As an example, against a smaller vessel with an estimated RCS of 1,000 m^2, the airborne radar detection range drops from 234 km to 100 km for the assumed height values used earlier. However, radar detection is not the only means of aircraft search, there is also electro-optical search.

(ii) Search Sweep Width of electro-optical (EO) Sensor Based on Johnson's Criteria

Johnson's criteria were the governing concept used to determine the detection range of aircraft using electro-optical sensors. In the mid-1950s, John Johnson performed a series of imaging experiments and found a strong correlation between how much details could be observed about the target and the minimum number of line pairs across the target (Harney 2013). Statistically, if two lines (also known as one line pair) across the target could be perceived, then the observer had a 50% probability of detecting the target. His results became known as Johnson's criteria, which stipulate the minimum required resolution, in terms of line pairs (also known as cycles) of image resolution across a target, for specific tasks of object detection, recognition or identification.

Furthermore, Johnson's criteria relate sensor resolution to probability of detection when the sensor sweeps a target. For a sensor with a fixed number of pixels, resolution can be improved by adjusting an aperture to focus on a smaller area. This comes with the negative effect of a smaller sweep with. Therefore, when searching for a large target, an imaging sensor can employ a larger sweep width when compared to a search for a smaller target. For this section of the model, we assumed that EO sensors on search aircraft are staring sensors looking directly below the aircraft. The sensor field of view can expand or contract to adjust the resolution achieved, and is the angular equivalent to sweep with as illustrated in Figure 30.

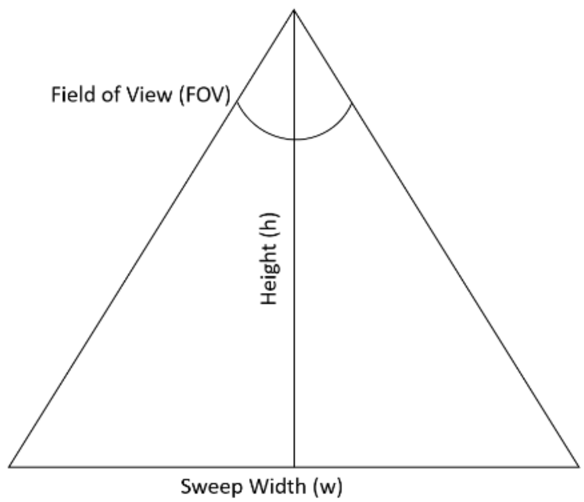


Figure 30. Field of View Directly Corresponds to Sweep Width. Adapted from Payne (2010).

To achieve a 90% probability of detection with an imaging sensor, the resolution must be high enough that the critical dimension is covered by at least two cycles (Harney 2013). The logistic vessel's critical dimension is defined as "the geometric mean of the target's vertical and horizontal dimensions" (Harney 2013, vol 1, 456). This relationship is shown in Equation 6,

$$L_C = \left(L_X L_Y\right)^{1/2}, \tag{6}$$

where *Lc* is the logistics vessel's critical target dimension, L_X is the horizontal dimension, and L_Y is the vertical dimension (Harney 2013, vol 1, 456). If the logistics carrier is an oiler that is 41.75 meters long and 9.25 meters wide, its critical dimension is 19.65 meters. We then define the instantaneous field of view (IFOV) as field of view per pixel in the sensor element. IFOV was calculated via Equation 7,

$$IFOV = \frac{\left(\frac{Critical\,Dimension}{Altitude}\right)}{Number\,of\,Cycles \times 2}. \tag{7}$$

Under Johnson's criteria, two cycles are required for a 90% detection probability as shown in Table 10. When we assume a search altitude of 5,000 meters, substitute the previously derived critical dimension, and substitute two for the number of cycles, the IFOV becomes 0.98 milliradians.

Table 10. Johnson's Criteria. Adapted from Harney (2013, vol. 1, 451–56).

	50% probability	***90% probability***
Detection	1 cycle	2 cycles
Recognition	3 cycle	6 cycles
Identification	6 cycle	12 cycles

A multiplier of 2.0 is used to derive the number of cycles for 90% probability based on the original values from Johnson's experiments, which was for 50% probability.

If we assume the EO sensors are on a search aircraft looking directly below the aircraft, then the range is equivalent to the search aircraft's altitude. Hence, the IFOV of the sensor can be derived from Johnson's criteria, by determining the number of pixels (number of cycles x2). We assumed that the EO imager will utilize a modern camera with 4,000 pixels in each dimension. Field of view (FOV) is dependent on the IFOV and the resolution of the EO sensor, in pixels. With the values of IFOV and sensor resolution, we solved for FOV via Equation 8,

$$FOV = \frac{IFOV \times pixels}{\left(\frac{\pi}{180}\right)1000}, \quad (8)$$

where the denominator, $\left(\frac{\pi}{180}\right)1000$, was used to calculate the FOV in radians (FLIR 2018). We then substituted our example values for IFOV and pixels to yield a FOV equal to 0.23 radians. This result served as an input for Equation 9,

$$Sweep\,Width = 2\,\tan\left(\frac{FOV}{2}\right) \times altitude, \quad (9)$$

to generate a sweep width, as shown in Figure 30, for the Red aerial searchers. Thus, at a search altitude of 5,000 meters, this FOV corresponds to a sweep width of 1132 meters. In this manner, sweep width for searching EO sensors was derived, then applied to random search theory as previously described in other sections to estimate the probability that a logistic asset is detected.

(2) Ship Random Search (ASuW)

Random and barrier searches were both applied to the searching efforts of Red surface assets. A random search was applied for large areas in the AO, whereas a barrier search is applied for chokepoints along a sea-line-of-communication. This following section covers surface ship random search.

For the modelling efforts, Red Force surface assets were assumed to perform random search at a fixed speed within the Blue Force logistic platform transit AO. The probability of successful detection is influenced by the size of the search area, the sensor capability of the Chinese ship, the speed of the U.S. ships, and the time spent within the search area (Harney 2013). Since the relative speed of the searching and evading platforms are similar, the target cannot be assumed to be stationary as it was with the search aircraft. The cumulative probability of detection as a function of time using random and dynamic search theory was found using Equation 10,

$$F_D(t) = 1 - \exp\left(\frac{w\tilde{v}t}{A}\right), \tag{10}$$

where all variables are defined as in Equation 1. However, $\tilde{v}$ in this equation is now the relative velocity between the Red and Blue surface assets (Washburn 2014). The relative velocity was calculated from Equation 11,

$$\tilde{v} \approx \frac{1}{2}\left(\max(u,v) + \sqrt{u^2 + v^2}\right), \tag{11}$$

where u is the speed of the searcher and v is the speed of the target (Washburn 2014).

The maximum detection range of the sensors depends on multiple factors. The first factor was the detection horizon that is governed by the height of the sensor mounted on the Chinese ships and the height of the U.S. ships.

As such, we reapplied Equation 3 to determine the radar horizon and Equation 2 to determine the visual horizon. The nominal radar antenna of naval ships is typically 49 feet (15 m). For a target height of 16 feet (5 m), as an example, this translates to a radar horizon of 13.6 nautical miles (25.2 km) versus a visual horizon of 11.8 nautical miles (21.8 km). In this regard, it can be observed that a radar sensor, under nominal conditions, can be expected to offer a longer detection range than an EO sensor. As such, taking a conservative approach towards subsequent analysis, only the detection capability of radar was considered.

As a datum for surface ship search, we assumed that a modern radar would be able to exploit the full radar horizon range and positively detect a large RCS target, such as a CLF fleet oiler (T-AO class) with an approximate average RCS of 30,000 square meters. Referencing Figure 29, these oilers are equivalent in size to a medium tanker which have an RCS range from 5,000 to 80,000 square meters. Therefore, if a target has an RCS of 30,000 square meters, we assumed that the probability of detect would be 100% if it came within the radar horizon of the Chinese ship. In other words, we assume the radar on a PLAN ship is a generic sensor with a range of 22.2 km.

With different U.S. logistics platforms employed, there were variations to the RCS that would affect the detection capability of the Chinese ship. In general, as RCS decreases, the shorter the range at which detection would occur. Equation 5 was again used to determine the radar detection range.

Finally, once the maximum detection range was established, sweep width was defined as the full left and right lateral limits of the search, equivalent to twice the maximum detection range.

(3) Derivation of Detection Range for Acoustic Search

Like radar search conducted by aircraft and surface ships, acoustic searches exploit energy that is transmitted from waves, however, these waves were derived from sound. This model accounts for passive search, as the use of passive sonar systems is typical for detecting undersea targets and for attack submarines to detect and track threats. For the modelling efforts, the key concern was the detection of Blue logistics platforms by Red submarines. Once detected, Red submarines will close and engage the platforms with torpedoes and cruise missiles. For a logistics ship with no escorts, the probability of kill was high. The role of acoustic detection in the survivability modelling of a Blue logistics ship is illustrated in Figure 31.

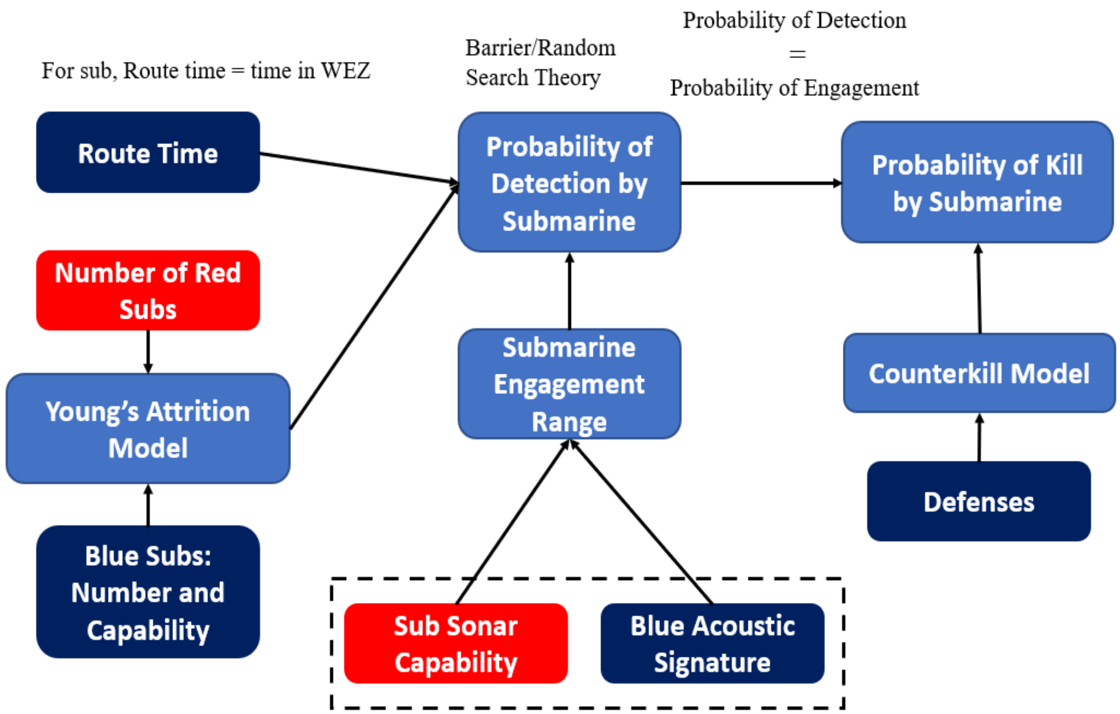


Figure 31. Survivability Modeling against Red Submarines

Passive sonar detection performance can be determined by first determining the carrier-to-noise ratio (CNR). The CNR performance of a passive sonar was used via Equation 12,

$$CNR = SL - TL - (NL - DI), \tag{12}$$

where *SL* is the source level, *TL* is the transmission loss, *NL* is the background noise level and *DI* is the directivity index (Harney 2013, vol 2, 581). This is a logarithmic equation with the terms in decibels. The *SL* depends on the platform of interest. Equation 12 helped in determining the performance of a platform's passive sonar. However, it does not incorporate the detection threshold (DT). According to LCDR Craig M. Payne, USN (Ret.) (2010), the DT is defined as "the signal minus the noise level required inboard of the of the hydrophone array such that an operator can detect a target" (179). In other words, it is the minimum CNR required for detection (Wagner, Mylander, and Sanders 1999). Thus, the CNR equation becomes Equation 13,

$$CNR = SL - TL - (NL - DI) \geq DT \ , \tag{13}$$

which can be found on page 584 of volume two of Harney's (2013) work. This passive sonar equation was used and rearranged to determine a platform's respective detection range, which was then applied to the sweep width for the random search equation.

The first step in determining an equation for the detection range was finding the sound level for each Blue Force asset modeled. Figure 32, Figure 33, and Figure 34 illustrate how the *SL* varies for different submerged and surface platforms.

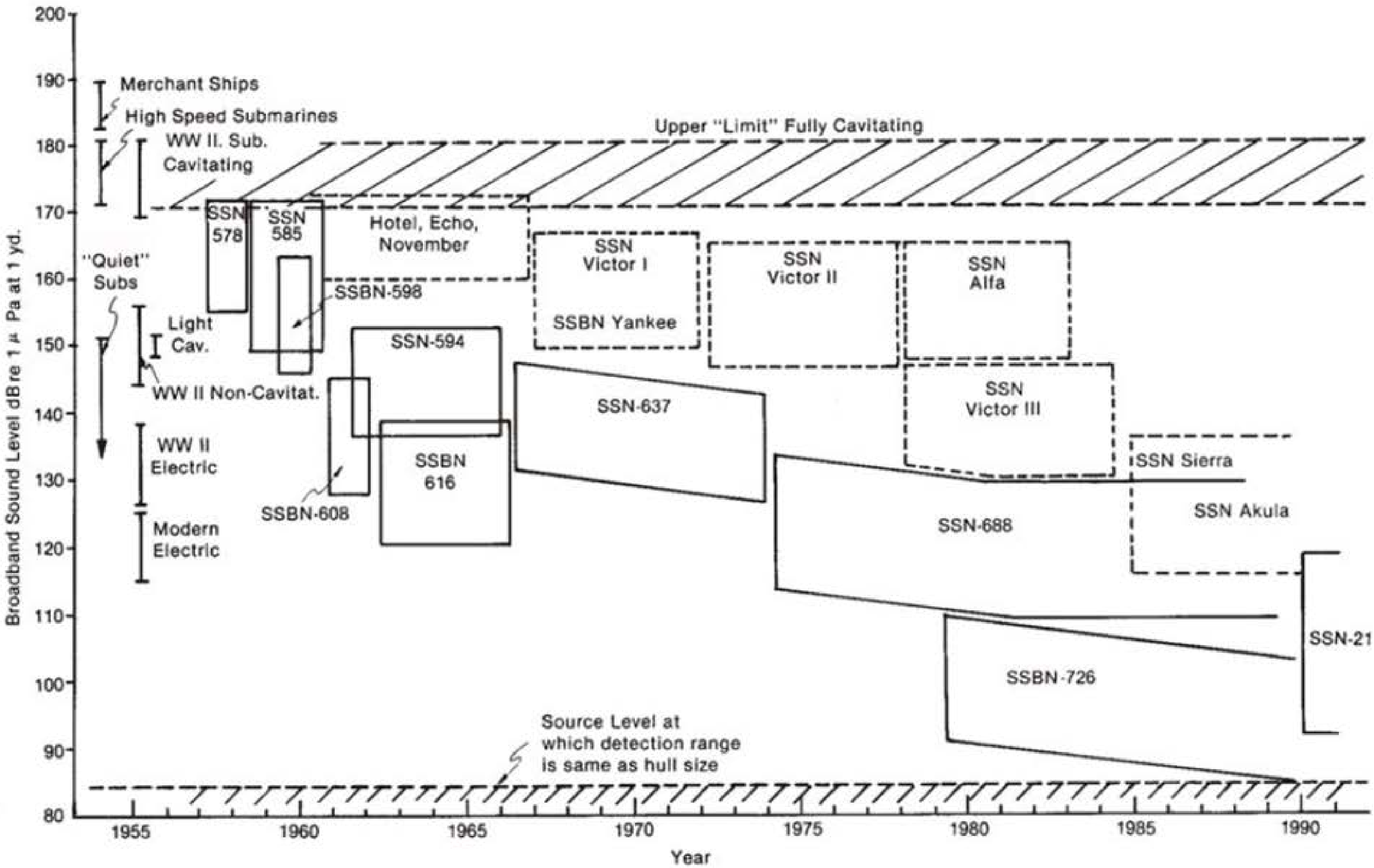


Figure 32. Estimated Broadband Acoustic Source Levels of Submarines. Source: Harney (2013, vol. 2, 585).

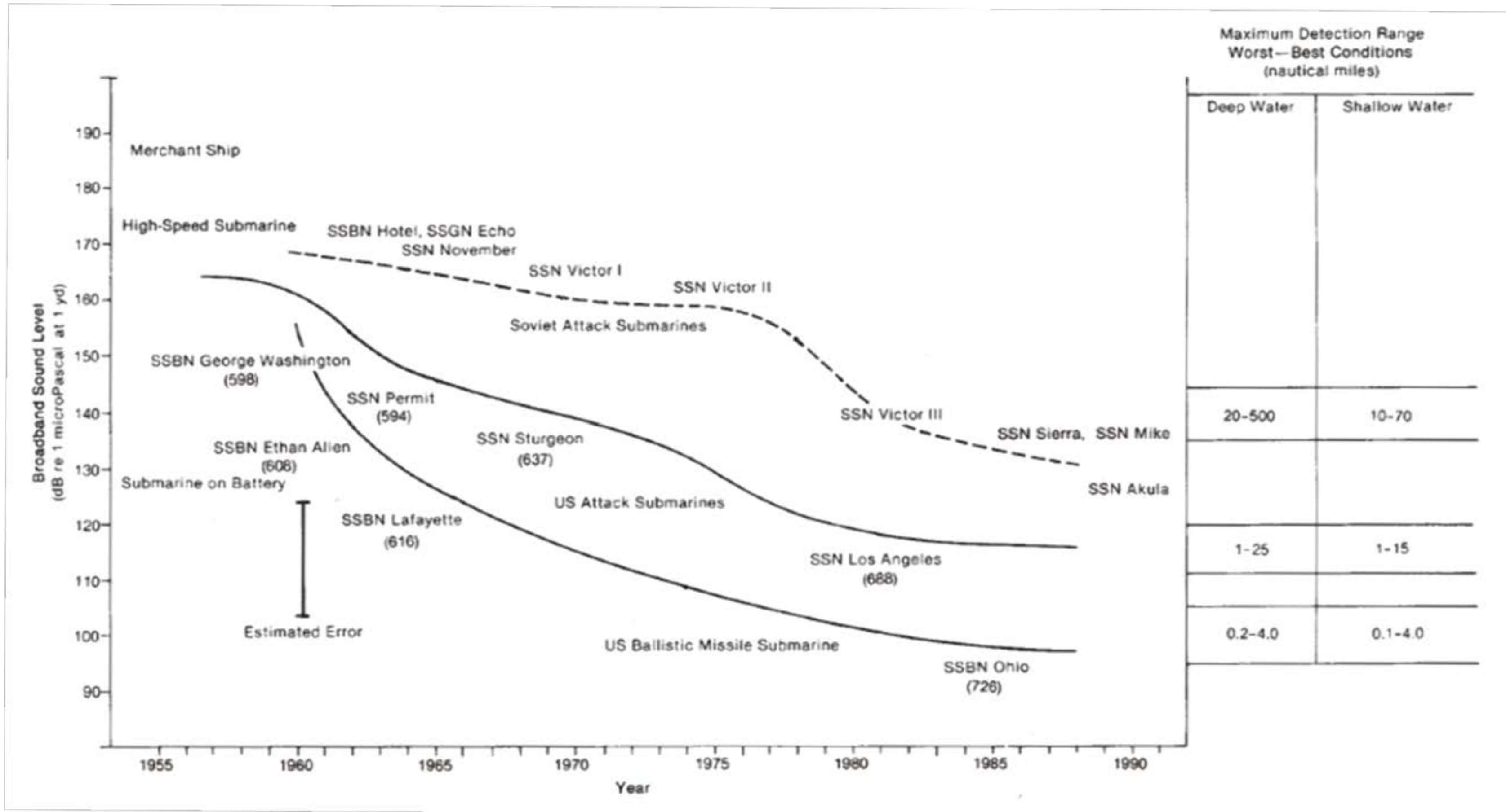


Figure 33. Trends of U.S. and Soviet Submarines Source Levels 1958–1987. Source: Harney (2013, vol. 2, 586).

Frequency (kHz)	Freighter 10 kts	Passenger 15 kts	Battleship 20 kts	Cruiser 20 kts	Destroyer 20 kts	Corvette 15 kts
	Source Levels (dB relative to 1 mPa at 1 yd)					
0.1	152	162	176	169	163	157
0.3	142	152	166	159	153	147
1	131	141	155	148	142	136
3	121	131	145	138	132	126
5	117	127	141	134	128	122
10	111	121	135	128	122	116
25	103	113	127	120	114	108

Figure 34. Typical Source Levels Spectra for Various Surface Ships. Source: Harney (2013, vol. 2, 591).

Using Figure 32 and Figure 33, it was determined that the state-of-the-art, ultra-quiet submarines, generate an *SL* of approximately 100 dB (based on SSN-21 class), while legacy merchant ships can have an *SL* as high as 180 dB. The detection range of the former is as low as 0.1 nautical miles for current passive sonar technology. For the latter, detection is as far as 500 nautical miles. However, these are just example values for the dB sound levels used. Each Blue Force logistics platform had an estimated source level determined from Figure 32, Figure 33, and Figure 34. The next factor determined was the transmission loss.

Transmission loss was a necessary value to account for, given that as sound waves travel through the ocean, a signal gets delayed, distorted, and weakened (Payne 2010). To find the transmission loss from a modeled Blue Force logistics asset, we used Equation 14,

$$TL = 20 \log R + \alpha(0.001R), \tag{14}$$

where R is the detection range (in meters), and α is the attenuation coefficient (Harney 2013, vol 2, 595). Taking this, Equation 13 was manipulated to find a detection range, which in turn was applied for a sensor's sweep width. Part of this process also required finding the attenuation coefficient of the sound waves through seawater. Figure 35 illustrates how α varies for different environments and sound frequencies. A nominal value of 0.03 was determined based off the 50–60 hertz assumption. However, because this factor is so low, for simplicity, we assumed a value of zero. This range was selected because it is the commonly used alternating current electrical bus frequency, including on civilian merchant vessels. This logic also applies to our determination of noise level.

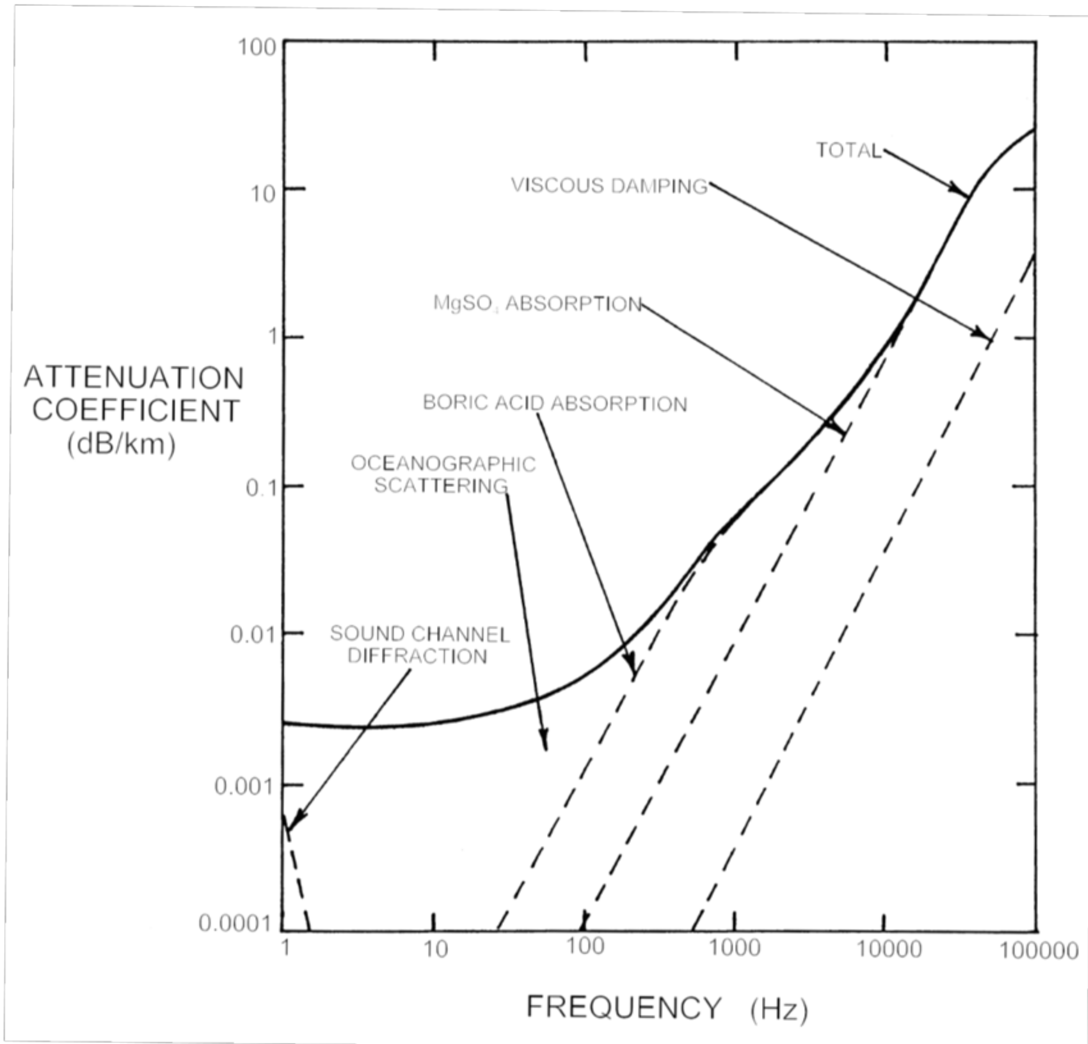


Figure 35. Acoustic Attenuation of Sea Water. Source: Harney (2013, vol. 1, 229).

The next part of Equation 13 determined was the background noise level, which is the total contribution of noise from both ambient and vessel traffic in an area (Payne 2010). By estimating or assuming information regarding the different threat regions from Figure

26, different background noises were determined based on sea-state, depth, and civilian traffic density, allowing for the development of an expected *NL* for each.

To account for the level of civilian traffic density (such as fishing vessels, merchants, passenger vessels, and tugs; see Figure 37 for full list of vessels) in the Pacific AO, we utilized data collected from the Automated Identification System (AIS) at 1530 Pacific Daylight Time on April 26, 2020 to serve as a point estimator for traffic density in the region. AIS is utilized on civilian craft to aid in vessel tracking and safety of navigation. It displays a wealth of information about each vessel including name, current location, heading, course, speed, origin, destination, and other data. Figure 36, with its associated legend in Figure 37, demonstrates the high level of traffic that was accounted for in determining the background noise from traffic.

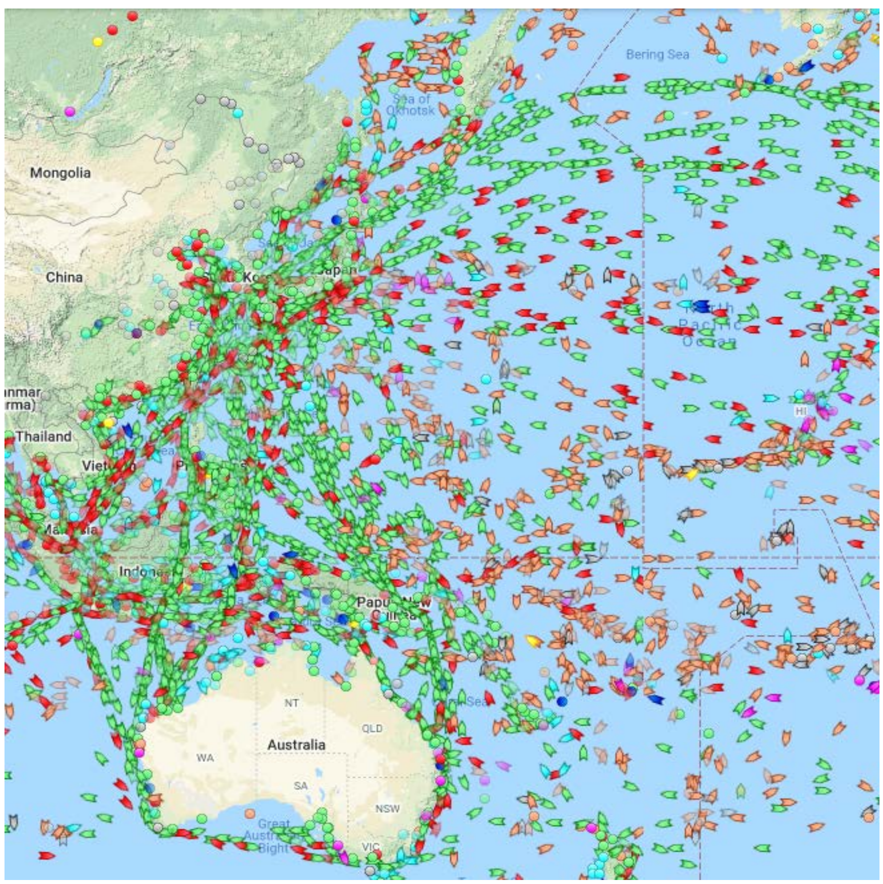


Figure 36. Typical Traffic Density of the Pacific AO. Source: MarineTraffic (n.d.).

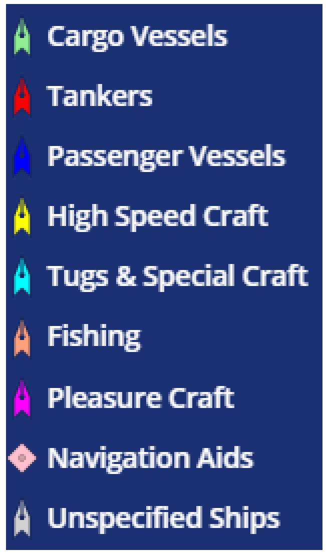


Figure 37. Legend for Figure 36. Source: MarineTraffic (n.d.).

In addition to vessel traffic, we also estimated the average depth of water for the various routes in the AO. We assumed shallow water and coastal depths within the first and second island chain and then deeper water for routes between the second island chain and Hawaii. These water depth assumptions were made after consulting the depth chart provided by *Encyclopædia Britannica*'s (2017) online encyclopedia, shown in Figure 38.

Figure 38. Depth Contours of the South China Sea, East China Sea, and Western Pacific Ocean. Source: *Encyclopædia Britannica* (2017).

Combining these factors and our understanding that most of the world's merchant and fishing traffic emits a general broadband noise level between 50 and 60 hertz, Wenz' acoustic curve, Figure 39, was used to determine an estimated background *NL*.

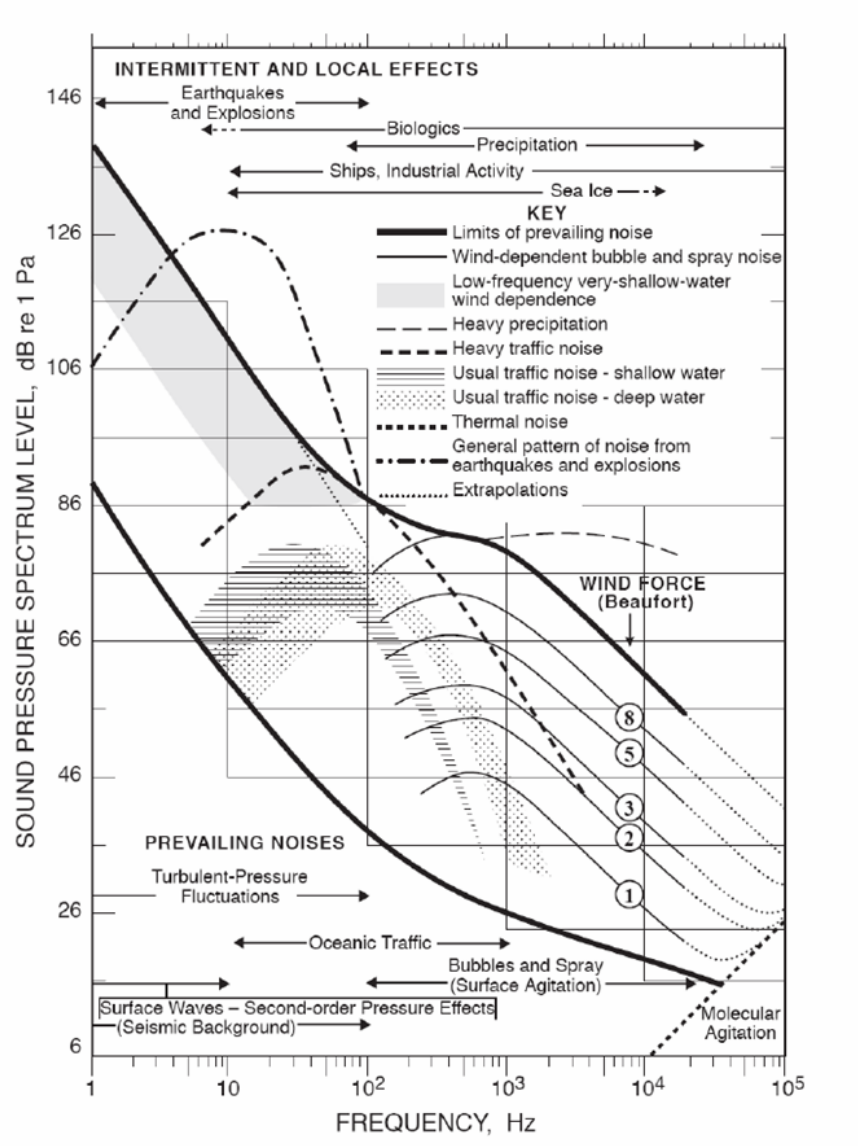


Figure 39. Wenz Curves for Acoustic Ambient Noise in the Ocean.
Source: Wenz (1962).

To simplify the modelling efforts for routes across multiple threat regions with differing depths and traffic densities, an average sound level of 81 dB was used for all Western Pacific routes.

The DI was the other factor that was directly subtracted from this NL determination. For simplicity of calculating the range from source level, the DI was assumed to be zero, as the sound propagating away from the source was omnidirectional, and the characteristics of the enemy sonar array are unknown (Payne 2010).

The detection threshold was the last value included in the CNR equation, where the CNR that is required for detection of a target platform. This value is largely affected by the technical ability of the sonar suite employed. Thus, a value can be as low as -6 dB or as high as -15 dB depending on the type of signal processing (Wagner, Mylander, and Sanders, 1999). Because unclassified data on Red Force equipment capability is not available, the average of the two values was used and calculated as -10.5 dB. This was then substituted into the CNR equation along with the rest of the determined variables.

Taking these variables into consideration, Equation 13,

$$CNR = SL - TL - (NL - DI) \geq DT \ ,$$

becomes

$$SL - TL - \left(NL - DI\right) \geq DT \ .$$

We then substituted all the variables described to yield

$$SL - 20\log\left(R\right) - 81dB = -10.5dB \, .$$

This was then rearranged to yield

$$R = 10\left(\frac{10.5dB + 81dB + SL}{20}\right),$$

which determined the maximum range that a Blue asset can be acoustically detected, given its sound level. This calculated detection range was then used to calculate the sweep width of the searching Red Force assets, where sweep width was defined as the full left and right lateral limits of the search, equivalent to twice the maximum detection range. This was a conservative assumption applied for each Blue Force asset.

(4) Derivation of Probability of Detection by Hostile Submarines

The probability of detection for submerged threats was derived from the random search equation, using the ranges for sweep width from the *CNR* equation previously discussed. For this model, Red Force submarines, including both SSNs, SSBN (converted to guided missiles) and SSKs were assumed to perform a random search at a fixed speed within a pre-defined threat region (where U.S. supply platforms are expected to transit). This assumed that Red assets were not pre-alerted and had no information on the chosen logistics route. The probability of successful detection was influenced by the size of the search area, the sensor capability of the Chinese submarines, the speed of the Chinese submarines, and the time spent within the search area (Harney, 2013). The cumulative probability of detection as a function of time using a random search was derived from Equations 10 and 11.

These equations gave the probability that one enemy searcher will detect a transiting friendly asset. To calculate the total probability of detection of many different assets searching, we used Equation 15 from Wagner, Mylander, and Sanders (1999, 134),

$$F_D, tot = 1 - \prod_{1}^{n} \left(1 - F_{D_n}\right) . \tag{15}$$

Equation 15 was selected because it was assumed that the glimpses performed by each searching Red Force asset were statistically independent of one another. To further understand this equation, each of the individual parts are broken down in the following paragraphs.

The first part of Equation 15 shows the probability of detecting on a single glimpse D or F_{D_n}. Therefore, to get the probability of *not* detecting on any number (n) glimpses, we subtract F_{D_n} from one,

$$\left(1 - F_{D_n}\right).$$

Taking this into account, we get the probability that all glimpses fail to detect as

$$\prod_{1}^{n}\left(1-F_{D_n}\right),$$

where each layer is multiplied against the other. Thus, Equation 15, came from taking this probability of not detecting during *n* independent glimpses *D* and subtracting that from one. Combining Equation 1 and Equation 15 yields Equation 16:

$$F_D, tot = 1 - e^{-n\left(\frac{wvt}{A}\right)}. \quad (16)$$

Equation 15 and Equation 16 are equivalent and demonstrate the process used for the cumulative probability of detection for the independent assets of Red Forces searching for Blue Force logistics assets. The results from these equations were then taken and placed into the analysis of the differing threat regions.

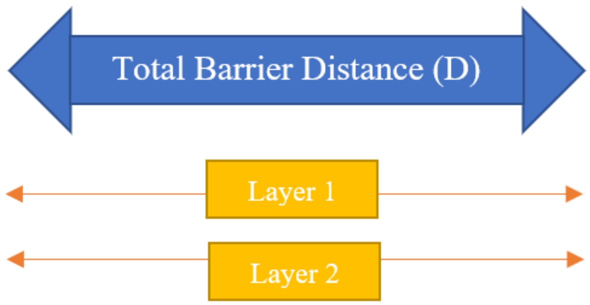
The Pacific AO was divided into different threat regions, each serving as its own respective threat area as shown in Figure 26. Inside each threat area, was an assumed allocation of differing PLAN or Red Force distribution of platforms (air, subsurface, and surface) searching this area for Blue Force assets, as detailed in Appendix D and Appendix E. This area was then used as a factor to estimate the number of enemy submarines within a set distance from the Blue Force's transit. This was done to avoid using an inflated number of searchers in the vicinity of the logistics vessel's track. Accounting for *A* as the total area of the threat region and A_t as the track area, we determined the total probability of detection can be found via Equation 17, which we developed:

$$F_D = \frac{A}{A_t} F_D tot. \quad (17)$$

Generalizing enemy tactics, we also assumed a chance of barriers placed at strategic chokepoints within operating distances from hostile homeports. Using the equation of independent layered barriers, which was the strategy assumed for hostile forces, we arrived at Equation 18 for probability of detection by independent layered hostile barriers (Wagner, Mylander, and Sanders, pg. 223):

$$F_D = \frac{W}{D}\sqrt{1+\left(\frac{v}{u}\right)^2}\,, \tag{18}$$

where W acts as the sweep-width of a hostile searcher, D is the length of the barrier, v is the search speed of the hostile searcher, and u is the speed of the friendly logistics asset (Wagner, Mylander, and Sanders 1999, 223). This concept is also shown in Figure 40.



This shows the general approach to a linear barrier, with multiple layers. There is a total length that needs to be covered, and thus there should be more than one asset covering this layer.

Figure 40. Independent Layered Barriers

Figure 40 demonstrates the multiple layers that different searching assets perform as a general surveillance of an area. The large blue arrow demonstrates the area that needs to be covered, with the smaller orange arrows showing the independent layers. Figure 41 demonstrates the movement of the assets relative to one another, with the geographic track of the Red Force asset (v) searching for a Blue Force logistics target (u) attempting to pass the barrier.

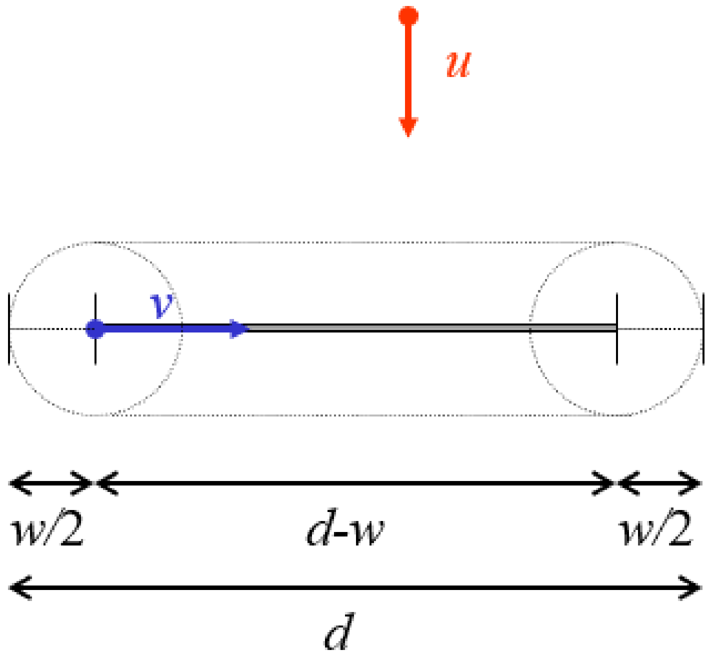


Figure 41. Generic View of Both the Target (*u*) and Searcher (*v*) Moving Relative to the Earth. Source: Jeffrey Kline, class notes (2019).

From this perspective, the linear patroller is moving left and right along its line, or fixed search length, reversing course once it reaches the end. Additionally, this Figure 41 shows the target, or Blue Force, moving from the top to the bottom of the area, trying to cross the barrier. The cone around the Red Force asset is the searching platform's sweep width. These two figures provide the basis for Equation 18, which gives the barrier patrol formula for each layer.

Assuming each layer is probabilistically independent, if every layer fails to detect the incoming asset, the Blue Force remains undetected. Thus, the overall detection of the asset is $F_{D,tot}$ which is equivalent to one minus the probability of every layer failing to detect, which can be shown as,

$$F_D, tot = 1 - \left[(1 - F_{D1})(1 - F_{D2}) \ldots (1 - F_{Dn}) \right].$$

This is equivalent to Equation 15 for the probability of detecting during several independent glimpses. However, because each layer is assumed to be equivalent for the case of barrier search, this overall equation was simplified to Equation 19,

$$F_{D,tot} = 1 - \left(1 - F_D\right)^n . \tag{19}$$

Lastly, it is unreasonable to assume that in either the random search or barrier case, that an enemy force will allocate all their resources to finding either a Blue Force logistics asset or convoy. Additionally, it is unreasonable to assume that there will be no deployed Blue Force combatants sanitizing the area beforehand. To account for this problem and make the probability of detection more effective, Henry Young's model was applied to help estimate the number of active searchers in each search area.

b. Young's Model

Henry Young's model was applied for the submarine campaign of this model both to provide fidelity on the force size of each asset, and because one of the goals of this submarine campaign is to reduce the enemy submarine force to a desired low level. The U.S. maritime strategy is one of early and heavy attrition of a large fraction of the enemy submarine force. Young's model is an application of the Lanchester attrition model, as it applies the concepts of linear law (Young 1985).

The Lanchester Model was developed by Fredrick William Lanchester in 1914 to estimate the attrition rate based on relative force strengths and combat capabilities (Harney 2013). This model is a time-stepped analysis that incorporates a force-on-force interaction with losses on both sides due to an engagement rate (ORD 1999). This engagement rate is proportional to the product of enemy and Blue Force submarines. The output suggests a realistic number of adversary submarines that could be encountered along a route. In this case study, an estimate was needed of the force size of Red Force submarines available to attrite Blue Force logistics assets.

To derive the submarine attrition rates of both sides, a random search of the area, or a general sweep, was applied as shown in Figure 42.

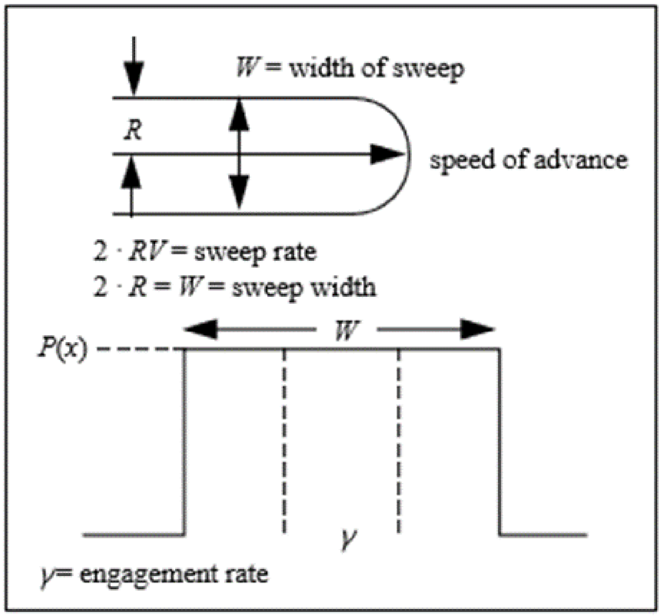


Figure 42. General Sweep Model Applied for Young's Model. Source: ORD (1999, 3a.5).

In this defined area, all submarines had an equal probability of encountering one another. The smaller the number of submarines in an ocean theatre, the smaller the number of engagements that could occur. As the campaign unfolded and submarines were destroyed on both sides, the numbers continued to fall. The exchange ratio, which is the expected number of enemy submarines destroyed per Blue SSN lost in a single engagement, was set to five to account for the superiority of U.S. submarines. The theory behind this concept is explained in the following Lanchester description.

For the change in Blue logistics platforms over time (time rate of change, or the derivative) given several Red Force assets we adapted material from a class taught by NPS Professor Jeffrey Kline (2019) to yield Equation 20,

$$\frac{dB}{dt} = \dot{B} = -\alpha_R BR, \tag{20}$$

where R is the number of Red Force assets, B is the number of Blue Force platforms, and α_R is the rate constant describing the average combat power potential of a Red Force asset

(Harney 2013, vol 6, 340). A similar process was completed for Red Force attrition, as shown in Equation 21,

$$\frac{dR}{dt} = \dot{R} = -\alpha_B BR\,, \tag{21}$$

where α_B was the average combat power potential of a Blue Force asset (Jeffrey Kline, class notes, 2019). These are the equations for the Lanchester Linear Law used, where random search applies, and little can be known about the specific location of an opposing force's whereabouts. Regardless, according to Professor Kline (lecture, 2019), by multiplying Red Force's equation by α_B and the Blue Force's equation by α_R, the two sides become equal as shown in Equation 22,

$$\alpha_R dR = \alpha_B dB\,. \tag{22}$$

Integration of both sides of the equation yields the Linear Law, shown in Equation 23,

$$\frac{B_o - B_t}{R_o - R_t} = \frac{\alpha_R}{\alpha_B}\,. \tag{23}$$

This is equivalent to the exchange ratio used in Young's Model (Equation 24) and was how the linear law was applied to a submarine on submarine campaign. Equation 23 then becomes Equation 24,

$$Exchange\,Ratio = \frac{Y - y}{X - x}\,, \tag{24}$$

where the difference is that *Y* accounts for Red Force platforms, *X* accounts for Blue Force platforms, and lowercase and upper case *Y* and *X* are the starting number of submarines for each side compared to the ending number on each-side, respectively (Young 1985). In other words, these equations are one in the same when applied to a submarine campaign, but Young's model (Equation 24) is expressed in simpler terms.

Using this concept allowed us to factor in the technology difference between Blue and Red Force submarines, where the assumption was that Blue Force submarines have an inherently higher exchange ratio due to technological superiority. Additionally, even though the Blue Force submarines were assumed technologically superior, the Red Force was assumed to have more submarines. Thus, the Linear Law enabled us to understand how both factors affected the remaining number of submarines for a submarine-on-submarine campaign, lasting the duration of the Blue Force logistics transit. This transit went directly through the search area of an allocated Red Force, as previously discussed. The search area was bounded by the first island chain and the Chinese landmass with an estimated size of 3,088,247 square miles. The search rate of each submarine was estimated at 150 square miles per hour (ORD 1999).

In addition, two parameters, engagement probability and search time, were introduced to the model to simplify the calculations. Engagement probability was the probability that an engagement occurred given that two vessels encounter each other; however, to remain undetected, a submarine may not engage a submerged threat. Taken together, the daily engagement rate (γ) was calculated by Equation 25,

$$\gamma = \frac{X \times Y \times R \times E \times H}{A}, \qquad (25)$$

where *X* is the number of friendly SSNs, *Y* is the number of enemy submarines, *R* is the search rate in square miles per hour, *E* is the probability of engagement, *H* is the number search hours per day and *A* is the search area. To link back to the Lanchester equations using the variables defined in Young's model we redefined α_R and γ as shown in Equation 26,

$$\alpha_R = \frac{R \times E \times H}{A}, \qquad (26)$$

and Equation 27,

$$\gamma = X \times Y \times \alpha_R. \qquad (27)$$

Thus, Equation 25 and Equation 27 are equivalent and continue to demonstrate the utility of Lanchester's equations for modeling a submarine campaign's attrition values. Using this concept, a simulation was run from day one with X_1 number of friendly SSNs and Y_1 number of enemy submarines. On the *nth* day, the remaining number of friendly SSNs X_n was calculated by Equation 28,

$$X_n = X_{n-1} - \gamma \times \frac{1}{1 + Exchange\,Ratio}. \tag{28}$$

The corresponding remaining number of enemy submarines Y_n was calculated by Equation 29,

$$Y_n = Y_{n-1} - \left(X_{n-1} - X \right) \times Exchange\,Ratio. \tag{29}$$

Thus, Equation 28 and Equation 29 were a rearrangement of the Linear Law and were used as a determination for the value of Blue and Red Force submarine assets given an *n*th day transit.

To obtain the approximate number of submarines in the region for any given time during a transit, *n* was set to a large number and a simulation was run over the number of days of a given Blue Force transit. The initial days of the transit account for the greatest possible rate of engagement because this was when it was assumed that the number of submarines present in the contested region was the largest. As the number of Blue and Red submarines decreased over time, the rate of engagement slowed because the time required to seek out a shrinking number of Red submarines with a smaller force of submarines became disproportionately longer. Thus, when *n* was sufficiently large, a lower, more accurate number of submarines was estimated. Given that each side allocates some (but not all) to this submarine interaction, Young's model gave us a reasonable estimate for the final number of actively searching Red and Blue Force submarines. These approximate numbers were then used as input in calculating probability of attack by enemy submarines in the region.

Ultimately, the goal of using Young's case study in the model was to ensure that the game theory aspect of the anti-submarine warfare (ASW) problem was managed, meaning that it was unrealistic to assume that the Red Force would allocate all their assets in one area. Thus, using the Young's Model, attrition was accounted for to produce a realistic density of submarines around the transit route of the asset or convoy. Essentially, this accounted for any area sanitization completed by deployed Blue assets (such as SSNs, DDGs, LCS), as a separate action and prior to any logistics movements. As a result, a quantitative assumption was generated based off a qualitative assessment of Red Force allocation within the assigned threat regions.

2. Engagement Analysis

The previous section focused on detection models; but now, given a detection has occurred, we move to the engagement analysis phase. Engagement analysis between the Red and Blue Force assets creates a level of attrition. To attrite forces, salvos are launched against one another, with defensive countermeasures employed to prevent the attrition. To incorporate this into useful survivability analysis, Monte Carlo simulations, Raid Annihilation and Simple Initial Threat were used.

a. Monte Carlo Simulation

Given the amount of randomness and uncertainty in the complex problem of logistics in a contested environment, a Monte Carlo simulation was chosen as the method to quantify probabilities that would ultimately be inputs into the circulation model. A Monte Carlo simulation provided a statistical model that utilizes random variables and a probability distribution associated with those variables to quantify a result (Wagner, Mylander, and Sanders 1999). Thus, our adaptation of this simulation utilized many iterations for a specified threat scenario and logistics asset moving through the threat-layers to provide an expected survivability rate of that asset. The previously described models provided detection probabilities from Red submarines, aircraft, and surface vessels that fed the engagement analysis. This was how randomness and uncertainty of the assumptions were captured.

The Monte Carlo simulation also involved a complex system of Red and Blue Force assets to determine the survivability of Blue Force logistics. It was important to include many random variables in the simulation to account for the uncertain nature of warfare and the many different assets available to those countries involved in great-power competition.

The input variables in the Monte Carlo scenario's include: the probability of Blue logistics detection by Red Forces, the number of weapons fired in a Red Force salvo, the defensive capabilities of Blue Forces (if any), and the effectiveness of Blue and Red weapons. However, the probability of Blue assets being detected is the primary concern and main driver in this simulation. The outputs ascertained from the Monte Carlo scenarios were the average survivability rates from all Red Forces.

The first uncertainty incorporated into the simulation was the affect Red Force submarines would have on Blue survivability. This included the random search and barrier search theories prescribed to Red submarines and the number of Red submarines in the area found using Young's model previously described. The resultant probability of detection using these three methods fed the Monte Carlo simulation. Each iteration of the scenario independently calculated a different probability of engagement that feds into each engagement phase once a Blue asset was detected. An overarching detection probability was assigned based off the cumulative efforts of all Red submarines in a threat region, based on discrete glimpses from each submarine. Where each glimpse was assumed to be statistically independent, along with the probability, a detection would occur at least once during the Blue logistics vessel transit. The overall probability of detection was found using the detection probability equation in Equation 30,

$$F_{dn} = 1 - \prod_{i=0}^{n} \left(1 - P_i\right), \tag{30}$$

where F_{dn} was the probability there was at least one detection by at least one Red Force asset and P_i was the instantaneous detection probability on glimpse i (Wagner, Mylander, and Sanders 1999, 134).

Another uncertainty in the model was the impact level Red Force missiles would play in the equations. These missiles include both anti-ship cruise missiles and anti-ship ballistic missiles. The ASCM threat incorporated random search theory for Red aircraft with detection capabilities of EO and radar, as well as random search theory for surface ships with line of sight detection capability. Once the probabilities of detection were determined for EO and radar of Red aircraft based on assumed input values, an overall probability of detection was prescribed for the air domain. Assuming Red assets were not continuously transmitting to avoid detection themselves, an "on/off" factor for Red sensors was used which reduced the likelihood that Blue assets were detected by either a Red air or surface threat. This factor was implemented using an assumed ratio of time Red Force sensors will be actively transmitting to the time those sensors would be passive. Using Equation 30, a complete probability of detection was determined which encompassed both the air and surface domains by combining their individual detection probabilities. Similarly, the ASBM threat incorporated the same process in determining the detection of Blue Forces by Red assets, with the exclusion of surface ships, since surface vessels were not assumed to carry ballistic missiles.

The Monte Carlo simulation incorporated ten-thousand iterations for each scenario; this number was chosen to increase the confidence in the results given the randomness and uncertainty of the inputs to the model. In determining if an attack occurs from either a Red Force mine, submarine, ASCM, or ASBM weighed heavily on the probability of Blue Forces being detected. However, the assumption in play was that if the Blue Force asset was detected, then it would be attacked. Probability of detection was the initial input to the simulation, and a random generator was used to determine if a detection occurred; then a subsequent attack followed, given a detection.

If there was a detection in the simulation, then the process proceeded through multiple potential engagement scenarios. For example, Red Force submarines can launch both torpedoes and ASCMs. If an attack occurred, the submarine would launch its torpedoes. If it hit and killed all Blue assets, then the simulation would show all Blue assets destroyed. However, if the torpedoes missed, or there were any Blue assets remaining, the simulation would run through a subsequent ASCM launch scenario. The simulation then determined the number of Blue Forces, if any, that remained.

The number of Red weapons launched at any one time and from any platform was a user input that would vary based on the best intelligence at hand and at the time of use. In determining the number of weapon/weapons launched from Red Forces that make a Blue Force kill was a binomial random variable. This distribution treated each weapon as an independent trial and a probability of success was assigned to each or all weapons in the salvo (CFI n.d.).

The simulation accounted for scenarios where there were:

- undefended Blue logistics assets
- defended Blue logistics assets
- undefended Blue logistics assets with escort defenses
- defended Blue logistics assets with escort defenses

The major difference between these scenarios were whether the Red Force weapon(s) penetrated the Blue defense layers. When a Blue asset was undefended, there was a probability assigned to the weapon that it would either kill or not kill the asset. It was solely the effectiveness of the Red weapons that determined a kill or no kill. When the asset was defended, there was a probability assigned that the Blue asset would survive the engagement given the defense layers onboard or surrounding them. When defended, the binomial distribution was still utilized, but this time the probability of success was affected by the defensive measures of Blue Forces and the capability of Red Force weapons.

After the ten-thousand iterations were run, the simulation calculated an average survivability rate for the given scenario. This probability of surviving a one-way transit was the q value which served as the primary input to the circulation model.

b. Raid Annihilation

A facet of the Monte Carlo simulation depended on the logistics asset defensive layers. Self-protection systems and escorts reduced the probability of kill (P_K) of Red threats. For instance, incoming ballistic missiles and cruise missiles could be shot down by Aegis air defense systems. The P_K was thus dependent on the effectiveness of the countermeasures in killing the incoming threats. This was modelled using counter-kill shown in Equation 31,

$$q = 1 - P_{CK} \prod_{i=1}^{L} \left(1 - P_{Ki}\right), \tag{31}$$

where q is the defender's survival probability against one type of Red threat, L is the number of defensive or countermeasure layers against Red threats, P_{CK} is the probability of the attacker destroying the defender and P_{Ki} is the probability of destroying the attacker of a specific defensive layer *i (*Wagner, Mylander, and Sanders 1999, 291).

Furthermore, countermeasures were studied for effectiveness against cruise missiles, ballistic missiles, and torpedoes from submarines. Figure 43 illustrates how the counter kill model fits into the overall survivability model. Given detection and engagement by the Red threats, the counter kill model was used to factor in the role of escorts and countermeasures in enhancing survivability. Three layers were studied for ASCM model: the first layer was Blue airpower (such as combat air patrols) destroying launch platforms (air, land or sea-based) before they can launch an attack; the second layer was Aegis-equipped ships which can use the standard missile to shoot down incoming threats (while the Aegis ships could also shoot down Red aircraft, the standoff range of Red ASCM generally allowed them to launch without coming within range of Blue air defenses); and the last layer of defense was close-in-weapon systems (CIWS) such as the Phalanx which has the ability to shoot down incoming cruise missiles.

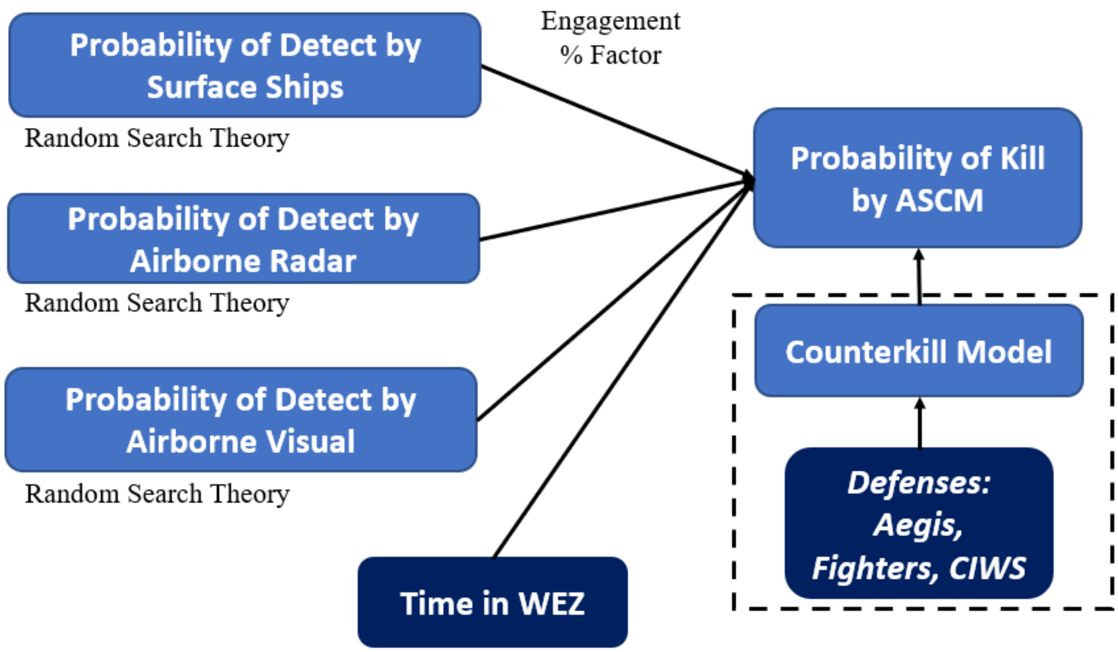


Figure 43. Survivability Modelling against Anti-ship Cruise Missiles

Coupling this with example engagements, if a Red aircraft attempted to launch an ASCM at a Blue ship, a 90% weapons effectiveness rate made a kill likely. When factoring in a 70% chance that the aircraft was killed before it could launch any missiles, a 90% chance that Aegis destroyed the incoming missile, and a 70% chance that CIWS destroyed the incoming missile, the resulting probability of survival was 99.29%. For Anti-Ship Ballistic Missiles (ASBM) with a P_K of 90%, the only relevant layer of defense was the Aegis systems which had a P_K of 70% and resulted in a survivability rate of 73%. Lastly, against Red submarines, the defenses were maritime patrol aircraft, anti-submarine escort ships and Blue submarines. These defenses decreased the P_K of the Red submarines from 90% to 49%.

c. Simple Initial Threat

The potential mine threat was also accounted for in the model, as mines pose a serious threat to the mobility and movement of an asset or convoy by restricting access. "Naval mines are weapons that are not required to do anything to achieve their purpose except to pose a threat, real or imagined" (Payne 2010, 294). Former Chief of Naval

Operations, Admiral Forrest Sherman, said it best, “When you can’t go where you want to, when you want to, then you haven’t gotten command of the sea” (Wagner, Mylander, and Sanders 1999, 234). It is because of this concept, that the Red mine layer was included. This model can be adapted for mines or can simply prohibit a region of access due to a specific story line (number of Red assets patrolling, fishing density, depth, etc.). Regardless, it provided a level of sensitivity for the nodal network analysis by providing a level of risk to a specific route to avoid all together. Additionally, it is an important factor because a Blue Force asset may plan to enter a mined area or enter accidentally. Regardless, most ships have some probability of entering a minefield and the majority can transit through without being damaged (Wagner, Mylander, and Sanders 1999).

Even though ships can enter a mined area and get damaged with some probability, this probability was hard to determine. It is hard to have an outcome for a model when the actual locations of the mines are unknown. Ideally, a Red threat would arrange mines in a clean, evenly spaced out line perpendicular to transit routes as to avoid any gaps in coverage (Wagner, Mylander, and Sanders 1999). Additionally, lines of mines would also be tactically convenient for the mine layer. Even with these assumptions, the reality assumed was that these mines will not be spaced out as described for two reasons. First, they are not spaced out evenly because some mines were possibly duds, some were configured differently than their neighbors, and other differences occurred because of navigation or timing errors in the actual minelaying (Wagner, Mylander, and Sanders 1999). The second reason is how could the Red minelayer know exactly the angle which a target would approach the mines? For these reasons, mines were assumed to be independent and randomly distributed throughout a channel. Thus, the danger of overstating the effectiveness of minefields is a possibility and to avoid this, the Simple Initial Threat (SIT) model was utilized.

SIT estimated the probability that the first ship to enter a minefield was damaged. This model assumed that the mines within the minefield are located independently and at random, as shown in Figure 44 (Wagner, Mylander, and Sanders 1999).

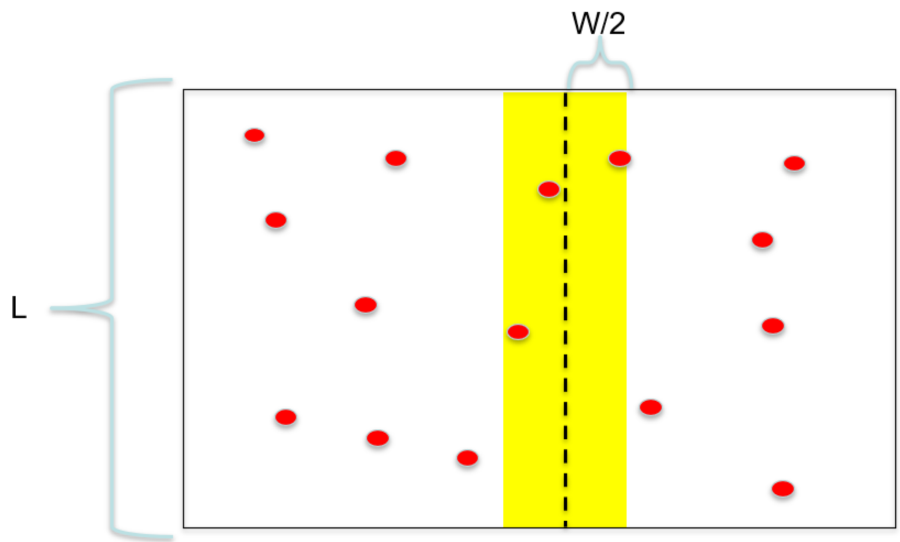


Figure 44. Simple Initial Threat for Modeling Minefields. Source: Michael Atkinson (class notes, 2020).

Figure 44 shows SIT, a subset of Enhanced Naval Wargaming System for modeling minefields, where N mines were placed randomly, uniformly, and independently in a channel of length *L* and area *A*. A Blue Force ship that was transiting through the field, on the dotted line of the ship's incremental track, was destroyed by any mine that it passed within a distance of *W/2* (Michael Atkinson, class notes, 2020). Equation 32,

$$SIT = 1 - \left(1 - \frac{w\,l}{A}\right)^{m}, \tag{32}$$

from Wagner, Mylander, and Sanders (1999) demonstrates the mathematical formulation for SIT, where *m* is the number of mines in the area, *w* is the mine sweep width, *l* is the incremental length of track of the ship and *A* is the minefield area (240). Again, SIT demonstrated the probability that the first ship in a minefield is damaged by a mine. In theory, the second ship has a lower probability than the first to hit a mine because the route has either been proven clear, or the first ship detonated one of the mines in the chosen path. SIT was not a perfect fit for our modeling effort because it does not account for the countermeasure effectiveness of the second ship, following the first ship via channelization—a basic mining countermeasure (Wagner, Mylander, and Sanders 1999).

However, using SIT enabled us to model the effects of a minefield against each asset individually, even if convoy tactics are employed. This is another conservative assumption of the worst-case scenario: that each asset had an equal probability of hitting a mine. Implementing SIT accounted for the presence of minefields without it being excessively complicated, hence the simple part of its name.

E. CIRCULATION MODEL

The circulation model was the overall model used, as it illustrated the statistical effectiveness of a force as it progressed through a campaign (ORD 1999). This was chosen as the basis for the modelling and simulation efforts because of its tangible results; the model allowed for the combination of a multitude of factors yielding a single output. Figure 45 shows a basic circulation model. Typically, some asset started at a base in an AO, went through a hostile layer with a probability of survival q as it traveled to some destination. In the case illustrated in Figure 45, the destination was a sea-line-of-communication (SLOC). The first half of a circulation model, from the Base to the SLOC in the case of the example, can provide some significant insights into a problem, such as the survivability of an asset from a source to a target. From this probability alone, many other MOEs and MOPs can be determined for analysis. The other half of the circulation is a return trip (back to the Base from the SLOC in the example). Notionally, the asset returns through the same hostile threat layers, which greatly diminishes the overall survivability. While alternate return routes could be used and the adversary may choose not to attack an empty logistics carrier, this analysis assumes equal risk on the delivery and return transit. Again, we have made a conservative assumption to bracket the worst-case scenario. As a result, the circulation model was used to generate the expected number of deliveries, and the expected number of round trips that a given Blue Force logistics platform would execute. Through Monte Carlo analysis, we used the model to evaluate the permutations of many different logistics carriers, various routes, and dynamically changing threat environments.

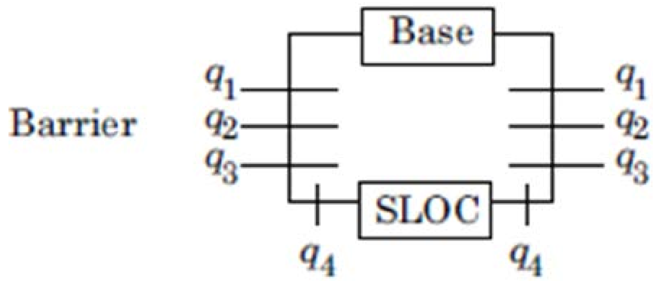


Figure 45. Generic Circulation Model. Source: ORD (1999, 1a.1).

The model described to this point was adapted to this project in the form shown in Figure 46 which demonstrates the different threat-layers that were considered for this project. The threat-layers shown, are generic in nature and do not demonstrate the specific values for each category. The overall threats that threaten a logistics asset, whether it be single or in a convoy, were air threats (such as aircraft, ASCM, ASBM), surface threats, submerged threats (such as submarines and torpedoes), and mine threats. Each individual layer produced a probability of kill, and when combined yielded the total probability of survival. The circulation model connected each of the previously discussed sub-models and simulations and enabled us to generate data for our MOEs.

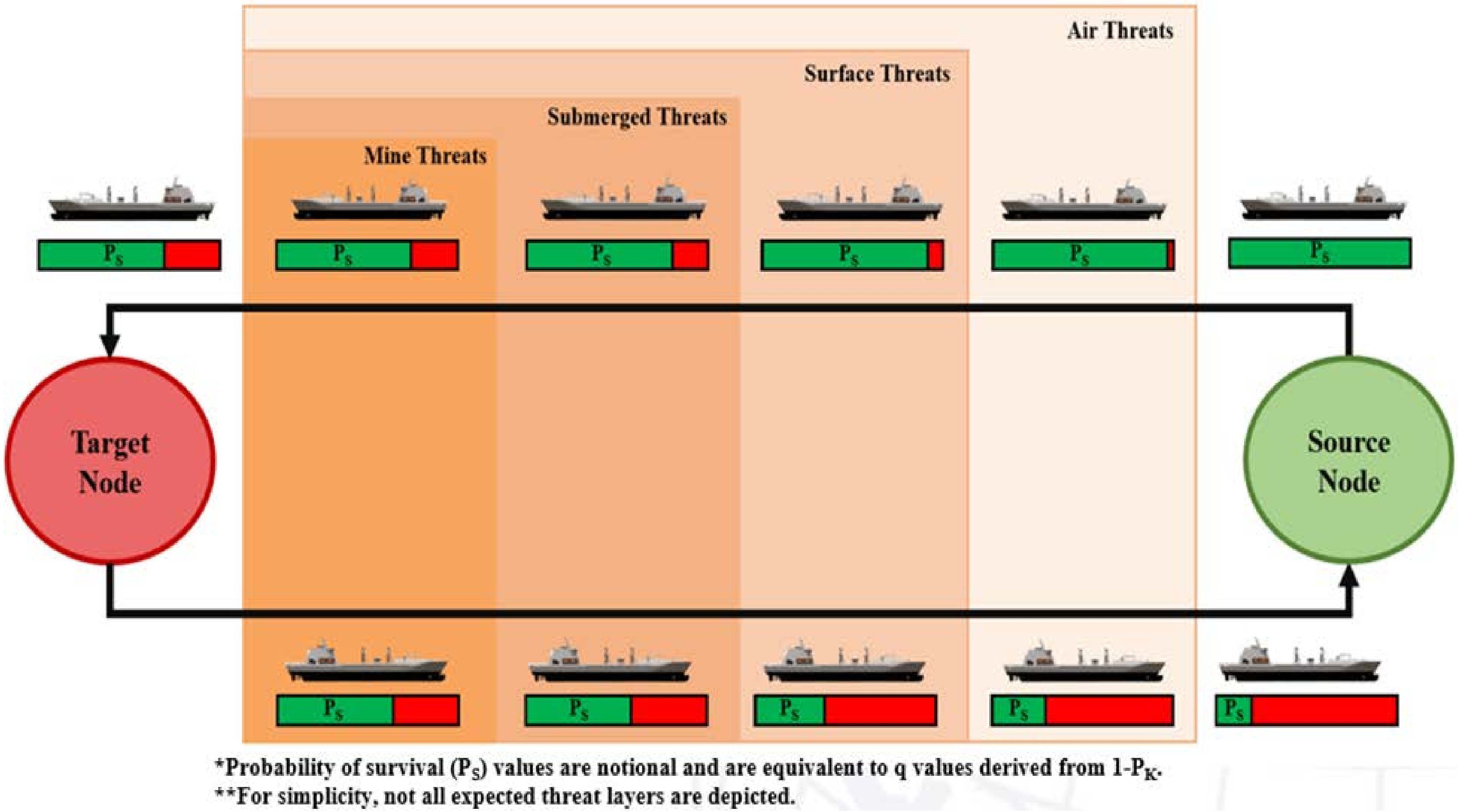


Figure 46. Illustration of Circulation Model Utilized

The following are specific circulation model outputs that were used for MOE analysis:

1. Probability of surviving a single round trip
2. Expected number of round trips (E[X]) and standard deviation
3. Expected number of deliveries (E[X])
   - 1/2 model from source to target node
4. Average tonnage delivered before an asset is lost
5. Average tonnage lost
6. Average Red Force ammunition expended per Blue trip

As a result, the outputs of the circulation model were very forthright in identifying the vulnerabilities of a specific asset throughout a campaign. As shown in Figure 45, there were various *q* values. These represented the probability of survival against an individual threat-layer. The equation from page 1a.1 of ORD's (1999) text demonstrated the relationship between the probability of kill, or P_K, and the probability of survival, q, for each threat-layer as shown in Equation 33,

$$q_i = 1 - P_{K\,i}\,. \tag{33}$$

Each one of these layers and their respective survivability were independent of each preceding barrier. Thus, the aggregate survivability for a half-length used is shown in Equation 34,

$$q_{HALF} = q_1 \times q_2 \times q_3 \times q_4 \times ...q_i\,. \tag{34}$$

To determine the probability of survival for a whole round trip, the q_{HALF} equation was multiplied together, or squared in this case, to get q_{TOT}, as shown in Equation 35,

$$q_{TOT} = q_{HALF}{}^2\,. \tag{35}$$

This equation provided the overall campaign round-trip survivability for a given route. Going forward, the survivability will only be referred to as *q*.

The goal of using the circulation model was to determine the number of deliveries (half-trips) and roundtrips made. This geometric random variable allowed us to generate tangible results in the form of MOEs and MOPs. The process applied for the follow-on formulas were representative of a geometric distribution, in that the goal was to ascertain data around the successful round trips until the transiting vessel was killed. In comparison to flipping coins, the goal was to find the number of tails flipped (successful trips) until the first head was flipped (killed during transit), which in turn was a geometric variable (Montgomery and Runger 2013). Even further, the form of the geometric distribution for this problem was relevant to where the number of successful trips could start at zero and then proceeded to one, two and so forth. The probability mass function for this assumption was given by Law (2007) in Equation 36,

$$p(x) = \begin{cases} p(1-p)^x & if\ x \in \{0,1,2...\} \\ 0 & otherwise \end{cases}, \tag{36}$$

where *p* is the probability of getting killed during the transit (305). Thus, these sequences of independent Bernoulli trials with probability *p* of failure, yielded the mean or expected value, shown by Equation 37,

$$\mu = E\left[X\right] = \frac{1-p}{p}, \tag{37}$$

(Law 2007, 305). When considering round trips in the circulation model, *p* was equivalent to $1-q_{HALF}{}^2$. Substituting for *p*, this provided us with the expected number of round trips, shown in Equation 38,

$$E\left[X\right] = \overline{X} = \frac{q_{HALF}}{1-q_{HALF}{}^2}, \tag{38}$$

(ORD 1999, 1a.2). Thus, this geometric sequence allowed for the derivation of expected number of round trips for a particular asset.

The same assumptions for the expected value of round trips holds true for the standard deviation of round trips. The logical progression commenced with the derivation of standard deviation from a geometric distribution shown in Equation 39,

$$\sigma = \sqrt{\frac{1-p}{p^2}}\,, \tag{39}$$

from Law (2007, 306). Taking this basic form and substituting $1-q_{HALF}^{\;\;2}$ for p yielded the standard deviation for the number of expected round trips shown in Equation 40,

$$\sigma = \frac{q_{HALF}}{1-q_{HALF}^{\;\;2}}\,, \tag{40}$$

from ORD (1999, 1a.2). This accounts primarily for round trip numbers. However, there was significant value in also obtaining the expected number and standard deviation for the number of successful deliveries, even if the asset is killed on its final return trip.

Like the previous equations, the determination for half-length was an involved process that also included the assumptions behind a geometric random variable. However, the number of deliveries here was similar, but not geometric in nature. Thus, to get the number of deliveries, in which only the q half-length was accounted for, the expected number was also calculated. The formulation for the expected number of half deliveries was derived from a geometric sequence shown in Equation 41,

$$E[X] = \bar{X} = \frac{q_{HALF}}{1-q_{HALF}^{\;\;2}}\,, \tag{41}$$

with a standard deviation determined by Equation 42,

$$\sigma_X = \frac{\left(q_{HALF}^{\;\;3} - q_{HALF}^{\;\;2} + q_{HALF}\right)^{1/2}}{\left(1-q_{HALF}^{\;\;2}\right)} = \frac{\sqrt{\left(q_{HALF}^{\;\;3} - q_{HALF}^{\;\;2} + q_{HALF}\right)}}{\left(1-q_{HALF}^{\;\;2}\right)}\,, \tag{42}$$

from ORD (1999, 1a.2). These are the formulas for the generic circulation model that were applied to this project.

F. IMPLEMENTATION

The tool that we chose to implement each model element was spreadsheet analysis in Microsoft Excel. Excel was the only tool used, as it allowed us to implement simple yet insightful analysis for results in a dynamic problem. This simple and user-friendly platform enabled all members of the team to participate in the modeling experience. Additionally, combining model elements was straightforward, which was important as each member contributed to building a certain facet. Ideally, this format will enable others to easily use our model for future, complex campaign models that require circulation model analysis. Lastly, this feature allowed us to easily implement and analyze various Blue Force assets as either an individual unit or a convoy with multiples units. By having it in an easy-to-use, excel spreadsheet, sensitivity analysis on these assets through various defensive layers, signature reductions, susceptibility and vulnerability features was quickly and adequately determined.

G. NETWORK ANALYSIS AND MAXIMUM FLOW OPTIMIZATION

The output from the circulation model assisted in network analysis, by assigning risk to the arcs within a static network. The assigned risk is equivalent to the probabilities of survival, or q, calculated for the circulation model shown in Figure 46. This section is a summary of the network analysis and flow optimization performed with those results. This network analysis is a different but complementary modeling effort for the problem of Logistics in a Contested Environment. For more information, refer to ENS Christian Sorenson's 2020 Naval Postgraduate School thesis, "Logistics in a Contested Environment: Network Analysis and Flow Optimization" (publication forthcoming).

1. Network Science Fundamentals

Network science has become a mainstay of analyzing complex systems in today's world, representing complex real-world networks as graphs, which are easier to examine and draw patterns from. A network of logistics hubs has been created as a part of the modeling and simulation effort, with the goal of examining the structure of the network based upon characteristics of both edges and nodes within the network. Figure 47 depicts a sample logistics network, where the nodes represent logistics hubs and the edges represent connections between the hubs.

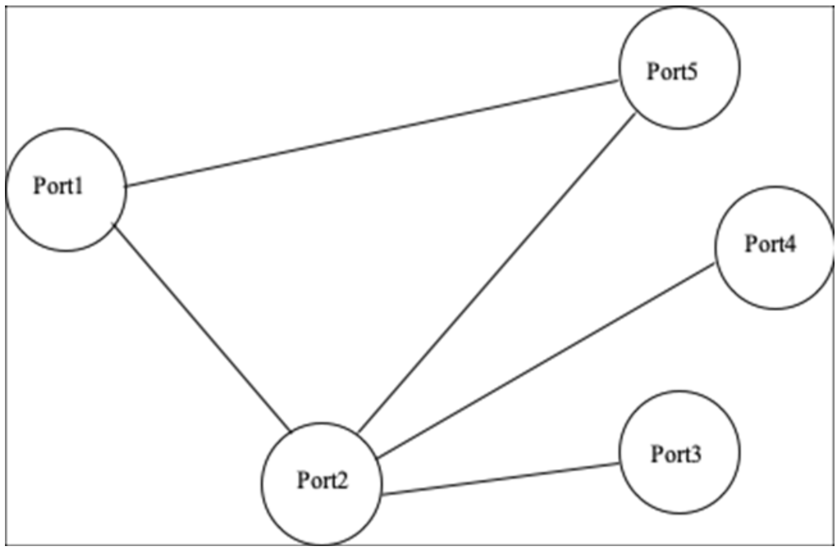


Figure 47. Sample Logistics Network of Five Ports with Undirected Edges Connecting the Nodes

A network graph is composed of two finite disjoint sets: edges and vertices, where edges are connections between vertices (Bollobás 1998). For this analysis, edges are connections between distinct vertices. In other words, a vertex cannot be connected to itself by an edge. Edges can be represented by binary values, where a value of one indicated the presence of an edge and a value of zero indicates that no edge is present. Additionally, both vertices and edges can be associated with non-binary values, called weights, that can represent the importance of a given vertex or edge in comparison to others in the network. In Figure 47, the edges are binary weighted, solely indicating the presence of the edge. The degree of a vertex can be taken as the number of vertices it is connected to; degree can also consider the weight of edges connected to a vertex. In Figure 47, for example, Port2 has degree four. A network is defined as: a simplified representation that reduces a system to an abstract structure capturing only the basics of connection patterns and little else. (Newman 2010).

A seminal graph theory problem is the Seven Bridges of Konigsberg, solved by Euler. The problem states that there are four islands in Konigsberg, and seven bridges connecting the islands, as shown in Figure 48. In this graph, the vertices are islands and the edges are bridges. The edges in this graph are binary valued. By representing the map of Konigsberg in graph form, it is possible to analyze the problem using network science.

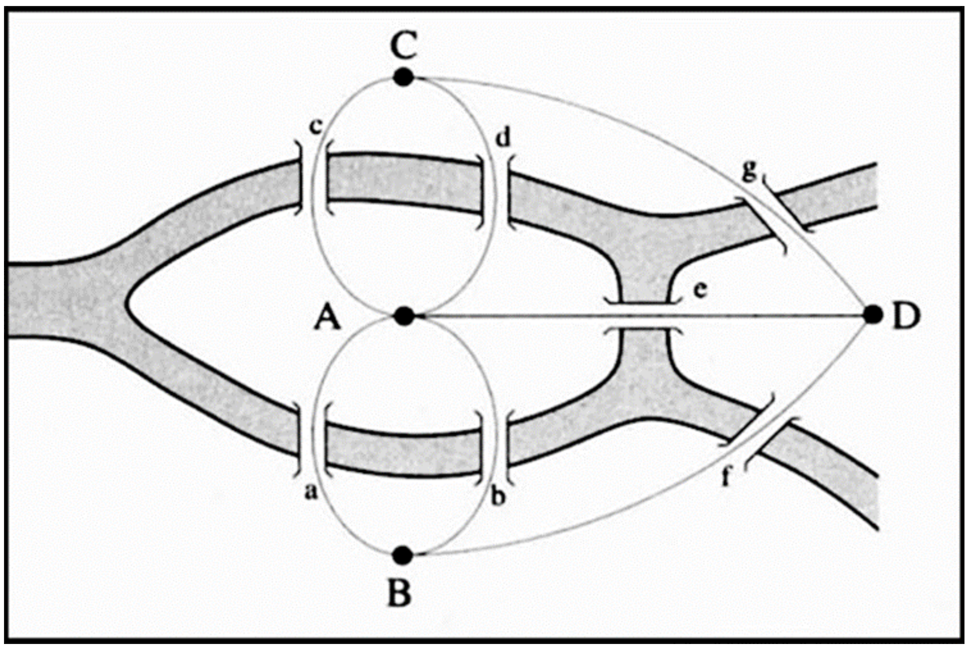


Figure 48. The Seven Bridges of Konigsberg. Source: Kadesch (1997).

In addition, metrics have been developed to analyze networks based upon the characteristics of vertices and edges. Some categories of these metrics that are used in analyzing the logistics network are centralities, network diameters, and clustering coefficients. From Sabidussi (1996), among the most popular centralities include: Eigenvector, Closeness, and Betweenness Centrality. For the purposes of this analysis, those centrality metrics suffice. The purpose of centralities is to quantitatively measure the importance of each node in the network. For example, the betweenness centrality, which is often used in logistics network analysis, provides a measure of how collocated each node is to the shortest paths in the network. Some networks have portions that are more interconnected than the average across the total network. Those subgraphs are referred to as communities, and defined by Radicchi et al. (2004) as: a subset of vertices within the graph such that connections between vertices within a community are denser than connection with the other communities in the rest of the network.

In addition to identifying communities, it is important to parametrize the strength of individual communities. Network modularity is used to generate communities and their relative strengths. Newman and Girvan (2004) use modularity to separate the total network into discrete communities and assign them a measure of strength.

2. Logistics Network Analysis

To apply the principles of network science to an analysis of a logistics network, we correlated the graph theoretic terms to characteristics of the real-world network. Vertices of the graph represented logistics hubs in the network, henceforth the vertices were referred to as nodes. The nodes had multiple different types, representing different capabilities of the ports. The important capabilities considered were as follows: dry cargo storage, ordnance storage, fuel storage, light crane lift capability, heavy crane lift capability, shallow draft pier accessibility, medium draft pier accessibility, and deep draft pier accessibility. These types were treated as binary values, indicating the capability, or lack thereof, of a given node. Different layers of the network were created by type, where all present nodes of a given type were connected by edges. Edges also had layers, where each layer represented a non-binary weight based on type. The edge types were as follows: distance and platform risk. The distance weight was the length of a sea lane connecting nodes, in nautical miles. The platform risk weight was generated from the circulation model risk assessment described earlier in the chapter. Each platform and its associated risk were analyzed as a separate layer. Using the Gephi open-source network analysis and visualization software package, we generated values for network diameter, network modularity, eigenvector centrality, closeness centrality, and betweenness centrality. We then analyzed these results and determined characteristics of our logistics network.

3. Maximum Flow Optimization

In addition to static network analysis, we applied a maximum flow algorithm to the logistics network model. This section presents an optimization model that determined the maximum amount of demand satisfied by logistics assets over a set period. The main goal of this model was to optimally allocate logistics vessels to routes, and configurations of supplies or tonnage allocation to vessels. This model fit the mold of a classic network flow model, as it did not include a time component (Ahujah, Magnanti, and Orlin 1993). Our network flow model used the same network of vertices and edges as the static network analysis but focused on optimizing flow from source nodes to demand nodes within the logistics network.

Drawing a parallel to the Seven Bridges of Konigsberg, shown in Figure 48, to formulate a maximum flow problem, vertices were partitioned into source nodes and demand nodes. Each edge had a weighted value indicating the penalty for crossing a bridge. A maximum flow optimization solved for optimal routing based upon the prescribed edge weights and source/sink nodes.

For the purposes of our model, we examined three subsets of demand: fuel, dry cargo, and ordnance. In the network flow model, each node was parametrized by its demand, the Blue Force logistics asset or assets prepositioned at the node, vessel or vessels loading time, and unloading time. Every edge was parametrized by the time it took a certain vessel to traverse the edge and the probability of survival of a certain vessel traversing the edge. The optimization assigned a cargo configuration to each vessel, where configurations allowed the optimization algorithm to prescribe an even distribution of fuel, cargo, and ordnance or prescribe a distribution that favored one of the supply subsets. Our model accounted for the risk that each vessel experienced traversing an edge, and for a parameter that assigned the penalty for losing a certain vessel. For a set demand signal and maximum time, the algorithm optimized a vessel selection and routing to achieve as much demand as possible within set constraints (Ahujah, Magnanti, and Orlin 1993).

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IV. RESULTS

A. RESULTS GENERATION

To generate the results, we created a survivability analysis simulation in Excel that implemented the previously discussed modeling methodologies and assumptions. The model was run to analyze the performance of 20 vessels, in four configurations, along 91 different routes in the operating area. The 20 vessel types we analyzed are listed in Table 11.

Table 11. Vessels Analyzed in Model

LCS (Littoral Combat Ship)
JHSV (Joint High-Speed Vessel)
T-AOE (Fast Combat Support Ship)
T-AO (Fleet Replenishment Oiler)
T-AKE (Dry Cargo/Ammunition Ship)
LHA (America-Class Landing Helicopter Assault Ship)
LSD (Dock Landing Ship)
LPD (Amphibious Transport Dock
OSV (Offshore Service Vessel)
Sea Train
ELS (Expeditionary Logistics System) Mothership
ELS MOLA (Marine Operations Logistics Asset)
Orca XLUUV
T-AK (Maritime Prepositioning Ship)
T-AKR (Maritime Prepositioning Ship)
T-AKR (Roll-on/Roll-off Ship)
Expeditionary Fast Transport (EPF)
LCU (Landing Craft Utility)
ESD (Expeditionary Transfer Dock)
ESB (Expeditionary Sea Base)

The four configurations used to analyze vessel performance were entitled:

- Solo Undefended: Transiting alone with present-day defensive capabilities.

- Solo Defended: Transiting alone with defensive layers defined below.
- Convoy Undefended: Five vessels transiting together with present-day capabilities.
- Convoy Defended: Five vessels transiting together with defensive layers which are defined in the following paragraph.

Defended vessels were given extra layers of defense within the model to analyze the level of effectiveness that these upgrades have on the survivability of the Blue Force logistics assets within the threat environment. These extra defensive layers simulated the addition of typical defensive layers seen on current U.S. warships as shown in Figure 49.

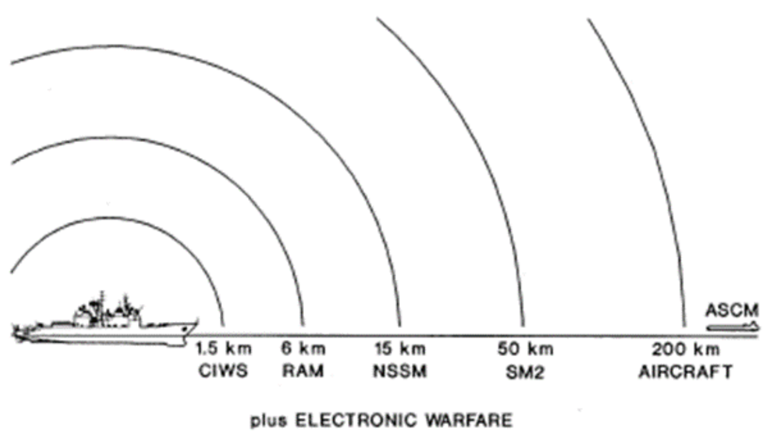


Figure 49. Example of Layered Defense against ASCM by U.S. Warship. Source: Harney (2013, vol. 6, 320).

The purpose was to analyze these effects as either permanent or modular additions to the Blue Force logistics platforms already in use or for future design considerations. The different defenses specifically used for this model are shown in Figure 50.

Prob Counterkill Solo Defenses		
q vs Anti Ship Ballistic Missile		
L =	0	(Number of Aegis or other ABM defense systems)
Pki =	0	(Prob of SM-6 destroying the incoming ASBM)
Pck =	0.9	(Prob DF-21 ASBM hits and kills logisitic ship)
q vs Anti Ship Cruise Missile		
L =	3	
Pk1 =	0	Combat Air Patrols
Pk2 =	0.7	CRAM or Aegis
Pk3 =	0.7	Close in Weapon Systems
Pk=4	0.5	ECM
Pck =	0.9	
q vs Submarines		
L =	3	
Pk1 =	0.1	Maritime Patrol Aircraft
Pk2 =	0	Anti-sub Ships
Pk3 =	0	Blue submarines
Pk=4	0.5	Torpedo Countermeasures
Pck =	0.9	
q vs Minefield		
L=	0	
Pk1=	0	Visual Lookout
Pk2 =	0	Mine Detection Capability of Escort
Pck=	0.9	Probability of Kill of mine

This figure demonstrates the defensive layers that "defended" Blue Force platforms had for each of the following major threats: ASCM, ASBM, submarine, and minefield. The Red Force surface ship and Air threat was coupled into the ASCM defensive layers, as it was assumed this would be the weapon of engagement against the Blue Force. Values depicted were either qualitatively determined from warfighter personal expertise or extracted from Harney (2013, vol. 6, 320–323).

Figure 50. Sample of Model Input Interface for Defensive Layers

For ships not in a convoy, the additional defensive measures included SeaRAM, CIWS, electronic countermeasures, acoustic countermeasures, and Maritime Patrol Aircraft as shown in Figure 49 and Figure 50. These measures were also included for the convoys, along with the addition of a missile defense system like Aegis or SSDS, combat air patrol support, and anti-submarine escort support.

1. Inputs Selection and Output Metrics

To run the model, the user selects the platform, and the origin (source node) and destination (target node) of the route. Choosing the route activated specific threat regions within the simulation. These threat regions determined the threat layers, threat densities, and regional characteristics applied to the simulation. There was also the option to select whether the vessel was modified to have additional reduction in RCS and self-noise. Specifically, for those vessels that did not already have signature reduction implemented into their designs. Thus, these reductions were used in sensitivity analysis to determine whether the additional reduction would be beneficial. Given the need for the Orca XLUUV to snorkel to recharge its battery, there was a selection for whether the Orca was transiting either at snorkeling depth or submerged.

This factor is significant, because the Orca will transit at a shallower depth when snorkeling to raise an exhaust mast out of the water. This exhaust mast, or snorkel, allows the exhaust from the diesel generator to leave the vessel as the battery recharges. Because of this, the results for the Orca needed to be proportioned, to adequately account for the time the XLUUV spends snorkeling. According to Dan Tubbs (email to author, March 13, 2020), Boeing's program manager for the Orca XLUUV, the Orca will snorkel for approximately six hours. A nominal battery charge allows the Orca to travel at the optimal speed from both of the Orca's operating modes and were combined using an operating mode ratio, to simulate a transit longer than one single operating cycle (Dan Tubbs, telephone call, February 6, 2020). Thus, the survivability and sensitivity analysis for the Orca accounts for 56 total hours, with six of those snorkeling and the other 50, transiting submerged. The actual time spent doing each varied with each route, due to the difference in distance travelled.

Figure 51 shows the user interface created within the Excel model to choose input options for the Blue Force asset being analyzed. Figure 52 shows an example of the threat region indicator that showed what threat regions were active after the route was chosen in Figure 51.

Logistics Platform:	JHSV
Is your ORCA Surfaced?	N/A
Source Node:	Okinawa
Target Node:	Manila

Added RCS Reduction?	No
Added Noise Reduction?	No

Figure 51. Input Variables User Interface

Active Threat Regions	
Sea of Japan	NO
East China Sea	NO
Philippine Sea	YES
South China Sea (North)	YES
South China Sea (South)	NO
Indonesia	NO

Figure 52. Threat Region Selection Interface

Once the input criteria were selected, the model iterated 10,000 Monte Carlo trials and populated the results table. Table 12 shows an example results table.

Table 12. Example Results Table

Results	***Solo Undefended***	***Solo Defended***	***Convoy Undefended***	***Convoy Defended***
q_1 - Survivability Against ASBM	0.6541	0.6588	0.4917	0.7503
q_2 - Survivability Against Submarines	0.9948	0.9956	0.9941	0.9983
q_3 - Survivability Against ASCM	0.6624	0.9932	0.4993	0.9693
q_4 - Survivability Against Mines	0.9777	0.9838	0.9823	0.9836
q - Survivability	0.4214	0.6409	0.2398	0.7141
Probability of Completing One Round Trip	0.1776	0.4107	0.0575	0.5099

Results	***Solo Undefended***	***Solo Defended***	***Convoy Undefended***	***Convoy Defended***
Expected Number of Round Trips	0.2159	0.6970	0.0610	1.0406
Standard Deviation of Number of Round Trips	0.5124	1.0876	0.2544	1.4572
Expected Number of Deliveries	0.5124	1.0876	0.2544	1.4572
Standard Deviation of Number of Deliveries	0.6864	1.1920	0.4698	1.5383
Enemy ASBM Used	3.12	3.07	4.57	4.64
Enemy ASCM Used	0.86	0.86	6.20	6.08
Enemy Torpedo Used	0.01	0.01	0.03	0.03
Enemy Mines Used	0.02	0.02	0.09	0.08
Tons Destroyed by ASBM	155.42	155.41	778.36	376.63
Tons Destroyed by ASCM	550.29	11.06	564.81	35.36
Tons Destroyed by Torpedoes	898.77	517.65	1341.10	383.44
Tons Destroyed by Mines	1400.00	1400.00	1400.00	1400.00
Average Cargo Ship Losses Per Inbound Transit	0.58	0.36	3.80	1.43
Average Tonnage Lost Inbound	810.02	502.76	5321.63	2001.28
Average Tonnage Delivered	589.98	897.24	1678.37	4998.72

The major data points that were extracted from the results data for analysis include:

- survivability of the vessel on the given route
- expected number of roundtrips completed by the vessel
- expected number of deliveries conducted by the vessel
- attrition cost per ton delivered
- total tonnage capacity of the system

From these data points three MOPs were calculated:

- number of ships lost per delivery
- average tonnage lost per system

- average tonnage delivered by system

Assuming a confidence level of 99%, the margin of error on the aggregate q value was on the order of 0.01. We determined that the magnitude of this margin of error was insignificant, and further error analysis did not alter our results or provide further insight. Therefore, we did not carry forward the margin of error in calculating the MOPs from our raw data. From these MOPs, we calculated the cost of losses per inbound transit by multiplying the estimated platform costs and supply costs outlined in Appendix C by the average number of vessels lost and average tonnage lost, respectively. This allowed us to analyze the cost of losses on a direct, inbound transit, or half-length of a round trip. By dividing this cost by the average tonnage delivered, we were able to calculate the attrition cost per ton delivered, as well.

2. Focusing Results

The results of our analysis determined that three major factors had a large impact: differences in route length, number of threat regions through which the route passed, and portion of the route within the weapons engagement zones of ASBM and ASCM threats. To focus our efforts, we chose to compare and analyze the results of 20 specific routes.

3. Choosing Routes to Analyze

We assumed that the routes used most frequently are those that transit to and from ports with current U.S. bases and major ports of current allies. However, the routes we chose were also meant to be a diverse selection that best encompassed the characteristics of the 91 routes within the network; to that end, they vary in length from 530 nm to 4,000 nm, have different route percentages within weapons engagement zones (WEZ), and are either contained within a single threat region or span multiple threat regions. The WEZs in this model were created by the ASCM and ASBM rings that emanate away from the PRC. Table 13 lists the 20 specific routes used in the focused analysis. Throughout this report, the figures shown use data taken from the routes that best exemplify the trend being discussed. However, the insights being discussed throughout were present on all the routes analyzed.

Table 13. Routes Used for Focused Analysis

From	***To***	***Route Length (nm)***	***Threat Regions Transited***	***Route Length Within ASBM/ASCM Range (nm)***
Hawaii	Okinawa	4035	1	870/1305
Singapore	Darwin	1826	2	1106/0
Cam Ranh Bay	Singapore	730	2	730/482
Manila	Okinawa	935	2	935/935
Cebu	Singapore	1341	3	1341/1341
Yokosuka	Guam	1347	1	1347/1347
Yokosuka	Okinawa	824	1	824/824
Yokosuka	Busan	630	3	630/630
Okinawa	Busan	537	2	537/537
Okinawa	Guam	1226	1	1226/1226
Zuoying	Guam	1514	1	1514/1514
Zuoying	Yokosuka	1326	2	1326/1326
Pattaya	Singapore	759	1	759/500
Pattaya	Darwin	2476	2	2100/800
Palau	Manila	976	2	976/976
Palau	Singapore	1945	4	1945/1745
Guam	Darwin	1891	2	1661/270
Guam	Sasebo	1459	2	1459/1459
Guam	Manila	1490	2	1490/1490
Guam	Singapore	2566	3	2566/2400

B. BASELINE RESULTS

To understand the major trends within the results generated by the model, we first examined the survivability of the vessels in their baseline configuration. The first major trend that arose was that vessels in undefended convoys tended to have lower survivability than undefended vessels transiting by themselves. The takeaway from this trend is that the increase in detectability and targetability inherent to a convoy is detrimental to survivability. Larger convoys tend to demand a larger salvo from the enemy, increasing the probability of hit from a missile attack. Figure 53 and Figure 54 exemplify this for a smaller sample of vessels transiting the route from Guam to Darwin.

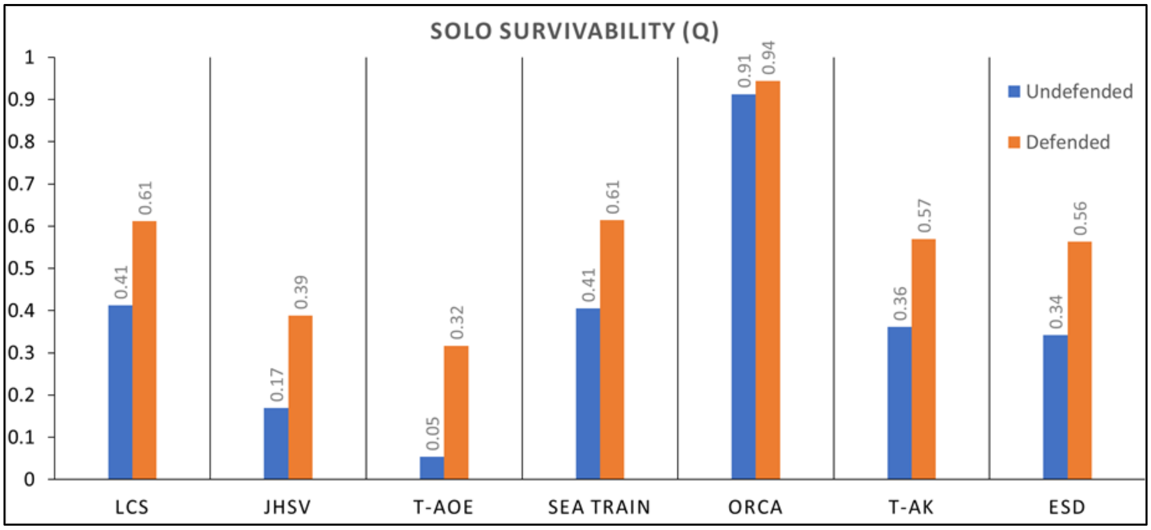


Figure 53. Sample Baseline Solo Survivability from Guam to Darwin

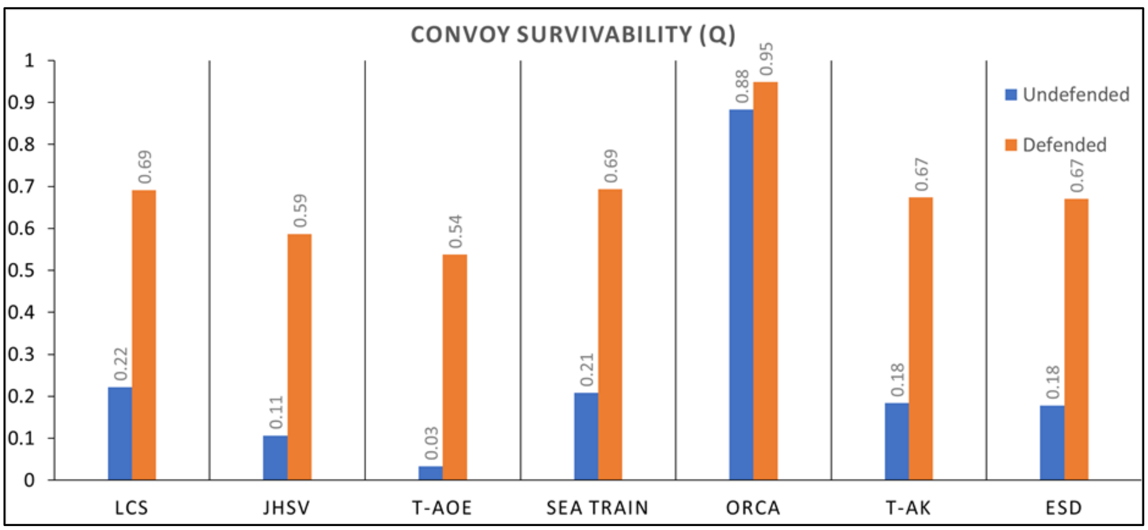


Figure 54. Sample Baseline Convoy Survivability from Guam to Darwin

Conversely, we found that vessels in defended convoys have a higher survivability than defended solo vessels. In this case, the whole was greater than the sum of its parts. Similarly, adding defenses to a convoy increased the survivability of its vessels much more than adding defenses to a solo vessel increased its survivability. The defenses overcame the inherent lack of survivability previously stated. In general, most of the vessels that were modeled and analyzed had very similar survivability. Outliers on the low end of the spectrum were the JHSV and the T-AOE. This can most likely be attributed to the high self-noise values for these two vessels. The outlier on the high end of the spectrum was the Orca XLUUV. This can also be seen in Figure 53 and Figure 54.

From the baseline survivability, other MOPs were developed and observed for the vessels. Figure 55 and Figure 56 show the number of expected deliveries and round trips conducted by each vessel on the route from Yokosuka to Okinawa.

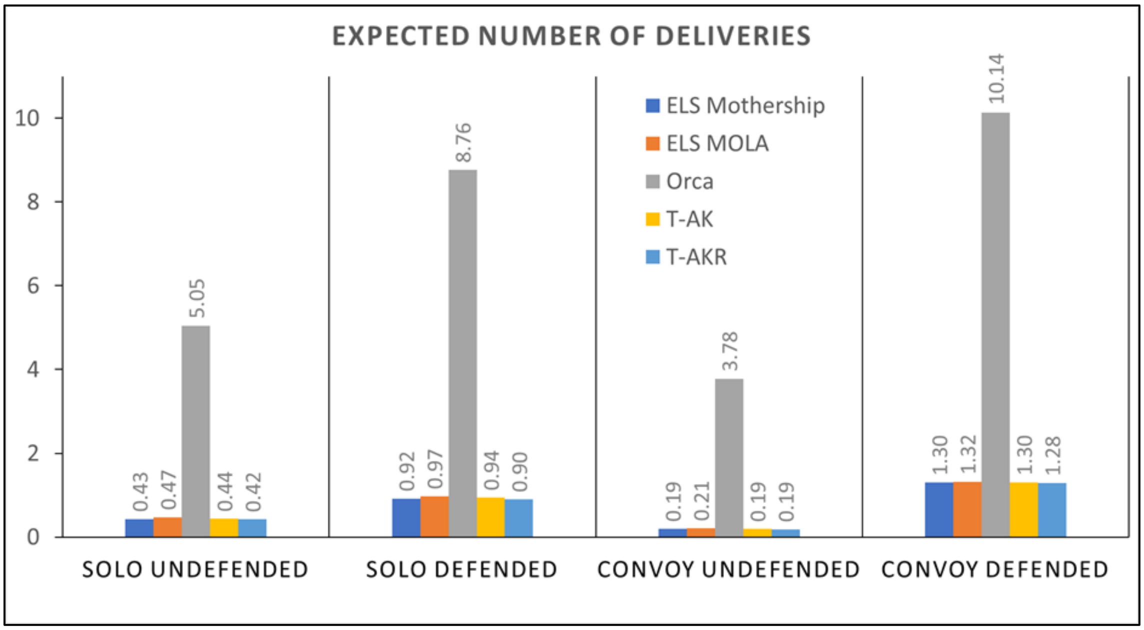


Figure 55. Sample (Reduced Size) Baseline Expected Number of Deliveries from Yokosuka to Okinawa

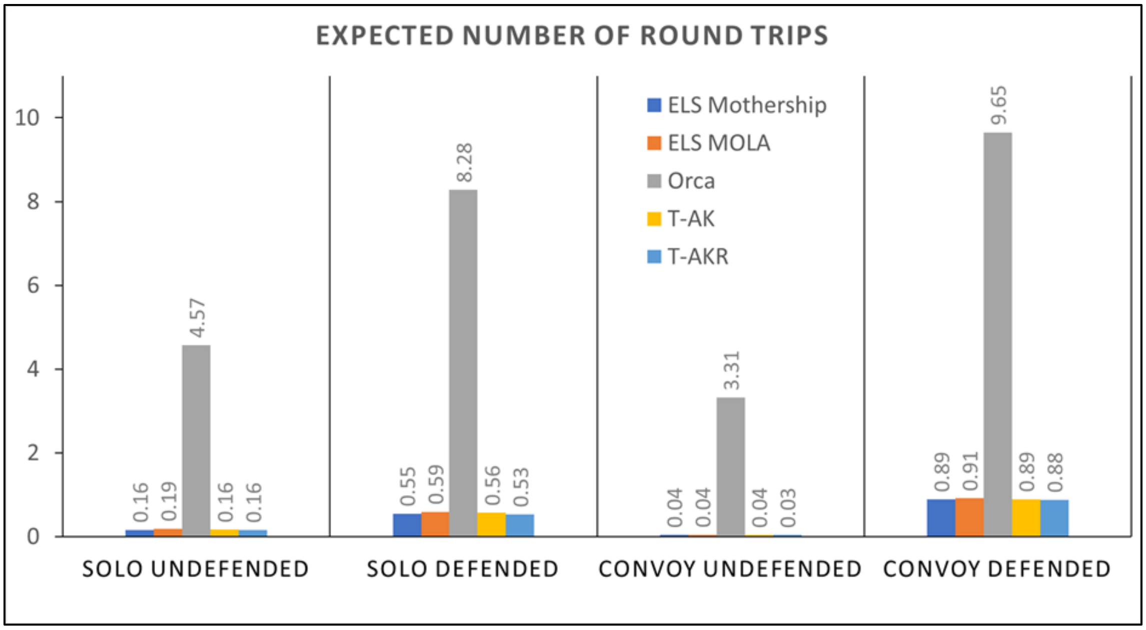


Figure 56. Sample (Reduced Size) Baseline Expected Number of Round Trips from Yokosuka to Okinawa

For almost all vessels, the expected number of deliveries were close to one for both the solo defended and convoy defended configurations. For the undefended configurations, the expected values were much lower. This was consistent across all routes. The exception to this trend was the Orca XLUUV. The XLUUV conducted between eight and ten deliveries in the defended configurations and between 3.5 and 5 deliveries in the undefended configuration. Our model generated this output for all assets, but providing a small, unmanned, subsurface vehicle an escort is an impractical CONOPS. This is because the escort would likely be more costly than the asset it is escorting and would likely negate the stealth benefits inherent to the Orca. Similarly, the expected number of round trips for the vessels, excluding the Orca, were always less than one. Thus, adding defensive layers did not significantly improve the expected number of round trips. The Orca round trip values were like its delivery values. Round trips in the defended configurations varied from eight to ten. Round trips in the undefended configurations varied from three to five.

The model also produced results regarding the average tonnage delivered and the average tonnage lost on an inbound transit for delivery. The results were expressed as tonnage per group of ships. Because of this, the data for convoys had to be normalized by dividing by the convoy size of five. This converted the data to be expressed as tonnage per ship per transit. Figure 57 and Figure 58 show the tonnage lost and the tonnage delivered for vessels transiting from Pattaya, Thailand to Singapore.

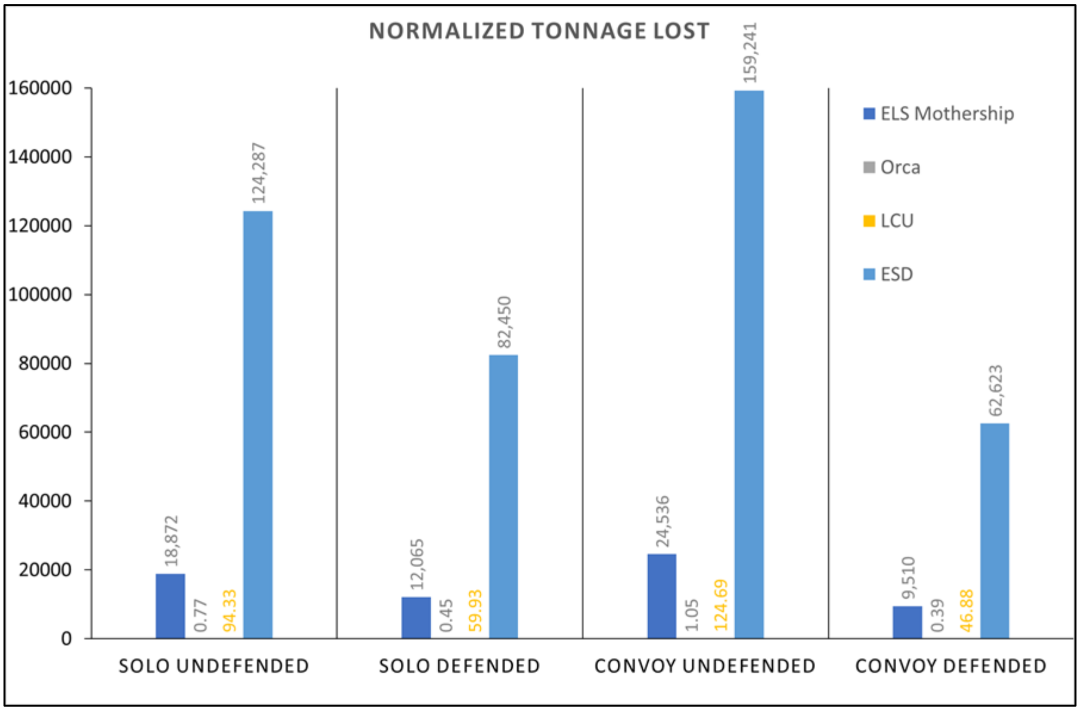


Figure 57. Sample Tonnage Lost per Ship per One-Way Transit from Pattaya to Singapore

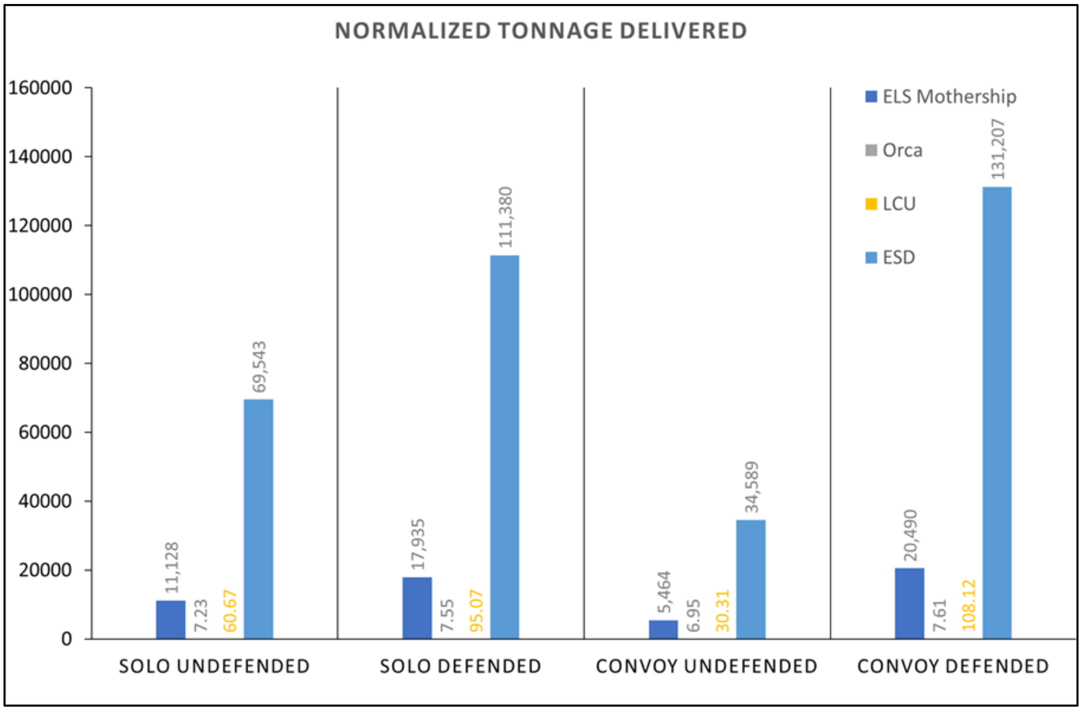


Figure 58. Sample Tonnage Delivered per Ship per One-Way Transit from Pattaya to Singapore

The major takeaway from this tonnage data is that undefended vessels tend to lose more tonnage of supply than they deliver. This is because the survivability values of all the undefended vessel configurations are less than 50%. Critically, these values alone do not indicate a preferable logistics asset. These values are very much dependent upon the cargo capacities of the vessels and must be further scrutinized. The ESD provided a good example of this. As, by far, the vessel with the largest cargo capacity, its tonnage delivered values dwarfed those of the other ships. However, its tonnage lost values did the same. As previously discussed, from the initial (before normalizing) tonnage lost data, we were able to calculate one-way costs of losses. This was accomplished by multiplying the average supply tonnage cost and estimated vessel cost found in Appendix C by the tonnage lost and vessels lost, respectively. Figure 59 and Figure 60 show the vessels with the lowest and highest costs calculated for the route from Manila to Okinawa.

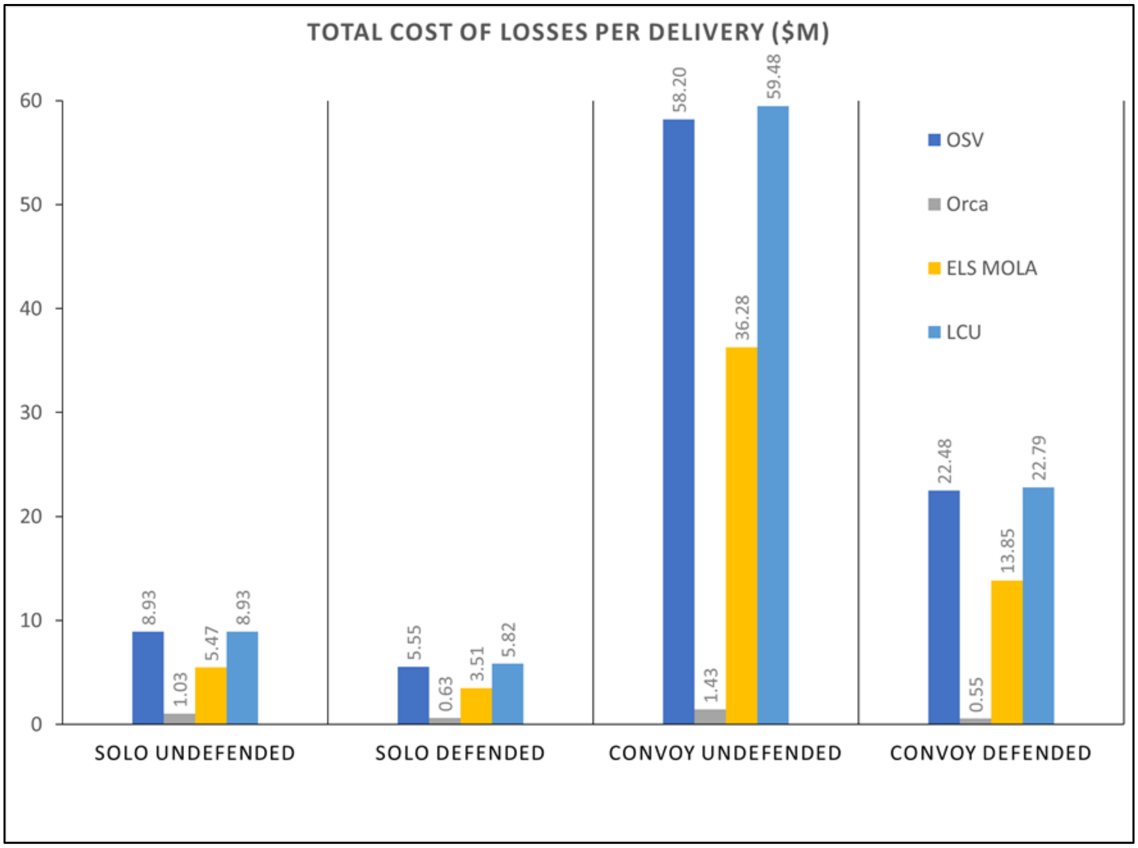


Figure 59. Vessels with Lowest Cost of Losses ($M) per One-Way Transit from Manila to Okinawa

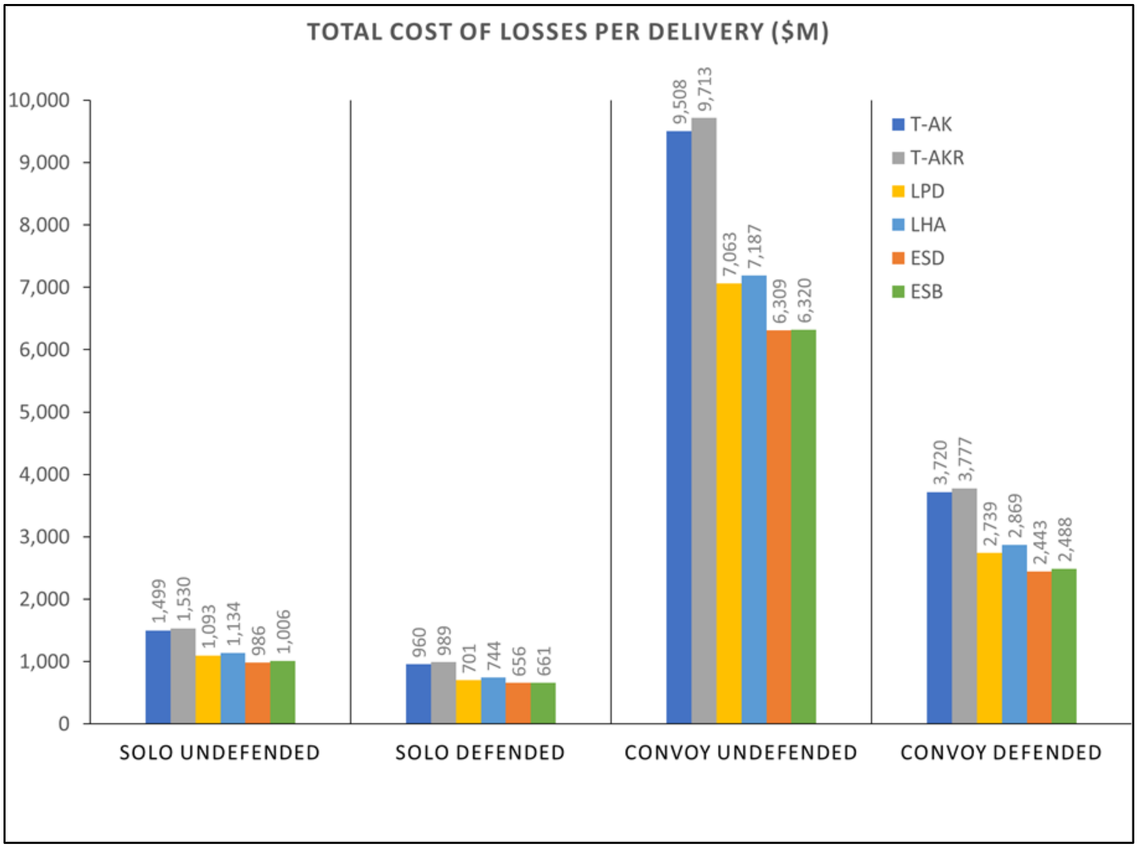


Figure 60. Vessels with Highest Cost of Losses ($M) per One-Way Transit from Manila to Okinawa

The data in the cost plots was beneficial in highlighting which vessels will have, potentially, more costly transits than others. The vessels with the lowest cost of losses were the OSV, ELS MOLA, Orca, and LCU. The vessels with the highest cost of losses were the T-AK, T-AKR, LPD, LHA, ESD, and ESB. Again, these values alone do not indicate a preferable asset. A vessel may have had a low cost simply due to its size, lack of capacity, or low unit cost. The Orca XLUUV was an example of this. It had the lowest values for cost of losses but also had the lowest tonnage delivered values. To apply the cost data more effectively, we divided the cost of losses by the tonnage delivered to create the metric "cost per ton delivered." This metric served as an MOE for each vessel that compared risk to reward. It was not all-encompassing in that it did not include all possible costs incorporated with conducting the transit, such as fuel, ordinance, and crewing costs, but included the cost of risk. That risk was losing vessels and the cargo that they were carrying. Figure 61 and Figure 62 show the vessels with the lowest and highest cost per ton delivered for the transit from Yokosuka to Busan.

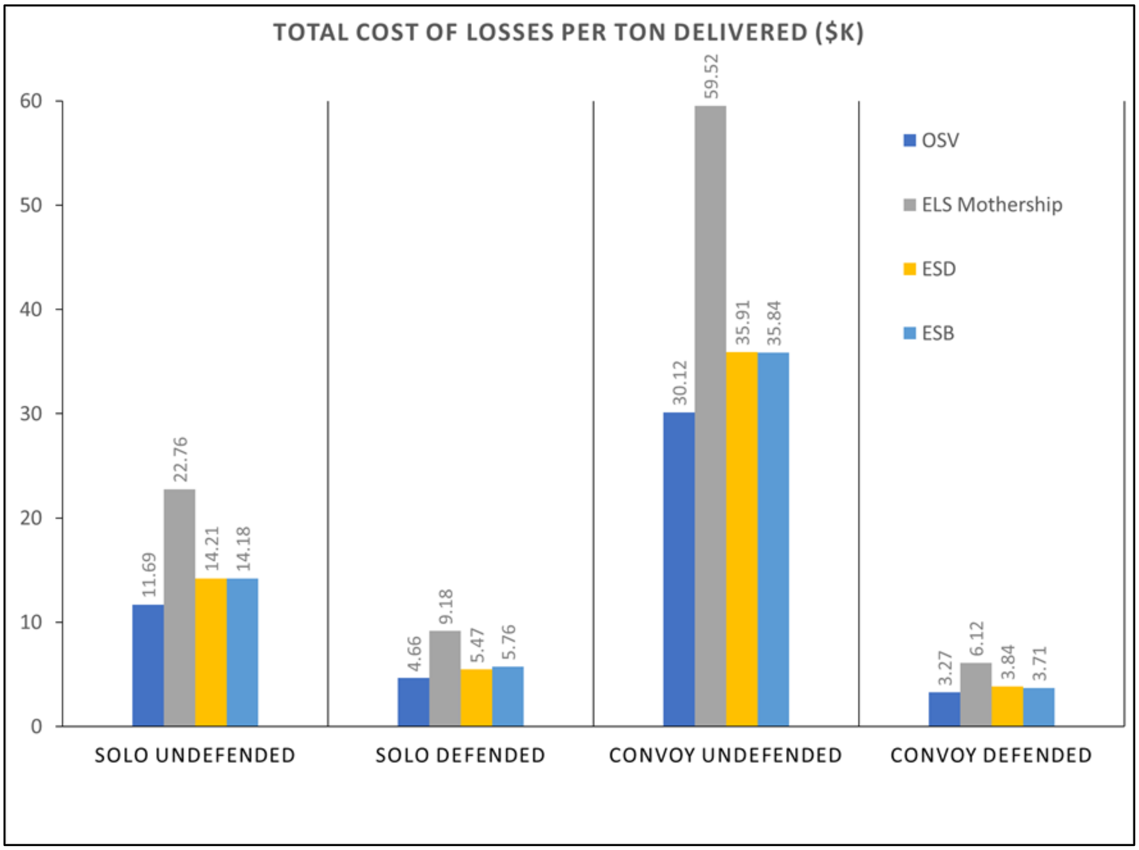


Figure 61. Vessels with Lowest Cost of Losses per Ton Delivered ($K) from Yokosuka to Busan

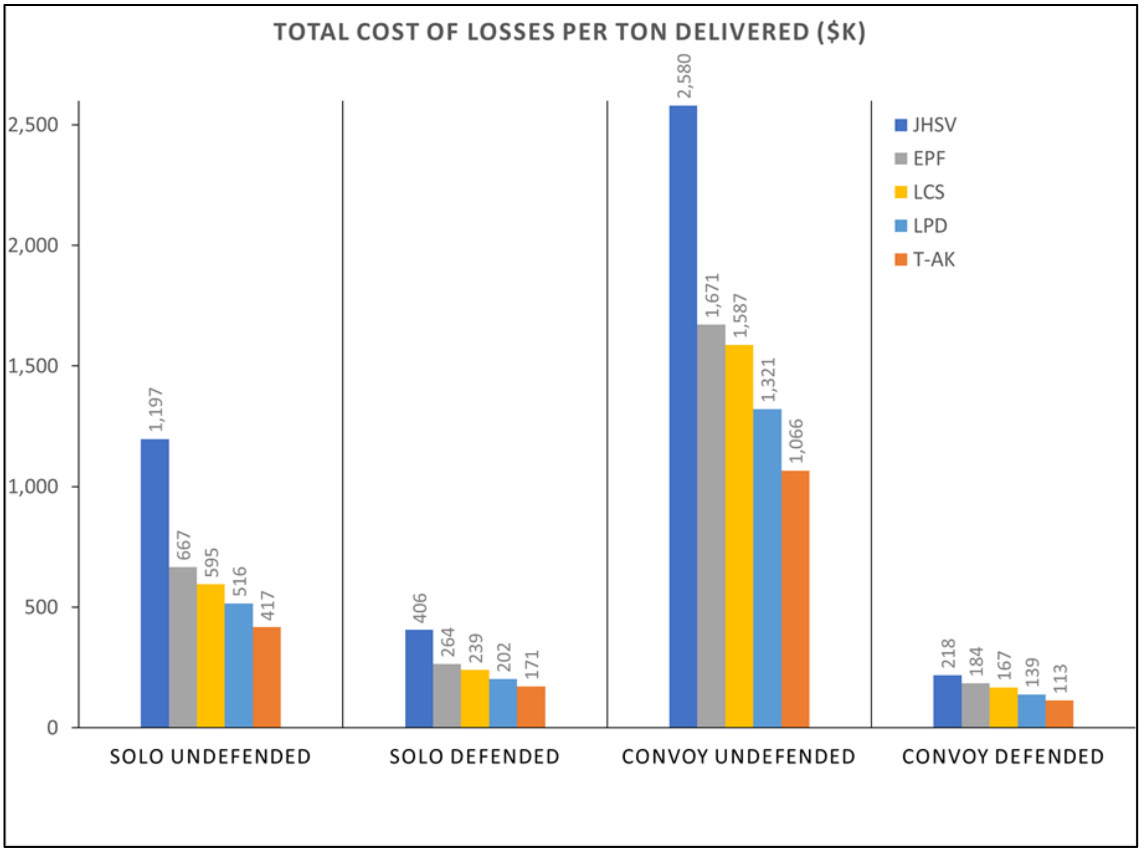


Figure 62. Vessels with Lowest Cost of Losses per Ton Delivered ($K) from Yokosuka to Busan

From these risk-to-reward comparisons, it was evident that some vessels with low cost losses were not as cost effective in terms of delivered tonnage as were some vessels which had very high cost losses. The OSV, ELS Mothership, ESD, and ESB were the most cost-effective in terms of delivered tonnage. The least cost-effective vessels were the JHSV, EPF, LCS, LPD, and T-AK.

C. SENSITIVITY ANALYSIS

Sensitivity analysis was conducted by comparing the baseline configuration results to the results after applying upgrades to the vessels. This was done to determine the effect that these upgrades may have on the vessels. These upgrades, as seen in the inputs interface, were an RCS reduction and a noise reduction. When selected, these reductions were applied within the model as described in Appendix F and Appendix G. The RCS reduction upgrade was applied to all vessels. The noise reduction upgrade was only applied to vessels that did not have the mitigations mention in Appendix G installed organically. The sensitivity analysis was conducted to analyze the effects of each reduction applied separately and applied in conjunction with each other.

1. RCS Reduction Results

To analyze the effect of applying an upgrade to these vessels that would not require the installation of a new combat system element, we first applied the RCS reduction as described in Appendix F. The reduction was applied as an option in the inputs interface of the model. Figure 63 and Figure 64 show RCS reduction data for a sample of vessels transiting from Yokosuka to Okinawa.

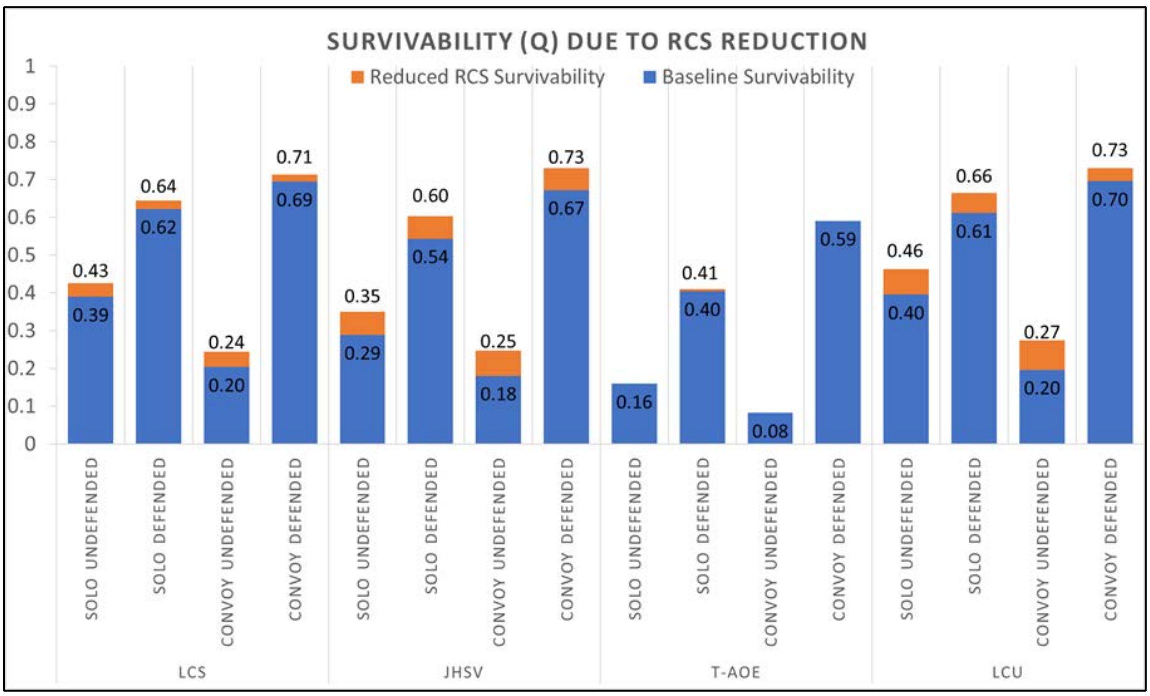


Figure 63. Sample Reduced-RCS Survivability from Yokosuka to Okinawa

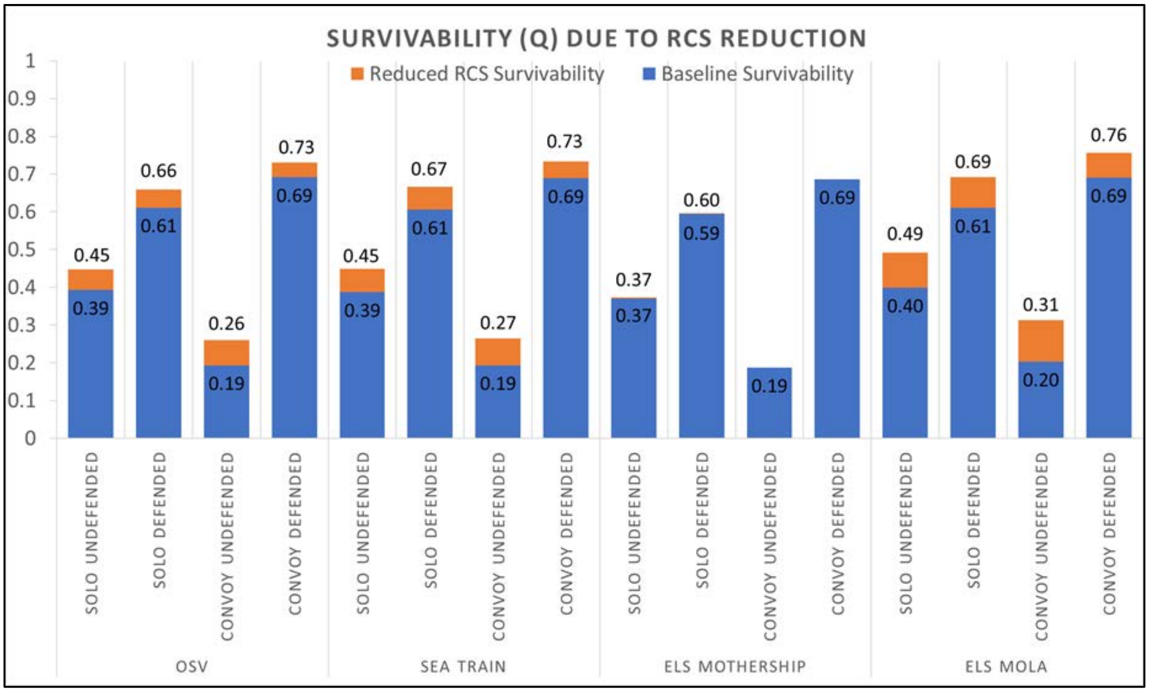


Figure 64. Sample Reduced-RCS Survivability from Yokosuka to Okinawa (Continued)

From the data, we were able to conclude that added reductions in RCS created a noticeable change in vessels with already small RCS. This included LCS, OSV, JHSV, Sea Train, ELS MOLA, and LCU. The added survivability ranged from 0.03 to 0.12 and RCS reduction was more effective for solo configurations than it was for convoy configurations. It should be noted that the route form Yokosuka to Okinawa is fairly low risk. It only crosses one threat region. When RCS reduction was applied to vessels crossing higher numbers of threat regions, the increase in survivability was present, but generated much less of an increase.

2. Noise Reduction Results

Like the RCS reduction, a noise reduction was applied to vessels that did not possess sound level reduction in their original design. The reduction applied was as described in Appendix G. The effect on overall survivability was analyzed. Figure 65 shows a sample of the results of applying a noise reduction for the route from Hawaii to Okinawa.

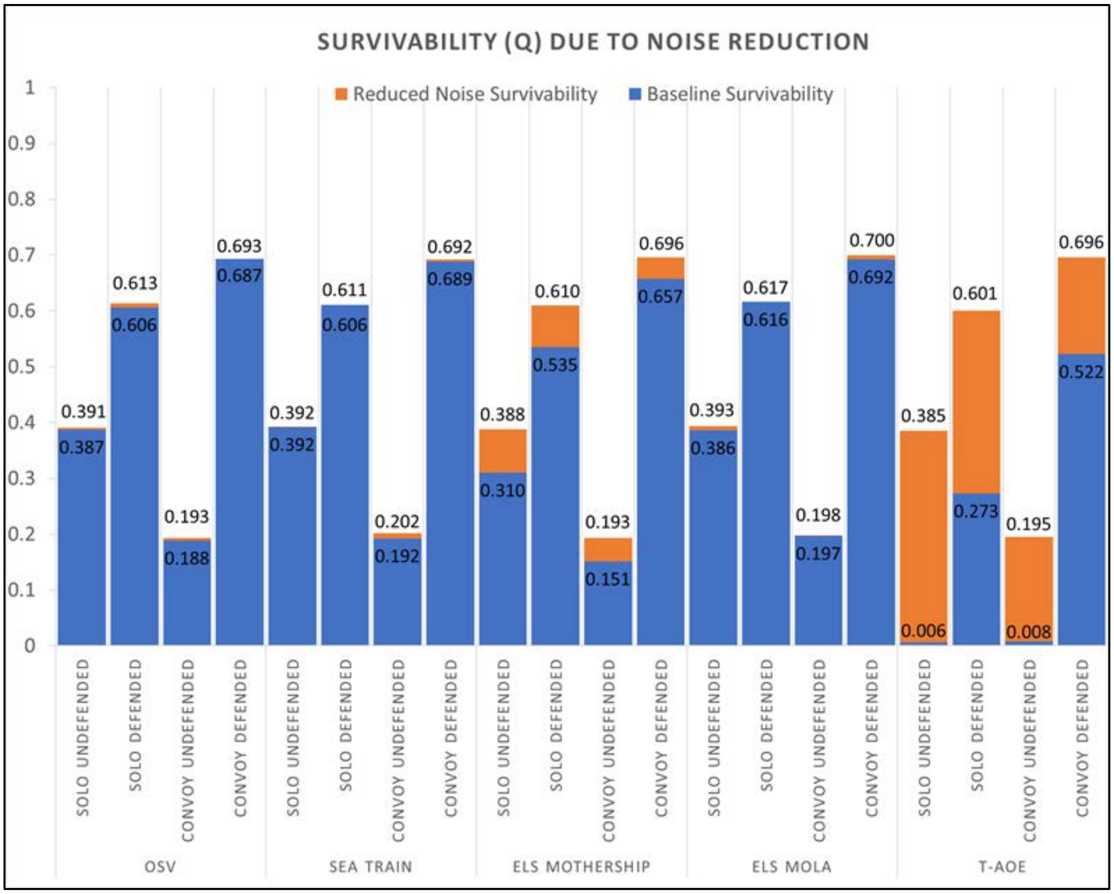


Figure 65. Sample Reduced-Noise Survivability from Hawaii to Okinawa

When we examined the effect of noise reduction, we found that there was an apparent limit to its effect. All vessel survivability values increased to approximately the same value for each configuration. This occurred across all routes. The reduction applied was large enough that it drove the subsurface survivability value to (or very close to) one, essentially removing the effect of the subsurface threat on overall survivability. Because all the vessels started at different noise levels, this shows that there may be a threshold noise value that could be achieved to gain the maximum advantage for noise reduction.

3. Combined Noise and RCS Reduction Results

The final analysis of upgrades analyzed the effect of adding an RCS reduction to the vessels that the noise reduction was applied to. Given the convergence of survivability values for the application of a noise reduction alone, the values for the application for both reductions were not surprising. For vessels whose RCS reduction survivability values were below the noise reduction survivability values, the values after applying both reductions were similar to, if not exactly the same as, the values after applying the noise reduction. For vessels whose RCS reduction survivability values were above the noise reduction survivability values, the values after applying both reductions were similar to, if not exactly the same as, the values after applying the RCS reduction. There were no synergies between the two reductions. The reduction that gave the vessel better survivability values dominated.

D. NETWORK ANALYSIS RESULTS

From the data compiled by the modeling and simulation team, we created a Pacific theater logistics network. The first level of analysis considered edge weighting based upon the distance between logistics hubs and described overall parameters of the network based on the connections between the nodes. The network's characteristics are presented in Table 14.

Table 14. Network Characteristics

Characteristic	***Value***
Number of Nodes	21
Number of Edges	91
Average Degree	8.66
Network Diameter	3
Average Shortest Path Length	1.69
Network Modularity	0.263
Number of Communities	2

The modularity value was on the lower side of the spectrum, indicating the presence of communities, but with a high level of cross-community connection. In the case of distance-based-weighting, the two communities were associated with the South East Asian and East Asian/Pacific Island node clusters. The network diameter value was equivalent to the greatest number of voyages necessary to travel from one node to any other node. Next, we used the threat level calculations to assign an edge weight for each class of assets. Threat level was not an adequate measure, so we formulated an alternative edge weighting scheme. To distinguish between assets, we had to account for the tonnage capacity of each vessel class, and the cost of the losses for each vessel class traversing a specific route. Betweenness centrality, by definition, prioritizes nodes that are endpoints of low-weight edges (Hagberg, Schult, and Swart 2008). We used the following metrics: cost of losses and average tonnage delivered per day by vessel class along an edge. To prioritize edges with low weights, we applied the following edge weighting metric:

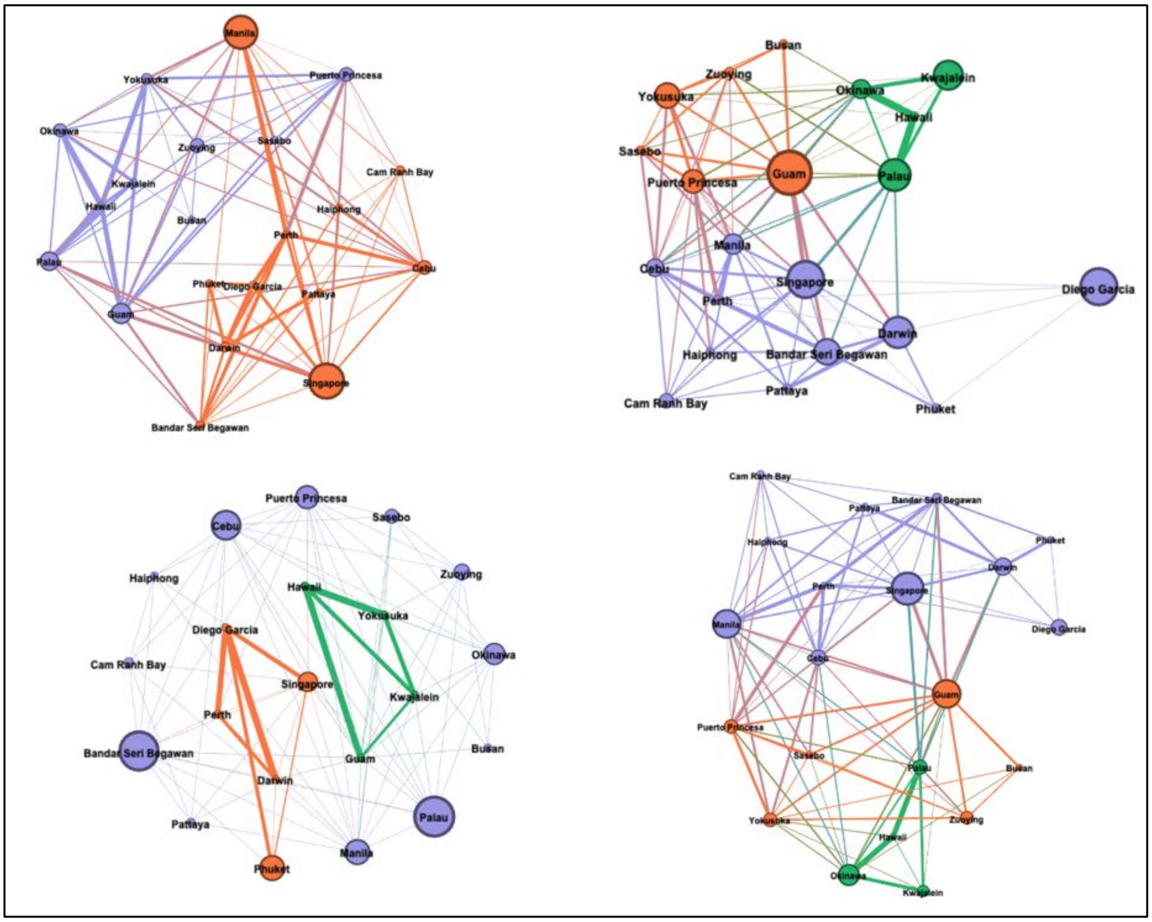
$$W_{ij} = \frac{Cost\ of\ Losses}{Tonnage\ Delivered\ per\ Day}\ .$$

This metric ensured that edges that had low losses and high tonnage deliveries were prioritized. This prioritization accounted for the traversal risk, the monetary value of the vessel and its supply load, the vessel's speed of advance, and the route distance. Table 15 presents the betweenness centrality values of the top ten nodes for four different network layers. Our network analysis only examined the current capabilities of each logistics platform. It did not examine changes to the network that resulted from using convoys or adding defensive layers to vessels. For example, LHA edges were calculated with defensive measures accounted for while T-AOE edges were calculated without defensive measures accounted for. The uncontested network assumed that there was no threat to logistics assets. The LCS layer highlighted the top centralities for a vessel that has defensive capabilities. The T-AKR layer represented large tonnage, slow vessels that do not have defensive capabilities. The T-AKR is most like the modern fleet of MSC vessels used to resupply forward deployed assets. The Orca layer represented a slow, small tonnage, hard to detect asset.

Table 15. Comparison of the Highest Centrality Nodes across Four Vessels

Uncontested		***LCS***	
Node	***Value***	***Node***	***Value***
Singapore	0.192	Singapore	0.189
Manila	0.179	Guam	0.158
Guam	0.089	Manila	0.158
Palau	0.079	Okinawa	0.105
Cebu	0.047	Darwin	0.079
Zuoying	0.047	Diego Garcia	0.068
Puerto Princesa	0.047	Cebu	0.063
Okinawa	0.042	Palau	0.058
Yokosuka	0.026	Yokosuka	0.053
Darwin	0.021	Puerto Princesa	0.053
T-AKR		***Orca***	
Node	***Value***	***Node***	***Value***
Guam	0.268	Palau	0.189
Singapore	0.216	Bandar Seri Begawan	0.184
Diego Garcia	0.216	Cebu	0.126
Palau	0.179	Manila	0.100
Darwin	0.174	Phuket	0.100
Kwajalein	0.158	Puerto Princesa	0.089
Bandar Seri Begawan	0.132	Okinawa	0.079
Yokosuka	0.126	Singapore	0.068
Puerto Princesa	0.111	Zuoying	0.047
Manila	0.089	Sasebo	0.037

The uncontested network favored centrally located nodes, with special emphasis on the importance of geographic hubs. The following three layers accounted for the presence of an enemy threat. The LCS layer continued to place an emphasis on Singapore and Manila, but also noted the increased importance of the out-of-threat-region hubs Diego Garcia and Darwin. The LCS has defensive countermeasures to enemy threats, so it was more survivable within the threat region than a large undefended asset. The T-AKR layer showed a massive shift in importance to hubs that lay on the fringe of the threat region, or completely outside it. This was an indication of the high losses that conventional logistics assets will suffer while operating in a contested environment. The Orca layer's most important hubs were characterized by short distances to other nodes and central geographic location. The Orca layer was notable, because its high probability of survival combined with its low cost focused its nodes within the threat region. Figure 66 is a network visualization of the four aforementioned layers (Bastian, Heymann, and Jacomy 2009). The color of the nodes represents their modularity class. The size of the nodes corresponds to their betweenness centrality value. The thickness of the edge represents the weight of the edge, with thicker edges being costlier. The community grouping is notable, because it was not always the best idea to take a direct, shortest-path route. The visualizations show that it was advantageous to route along less-costly edges on a total path from one node to another.



Clockwise from the top left: Uncontested, LCS, T-AKR, Orca.

Figure 66. Comparison of Network Visualization of Four Vessel Classes.

By analyzing the centrality values of the current nodes, shown in the uncontested network, we observed that a small subset of logistics hubs dominated. The high centrality values of nodes like Singapore and Guam implied the vulnerability of the network to single points of failure. If any circumstances denied access to high centrality nodes, the current logistics system would suffer drastically. The trend held when we examined logistics in a contested environment. Assets with similar attributes relied heavily on a small number of important nodes. Increased diversity of the composition of the logistics inventory would improve the resilience of the system. Adding nodes to the network would also help alleviate the high centrality values of a small selection of the nodes. Using additional ports or creating sea bases in the vicinity of high value nodes would serve to decrease the importance of each single node within the network. In addition to showing the need for increased resilience of the network in case of a nodal failure, our network analysis indicated that certain asset classes are more useful in different threat-level environments. In a highly contested environment, small, cheap, fast vessels delivered tonnage at a greater rate and lower cost. In low-threat environments, slow, large capacity assets are more efficient. Combining these insights, our network analysis supported the courses of action recommended by this capstone project. In particular, our network analysis indicated the need to diversify the logistics inventory in order to succeed in a contested environment. Table 50 lists the top 10 nodes by betweenness centrality in Appendix H.

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V. CONCLUSIONS AND RECOMMENDATIONS

After analyzing the data produced by the model, we developed some key takeaways and trends. First, most vessels shared very similar survivability values transiting routes within the network. The exceptions to this trend were the Orca XLUUV, the JHSV, and the T-AOE. The XLUUV had high survivability due to almost completely eliminated ASBM and ASCM threats. The Orca was only vulnerable to these threats during the time it was snorkeling. During this time, the RCS of its mast was the target for missile threats. Due to the short amount of time spent snorkeling and the small target that was its mast, the ASBM and ASCM threats to the Orca were almost negligible. The JHSV and T-AOE had lower survivability values that were most likely attributable to their very high noise levels.

The second set of takeaways came with the delivery and loss data. We concluded that almost all vessels completed less than one round trip and only about one delivery. This is a daunting outcome that alone proves the need for upgrade of the logistics capabilities of the U.S. Navy. It was clear that undefended vessels delivered less cargo tonnage than they lost and that defended convoys delivered the most tonnage per vessel. When we examined cost of losses alone, it seemed that smaller, more survivable assets were preferred. The vessels with the lowest cost of losses per delivery were OSV, Sea Train, ELS MOLA, Orca, and LCU. The vessels with the highest cost of losses were the T-AK, T-AKR, LPD, LHA, ESD, and ESB. This metric, however, was not a final indicator of preferred assets because it was affected by scale.

To better analyze the cost of losses, we divided the cost of losses values by tonnage delivered to create a measure of performance that related risk to reward. The risk was the monetary losses likely to occur on each transit. The reward was the tonnage delivered. The vessels that performed the highest under this MOP were the OSV, ELS Mothership, ESD, and ESB. The vessels with the lowest performance were the JHSV, EPF, LCS, LPD, and T-AK. This is contrary to the established notion that distributed logistics are the answer for distributed operations and should be examined. The OSV, ELS Mothership, ESD, and ESB perform well for this metric because they are relatively cheap and have a large cargo capacity relative to their size. Their low prices come from their lack of complexity as generic cargo carriers that are not overly inundated with excess systems.

These results do not exclusively conclude that using gross tonnage vessels in convoy configurations is the answer to logistics in a contested environment. Though not as well as the OSV, ELS Mothership, and ESD and ESB, other vessels performed fairly under this metric. This metric is very cost focused. If the main goal is to minimize cost and the fact that a certain level of loss may occur is accepted, then it is highly recommended that these options are explored and implemented. However, there are other factors that were not analyzed that should also be examined. These include speed of delivery and agility of assets. Large cargo vessels that can get the most delivered with the least amount of monetary losses are ineffective if they cannot deliver on time or in the correct manner.

Lastly, we analyzed the effect of reducing RCS and noise level on vessel survivability. Reductions in RCS were effective for vessels that already had a low RCS. These reductions were less effective as the threat level of a route increased and were more beneficial for undefended configurations. Reductions in noise seemed to be beneficial to only a certain point. The reduction used was large enough that it drove the survivability against submarines to nearly or exactly one for most vessels. This removed the effect of submarines on the overall survivability. The vessels in this configuration all had very similar survivability values. This not only showed that noise level reduction could play a crucial role in decreasing the submarine threat to almost nothing but also that it was variation in survivability against submarines that was the main cause for variation in the survivability values of most of the vessels. We examined the effects of adding both noise and RCS reductions to some vessels. We found that the reduction that created the best survivability values dominated.

Given the performance of the vessels analyzed with regards to losses per ton delivered, the course of action that we recommend pursuing are the Offshore Support Vessel Concept, the ELS Concept, and Traditional Logistics Utilizing ESD and ESB. For the OSV Concept and the ELS Concept the CLF HVU can be the ESD, ESB, or ELS Mothership. Contrary to what was initially proposed, the performance of these large vessels in terms of losses per ton delivered, allows them to enter the contested environment. The distributed logistics asset could then occur later in the supply chain. For the ELS concept, the MOLA should attempt to emulate OSV and/or Orca XLUUV characteristics as much as possible. No matter what course of action is chosen, added defense of these vessels is highly beneficial and highly recommend. This could come in the form of upgrading onboard defenses or providing some sort of defensive escort. Lastly, RCS and noise reduction should be done on all vessels as practical. This is especially important to vessels projected to be traveling alone. In consideration of cost, it is beneficial to determine which reduction would have the greater impact to survivability and apply that reduction alone.

A. RECOMMENDED FUTURE WORK

Over the course of this work, many concepts, variations, technologies, and questions arose that there simply was not enough time to fully evaluate. As such, our team has identified several related areas that warrant future analysis.

In some respects, we are fortunate to know that the efforts in this project have already inspired additional thesis work by one of our team members. As we have leveraged some portions of Ensign Sorenson's network model in this effort, an additional academic quarter will enable him to advance his findings. Some areas where his thesis, titled *Logistics in a Contested Environment: Network Analysis and Flow Optimization*, will further our efforts are:

- Evaluate our network to pinpoint critical nodes and expose vulnerabilities.
- Evaluate a maximum flow algorithm to determine optimal routing and upper bound for sustainable combat operations intensity in the Pacific theater.
- Evaluate the tradeoffs to consider whether it is preferred to operate using infrequent mass deliveries or frequent smaller deliveries.

Additionally, some members of our group will participate in the OPNAV N4 Logistics Wargame, tentatively scheduled in July 2020. Members of our team will directly contribute their subject matter expertise in addition to insights and recommendations contained within this work. This will enable evaluation of recommended concepts via a second analytic method, wargaming.

Other specific areas of interest for future work include:

- Application of our methods to a logistic network focused in the Atlantic Ocean. While we suspect that most of our insight and analysis will remain valid, understanding the impact of shorter overwater routes, the potential for more overland routes, and other variations in the operational environment may generate valuable information for decision makers.

- Exploring the effects of reducing the demand signal. What if, for example, the same units that define our demand signal could operate with the same effectiveness with 20% less supply? Will corresponding reductions in logistic asset attrition hold a proportional ratio? Understanding this question might highlight the value in concepts like additive manufacturing, locally sourced supply, and alternative fuels.

- Adding network layers that effectively estimate contributions of airborne logistics assets. Emerging technologies in hybrid airship vehicles and amphibious aircraft offer interesting alternatives that may accelerate delivery timelines and reduce threat exposure.

- Exploring solutions to reload missiles into vertical launch systems and torpedoes into submarine magazine in the AO and at sea. With a limited number of shore facilities currently capable of reloading our combatants, and no capability to reload at sea, combatants will spend considerable time off station to replenish their inventory. In a high-end fight, the rate of weapon expenditure is likely to be extraordinary and sustaining the conflict will require new and better ways to reload.

- Analyzing the enemy cost to sink and destroy assets. The modeling and simulation conducted made assumptions regarding the propensity of the enemy to attack. Further analysis regarding the cost and risk of attack for the enemy, versus the reward of sinking or destroying a particular asset, would lead to more accurate enemy attack doctrine. The information acquired could be applied to game theory processes to further determine both enemy and allied doctrine.

- Conducting cost-benefit analysis of modifying current vessels. We made recommendations regarding upgrading defense systems, reducing RCS, and reducing noise level. Determining the cost of these upgrades would further affect the decision to utilize them in the future.

- Analyzing vulnerability to specific threats. In our analysis of noise level reduction, we identified the submarine threat as the most variable across platforms. However, when this threat was practically eliminated, survivability remained low. Analysis regarding the most detrimental threat to the assets and ways to reduce the threats could lead to further course of action development.

- Conducting follow-on analysis inclusive of platform capability. This analysis focused on the ability to deliver tonnage and compared it to cost of said delivery. Though vessel characteristics and capabilities were factored into survivability analysis, time and manner of delivery were not constraining in determining performance of specific vessels and bounding recommendations. Exploring different operational constraints such as speed, manner of delivery, and nodal access constraints would be beneficial to continue analysis of the suitability of these platforms for use in future logistics architectures.

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APPENDIX A. COMMUNICATIONS ANALYSIS

Although we deemed communications (COMMS) beyond the scope of our analysis due to time and resource constraints, we recognized the vulnerability to U.S. logistics systems that COMMS present when operating in a contested environment (CE). Therefore, we analyzed threats to communication, researched current, planned, and conceptualized technologies, formulated scoring criteria, and proposed several potential COMMS solutions based on our findings.

Currently the United States armed forces operate logistics on a need-driven basis, known as "pull" logistics—supplies are not shipped based on estimates, but rather on reported need. This method requires a COMMS network that allows warfighters reliable connectivity to signal their demand and pull supply from the logistics system. Network speed/bandwidth requirements vary between assets. Currently the U.S. force operates primarily on vulnerable lines of communications, leaving the logistics communication network susceptible to disruption.

The types of supplies that are required range anywhere from basic human necessities such as food and water to fuel to armament consisting of bullets, mortars, missiles, rockets, and torpedoes to medical supplies. The wide range and disparity between types of supplies is coupled with a diverse fighting force. The U.S. forces illustrated in the "Global War 2030—Two Years In" scenario span across all branches and every available asset in the U.S. armed forces arsenal. This makes for a complex and complicated logistics network that dependent upon the communications network. The ability to maintain "pull" logistics is crucial to maintain efficiency with respect to logistics and the U.S. has not operated on a "push" logistics network to a large magnitude since World War II.

A. THREATS TO COMMUNICATIONS

In the context of the "Global War 2030," it is anticipated that the U.S. forces will be operating in a communication degraded or communication denied environment due to the presence of formidable adversaries. Peer competitors can disrupt communication networks through the hostile actions of jamming, denial, spoofing, hacking, and physical destruction. The resulting effects range from minimal to catastrophic. At the low end of the spectrum, communications are disrupted or delayed but can be rerouted successfully. At the high end of the spectrum, entire communication networks are disabled, and individual units will operate in complete isolation from one another. Attacks on information sharing will manifest in the logistics system by interfering with the ability to transmit demand signals from the warfighter in need to relevant sources of supply. Furthermore, maintaining inventory awareness will prove untenable without routine information sharing. This makes the entire logistics system vulnerable through communications, since failing to know which units are in need or where demanded supplies are within the system at any given time renders the system inoperable.

B. POTENTIAL SOLUTIONS

While developing a supporting communications system was deemed outside the scope of our efforts, we did evaluate several external threads of effort for potential COMMS architectures that could support the system. The candidate systems were drawn initially from ideas introduced at the 2019 WIC Workshop, relevant theses, and capstone efforts at NPS, and from commercial efforts referenced by stakeholders and subject matter experts.

1. Attritable Communications/Logistics System

Team Demeter was the nickname for one of the working groups at the 2019 WIC Workshop. Their presentation of the Attritable Communications/Logistics System described a system of autonomous, solar-powered UAV's, soaring in the upper atmosphere. The solar chargers on the UAV enable each unit to maintain indefinite, persistent presence in its area of operations. Furthermore, the maneuverability of the platform would enable it to exploit favorable positions in the environment to make jamming efforts less effective. By increasing and decreasing altitude quickly, the UAV can get close enough to burn through adversary jamming and interference. Each UAV would carry a communications payload to transmit and receive logistics data in a communication degraded or communication denied "Global War 2030" conflict. This system would utilize EHF point-to-point upload/download communications with naval assets, shore installations, and other UAVs to create a robust and resilient network. This would enable fast, reliable, and resilient communications to transmit logistics needs. Since this system is purely conceptual, attributes of the Airbus Zephyr, a commercially developed solar-powered glider, were utilized for comparison against other systems. The payload capacity of the Zephyr is 500 pounds (Airbus n.d.), which is enough to support an encrypted communications transmitter/receiver system as well as a camera to provide the capability to conduct ISR operations. As a tertiary mission and potential application of this asset is the capability of providing third-party targeting. We assess the Technology Readiness Level (TRL) to be a 6 for this system. For a price comparison, we utilized the ARC-210 cost estimate from the U.S. General Services Administration (GSA) and added a buffer bringing to a total estimate of $50,000 per transmitter/receiver.

2. Starry Night System

Another WIC Workshop group, Team Hermes, introduced the Starry Night System. In place of the gliders in Team Demeter's Attritable Communications/Logistics System, Starry Night utilized maneuverable stratospheric balloons. This resulted in a significant decrease in cost, as the estimated price tag for a weather balloon is between $200 and $300 (Stratostar n.d.), so we will assume the stratospheric balloon to cost $1,000. Stratospheric balloons modify their altitude in search of air currents that best support their desired ground track. As such, they cannot maintain station, but may be able to achieve favorable environmental conditions to mitigate enemy jamming efforts. Many balloons in series would be necessary to maintain continuous communication coverage over a desired area of operations. The network would also create a secure upload/download communications network linking ground-based units, naval assets, and balloons to transmit logistics information. A real-world application of this technology is already in existence. Loon is a project designed to connect people everywhere by extending connectivity to billions of people around the world. Loon partners with mobile network operators to provide LTE service to areas around the globe that lack the current capability (Loon n.d.). This type of technology would provide the same secondary and tertiary mission capabilities proposed for the Zephyr-style UAV. The benefit to this asset over the Zephyr-style UAV is the extremely low cost of an estimated $17,870 per balloon (comm suite and camera excluded) according to a report by James Burr (2016) this type of asset could also alter its altitude to achieve burn through, but it would take considerably more time to do so in comparison to the Zephyr style UAV. A stratospheric balloon can be manufactured in days and the launch process is about 30 minutes (Loon n.d.). For this reason, building a large inventory of these is not necessary until conflict seems imminent. The report by Burr also identifies the payload capacity is approximately 67 pounds, which is adequate for the communications equipment anticipated. As this system has already been fielded, we assess a TRL of 8. We utilized the ARC-210 cost estimate from the U.S. General Services Administration and added a buffer bringing to a total estimate of $50,000 per transmitter/receiver again for price comparison purposes.

3. Underwater LED-Based Communications Links

A current NPS thesis effort by Capt. Nowak (2020), proposes the use of underwater, LED-based Communications Links into tactical, military scenarios. This technology offers high bandwidth, low cost, and power efficient underwater communications. While the thesis aimed to improve short range underwater wireless communications between assets at ranges of 5 to 15 meters, it also references the capability for significantly longer-range underwater data transmission using traditional acoustic transmission. Potential benefits to using optical transmissions over acoustic and RF wireless communications include a narrow beam-width for directional links, increased data rates, faster transmission speeds, and low probability for intercept and detection (LPI/LPD). This system would utilize secure buoys as communications relays throughout an AO, preventing the need for underwater assets to snorkel as frequently and serve as a relay to satellite communications.

4. Starlink Satellite Program

SpaceX’s Starlink Satellite program is a current commercial endeavor to surround the Earth with 12,000 low-orbit satellites to provide high-speed, low-latency, and affordable internet to all corners of the globe by the year 2027 (Mosher 2019). These satellites will orbit at 273 miles above the surface. Geosynchronous orbit is orders of magnitude higher at roughly 22,000 miles above the surface. The reduction in distance between satellites and ground stations will greatly reduce the latency inherent in current satellite communications. Each satellite will act as a router, relaying information to four other satellites via lasers. The worldwide network created enables long range, resilient, and secure information sharing without going through traditional fiber optics (of which some networks may have been compromised by the adversary). Such a system will allow each user or platform to connect directly to the network from anywhere in the world, provide speeds equivalent to traditional terrestrial wire-based internet, improve security by reducing the ability of the adversary to tap the network, and improve resiliency by the sheer number of satellites used.

5. Current Army and Marine Corps Logistics Network

The logistics network currently utilized by the U.S. Army and USMC is the Logistics Communications Network, Global Combat Support System (GCSS). This system acted as our baseline for comparison against the other concepts and represented the way we currently utilize communications in a logistics capacity. This Oracle-based software and internet-based network rides on the existing tactical data network and can be accessed anywhere with network access, whether stateside or deployed. While deployed, various satellite assets can be utilized to provide the network connection, and operators of the system attend a few days of training and learn much of the system nuances on the job. The system provides enterprise wide visibility and accountability with a single point of entry for all logistics requirements (USMC n.d.)

6. Line-of-Sight Surface Vessel Network

The Line-of-sight (LOS) Surface Vessel Network operates in the same fashion as the Team Demeter and Team Hermes proposed networks. It was a concept proposed during the WIC but not included in the workshop's final report. The difference here is that this system utilized surface vessels, manned or unmanned, to transmit via LOS as a giant mesh network on the waters of the world. The range of communications at sea level will be significantly less than you can achieve in the upper atmospheres and the expected number of vessels required would be substantially greater than in the Team Demeter and Team Hermes systems.

7. Wireless Mesh Network

Another NPS Thesis effort by Edward Crapino (2019), advocates for a wireless mesh network (WMN) concept. He suggests that data flow can be maintained via directional antennas, ultrawideband sensor networks, and range augmentation using tactical airborne networks and the Defense Advanced Research Projects Agency's Towed Airborne Life of Naval Systems. This network can be realized with manned or unmanned vessels and suggests that unmanned vessels could be weaponized to add defense layers to the network.

C. ANALYSIS

The candidate communications systems were ranked using the Analytic Hierarchy Process (AHP). AHP is a weighted scoring method that combines system performance attributes with the relative value of each category to rank overall performance. The scoring matrix, shown in Table 16, breaks down attributes deemed to be defining characteristics of a communications system.

Table 16. Communications System Scoring Matrix

	1 (Worst)	2	3	4	5 (Best)	Notes
Network Susceptibility	>50%	25-50%	10-25%	1-10%	<1%	Probability that enemy will compromise the system and/ or data transferred
Adaptability and Interoperability	Completely independent system	-	Adaptable for at least 2 branches and a minimum of 5 assets	-	Universally adaptable across all assets and branches	Branches are USN, USA, USMC, USAF, USCG. Assets refers to ships, installations, aircraft, etc.
Robustness	Single point of failure exists	At least 1 element of redundancy per node	At least 2 elements of redundancy per node	At least 3 elements of redundancy per node	>3 elements of redundancy per node	-
Resiliency	>25%	25-49%	50-74%	75-99%	>99%	Attacks can be physical and/ or cyber
Time to Implement	>20 years	17-20 years	14-16 years	13-10 years	<10 years	Timeframe to implement at full operational capabilities (Acquisition estimate is 5 years)
Coverage	<25%	25-50%	50-75%	75-99%	>99%	% of global coverage
Speed & Bandwidth	<100 MB/sec	100-500 MB/sec	500MB-1GB/sec	1-10GB/sec	>10GB/sec	Average data exchange rate
Foreign Interoperability	U.S. Only	-	Interoperable with NATO	-	Interoperable with all major allies and coalition forces	Major allies are U.K., Canada, Israel, Japan, South Korea, France, and Australia.
Cost	>$10B	$1B-$10B	$500M-$1B	$1M-$500M	<$1M	Rough estimate of initial investment

Category weights were also established using input from stakeholders, subject matter experts, and the operational experience of the team. Attributes with a weight of three were deemed mission critical whereas a weight of one signified an attribute deemed not mission critical.

Table 17. Attribute Weights

Candidate Systems	***Weights***
Network Security	3
Adaptability & Interoperability	3
Robustness	2
Resiliency	3
Network Requirements	1
Coverage	2
Network Speed & Bandwidth	2
Foreign Interoperability	1
Cost	2

Raw scores for each candidate system were assigned individually using the matrix (higher scores are better). The scores were then averaged, and the resultant raw scores are annotated in Table 18. Table 19 lists the results after application of the weights to the raw scores. Finally, the systems were ranked based on their weighted scores where the number one ranking is the most favorable system. The system rankings are listed in Table 20.

Table 18. Raw Scoring of Communication Systems

Candidate Systems	***Network Security***	***Adaptability & Interoperability***	***Robustness***	***Resiliency***	***Network Requirements***	***Coverage***	***Network Speed & Bandwidth***	***Foreign Interoperability***	***Cost***	***Total Score***
Attritable Comms/Logs System	4.0	5.0	4.0	5.0	3.7	3.7	3.3	5.0	1.3	**35.0**
Starry Night System	4.0	5.0	4.3	4.7	4.7	3.7	3.3	5.0	4.0	**38.7**
Underwater LED-Based Comms Links	4.0	1.7	1.7	3.0	3.0	2.0	4.0	2.3	2.7	**24.3**
Underwater Wi-Fi Acoustic Networks	3.0	1.0	2.7	3.7	4.0	2.0	1.0	3.0	3.3	**23.7**
Current Logistics Comms Network	2.0	2.3	2.3	2.0	5.0	4.7	3.7	1.0	5.0	**28.0**
Starlink Satellites	4.7	5.0	4.0	4.7	2.3	5.0	3.3	5.0	1.7	**35.7**
LOS Surface Vessel Network	3.3	3.0	4.0	3.7	4.7	2.3	3.0	5.0	1.3	**30.3**
WMN Concept	3.3	3.0	3.7	3.7	4.3	2.3	3.0	5.0	2.0	**30.3**

Table 19. Weighted Scoring of Communication Systems

Candidate Systems	***Network Security***	***Adaptability & Interoperability***	***Robustness***	***Resiliency***	***Network Requirements***	***Coverage***	***Network Speed & Bandwidth***	***Foreign Interoperability***	***Cost***	***Weighted Score***
Attritable Comms/Logs System	12.0	15.0	8.0	15.0	3.7	7.3	6.7	5.0	2.7	**75.3**
Starry Night System	12.0	15.0	8.7	14.0	4.7	7.3	6.7	5.0	8.0	**81.3**
Underwater LED-Based Comms Links	12.0	5.0	3.3	9.0	3.0	4.0	8.0	2.3	5.3	**52.0**
Underwater Wi-Fi Acoustic Networks	9.0	3.0	5.3	11.0	4.0	4.0	2.0	3.0	6.7	**48.0**
Current Logistics Comms Network	6.0	7.0	4.7	6.0	5.0	9.3	7.3	1.0	10.0	**56.3**
Starlink Satellites	14.0	15.0	8.0	14.0	2.3	10.0	6.7	5.0	3.3	**78.3**
LOS Surface Vessel Network	10.0	9.0	8.0	11.0	4.7	4.7	6.0	5.0	2.7	**61.0**
WMN Concept	10.0	9.0	7.3	11.0	4.3	4.7	6.0	5.0	4.0	**61.3**

Table 20. Communication System Rankings

Candidate Systems	***Raw***	***Weighted***
Attritable Comms/Logs System	**3**	**3**
Starry Night System	**1**	**1**
Underwater LED-Based Comms Links	7	7
Underwater Wi-Fi Acoustic Networks	8	8
Current Logistics Comms Network	6	6
Starlink Satellites	**2**	**2**
LOS Surface Vessel Network	4	5
WMN Concept	4	4

D. RECOMMENDATIONS

To make our logistics communication network more survivable we recommend that we utilize a robust, resilient, and mixed network consisting of our current satellites, solar-powered UAVs and maneuverable stratospheric balloons. Our recommendation is a mix of the two, which could provide global coverage with as few as 153 stratospheric balloons and 100 solar-powered UAVs for approximately $515.4M, working in concert with the existing satellites. This should result in efficient and effective communication coverage for the Pacific and Atlantic AOs combined. These systems would communicate with one another via designated frequencies. Solar powered UAVs would be dedicated to major assets and installations to provide faster burn through, if necessary. The maneuverable stratospheric balloons would then be dispersed as required to ensure effective and efficient relay of communications is achieved at the lower orbits across the AO. The current satellites would maintain communications with these assets as well to serve as a form of redundancy and fortification to the system. Figure 67 is a conceptual illustration of what this system could look like operating in the Pacific AO.

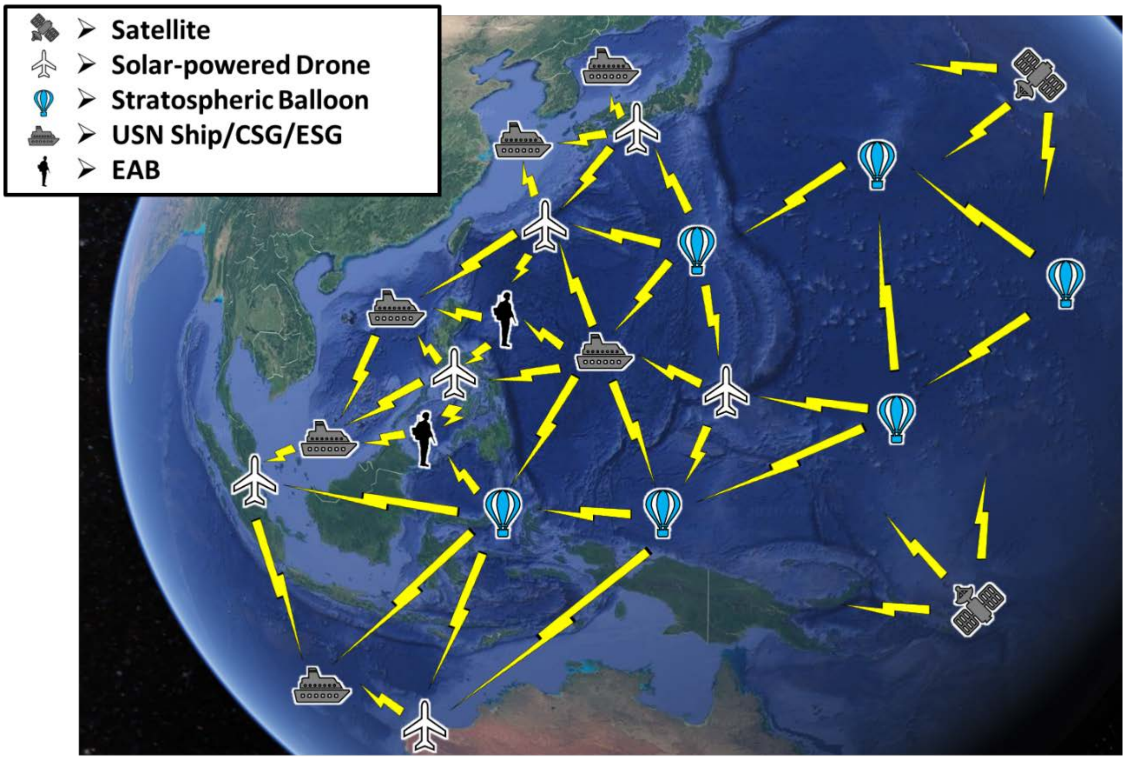

Figure 67. Recommended Communication System in Pacific

Of note, the reasoning for choosing Team Demeter's concept over the Starlink Satellite system is due to the uncertainty of the Starlink system being dedicated solely for military use. In the event it would be unreasonable or infeasible for the government to procure and have sole possession of the Starlink system, utilizing this system would add increased levels of susceptibility and vulnerability to a logistics communications network. Therefore, despite being outperformed by the Starlink System, we determined the solar powered UAVs was the better option IOT achieve a secure, reliable, robust, and redundant communications network.

Leverage cost asymmetry where possible.

A cost asymmetry advantaged is realized when the adversary must pay more to destroy an asset than it costs friendly forces to replace. This creates a win-win scenario where the asset either performs its mission freely or generates a net positive resource advantage if the enemy chooses to destroy it. The solar UAVs in the Attritable Communications/Logistics System is estimated to cost around $5M. Most, if not all, missiles capable of destroying the asset by the adversary will cost more. This imbalance generates a virtual defense for the asset. The maneuverable stratospheric balloons, costing less, would be an even greater imbalance.

We recommend employing one solar UAV for each major asset, and base, and EAB within the operating areas of conflict. Another asset that would comprise this fortified logistics communications network is a maneuverable stratospheric balloon.

Utilize flexible frequency bandwidth and encryption.

The communication transmitters and receivers must support encryption as well as possess the capability of spanning frequencies from HF to EHF. This provides a redundant means to overcome heavy interference due to atmospheric conditions and/or adversarial jamming. It also allows for smaller assets not capable of utilizing a wide range of frequencies to communicate with airborne relays. Our calculated RF ranges for this system is shown in more detail in the attached spreadsheet and assumes a conservative 50% attenuation factor. We estimated that the UAVs and balloons could transmit distances out to approximately 530 miles at an altitude of 70-thousand feet. This provides for over roughly 281-thousand square miles per asset. Taking in to account our cost estimate of solar-powered UAVs plus the transmitter/receivers it would cost approximately $1.3B to cover the Pacific Ocean, Indian Ocean, and Mediterranean Sea, and only approximately $35.5M to have global coverage with the stratospheric balloons.

Create links between underwater and airborne communication networks.

If UUVs and submarines are utilized in a logistics role, we recommend utilizing the encrypted underwater Wi-Fi acoustic networks between the assets and secure buoys. Though our scoring showed the underwater LED-based communications link performed better than the acoustic networks, its limited range of 5–15 meters made it very undesirable for application to covering millions of square miles. In the subsurface realm, our recommendation is to equip secure buoys throughout the conflict AOs that can act as communication relays between submarines and UUVs. These buoys could then transmit to and receive from the UAVs and stratospheric balloons. This would be a relatively inexpensive application as it would merely be an install of the acoustics communication systems, if necessary. The assumption in this case that UUVs are already being utilized, submarines already operating in need of logistics, and buoys that are already in the water therefore they are not cost considerations for this analysis. It is also known that submarines utilize encrypted underwater acoustic communications, so it is understood that the system is already technologically matured making for a quick application.

APPENDIX B. BLUE FORCE MODEL INPUTS

Table 21 contains data pertaining to the logistics assets utilized in our model and simulation. The data, unless otherwise annotated, was obtained online utilizing the Navy Fact File. For LCS, parameters were averaged between the Independence and Freedom Class variants. Regarding T-AO, the displacement is an average between the single and double hull designs. The TSSE Mothership's parameters were based on the motor vessel *Blue Marlin*. For T-AK, the parameters were averaged amongst the *Sgt. Matej Kocak, 2nd Lt. John P. Bobo, 1st Lt. Harry L. Martin, Gunnery Sgt. Fred W. Stockham,* and *Lance Cpl. Roy M. Wheat* classes. The T-AKR parameters were averaged amongst the *Gordon, Shughart, Bob Hope,* and *Watson* classes. The LCU parameters were averaged between the 1610 and 1700 classes. Finally, regarding the ESD and ESB, cargo capacity was based on General Dynamics NASSCO's *Alaska*-class crude oil carrier. These averaged parameters were used consistently in Table 22 and Table 23.

Table 21. Model Inputs: Logistics Assets (Non-Rendered Data)

Ship	***Range (nm)***	***Avg. Speed (kts)***	***Cargo Capacity (short tons)***	***Displacement (gross long tons)***	***Length (m)***	***Beam (m)***	***Height (m)***
LCS	3500	16	1400	3666	123.3	24.6	38.5
JHSV	1200	35	600	2461	103.0	28.5	20.0
T-AOE	6000	25	29291	48800	229.8	32.6	46.0
T-AO	6000	15	26838	41063	206.5	29.7	46.0
T-AKE	14000	20	11075	41000	210.0	32.3	46.0
LHA (America-Class)	9500	16	16460	43745	260.7	32.3	46.0
LSD	14800	15	6440	16708	185.6	25.6	46.0
LPD	5000	16	5691	24900	208.5	32.0	63.4
OSV	5500	13	2000	1450	60.0	11.2	25.0
Sea Train	9000	15	1000	1786	103.0	28.5	20.0
TSSE Mothership (1)	14000	15	30000	55000	153.6	41.5	46.0
TSSE MOLA (1)	4500	8	48	188	20.4	7.9	2.0
Orca (2)	6500	3	8	50	15.5	2.6	2.6

Ship	***Range (nm)***	***Avg. Speed (kts)***	***Cargo Capacity (short tons)***	***Displacement (gross long tons)***	***Length (m)***	***Beam (m)***	***Height (m)***
T-AK	6000	15	9578	46110	231.9	32.0	46.0
T-AKR	6000	15	13000	62583	288.0	32.3	46.0
T-AKR	6000	15	8158	61035	288.9	32.3	46.0
Expeditionary Fast Transport (EPF)	1200	25	600	2461	103.0	28.5	20.0
LCU	1200	8	155	314	41.8	9.3	6.0
Expeditionary Transfer Dock (ESD) (3)	9500	15	193830	78000	239.3	50.0	46.0
Exped. Sea Base (ESB) (3)	9500	15	193830	90000	239.3	50.0	46.0
Sentry USV (4)	1070	15	2.5	9	-	-	-
Sea Hunter (MDUSV)	10000	12	60 (5)	129	40.0	15.0	25.0

Adapted from DON (n.d.) unless otherwise annotated. (1): Alexander et al. (2020); (2): Boeing (2017); (3) General Dynamics (n.d.); (4): Vavasseur (2016); (5): NIWSC (2017).

Table 22 consists of those same logistics assets but contains analytical data pertaining to RCS, unadjusted and adjusted, angle reduction measures, radar absorbent material (RAM)/radar absorbent structures (RAS) reduction factors, and noise level. RCS was calculated utilized Harney's (2013) Equation 8.2, $\sigma \cong 52 f^{1/2} D^{3/2}$, where f is frequency in MHz and D is displacement in thousands of long tons (vol 6, 373). Noise level was estimated with Harney's (2013) Equation 11.24, $SL = 60 \log v + 9 \log D - 20 \log f + 35$, where v is the forward speed of the ship, D is displacement in metric tons, and f is frequency in kHz (vol. 2, 591). Regarding angle reduction to RCS, it is assumption based comparing the utilization of RAM to retrodirectivity. According to Harney (2013), "[m]any materials will only provide reductions to 10% of the original retrodirectivity" (vol 6, 384). Therefore, we concluded that up to 90% reduction in RCS can be achieved utilizing angles as well as an additional 90% RCS reduction utilizing RAM and/or RAS.

Table 22. Model Inputs: Logistics Assets (Detection Parameters)

Ship	***Angle Reduction to RCS***	***RAM/RAS Reduction to RCS***	***RCS (m^2)***	***Adjusted RCS***	***Noise level (dB)***
LCS	90%	0%	3.46E+04	3.46E+03	125.3
JHSV	90%	0%	1.90E+04	1.90E+03	144.2
T-AOE	0%	0%	1.68E+06	1.68E+06	147.1
T-AO	0%	0%	1.30E+06	1.30E+06	133.1
T-AKE	0%	0%	1.30E+06	1.30E+06	140.6
LHA (America-Class)	0%	0%	1.43E+06	1.43E+06	135.0
LSD	50%	0%	3.37E+05	1.68E+05	129.6
LPD	90%	0%	6.13E+05	6.13E+04	132.8
OSV	0%	0%	8.61E+03	8.61E+03	116.3
Sea Train	0%	0%	1.18E+04	1.18E+04	120.9
TSSE Mothership	0%	0%	2.01E+06	2.01E+06	134.2
TSSE MOLA	0%	0%	4.02E+02	4.02E+02	95.7
Orca	0%	0%	1.00E+00	1.00E+00	90 (110 snorkel)
T-AK	0%	0%	1.54E+06	1.54E+06	133.6
T-AKR	0%	0%	2.44E+06	2.44E+06	134.8
T-AKR	0%	0%	2.35E+06	2.35E+06	134.7
Expeditionary Fast Transport (EPF)	0%	0%	1.90E+04	1.90E+04	135.4
LCU	0%	0%	8.68E+02	8.68E+02	97.7
Expeditionary Transfer Dock (ESD)	0%	0%	3.40E+06	3.40E+06	135.6
Expeditionary Sea Base (ESB)	0%	0%	4.21E+06	4.21E+06	136.2
Sentry USV	90%	90%	4.16E+00	4.16E-02	100.1
Sea Hunter (MDUSV)	90%	0%	2.30E+02	2.30E+01	104.8

Values in table were calculated utilizing equations found in Harney (2013). Adapted from DON (n.d.) unless otherwise annotated.

Table 23 lists the total number of assets, an assumption of availability, and assumptions pertaining to cruise and ballistic missile salvos per asset. We utilized the Navy Fact File to determine the total number of assets, except for OSVs, Sea Trains, TSSE Motherships, TSSE MOLAs, Orcas, Sentry USVs, and Sea Hunters. For commercial or concept platforms a reasonable estimate was utilized for an assumed quantity. We could not reasonably determine the number of Sentry USVs or Sea Hunters as those projects are still infant in their development. The availability numbers are assumptions based on the type of asset, combatant, logistics dedicated, or autonomous. A combatant is assumed to have an availability of 80%, logistics asset 90%, and autonomous asset of 95% for this project.

Table 23. Model Inputs: Logistics Assets (Availability and Salvo Sizes)

Ship	***Total***	***Available***	***Cruise/Ballistic Missile Salvo (per Asset)***			
			Land	***Surface***	***Air***	***Subsurface***
LCS	25	20	4	4	2	4
JHSV	14	11	2	2	2	2
T-AOE	4	4	10	10	2	8
T-AO	15	14	10	10	2	8
T-AKE	14	13	10	10	2	8
LHA (America-Class)	8	6	10	10	2	8
LSD	8	6	4	4	2	4
LPD	11	9	6	6	2	6
OSV	40	36	1	1	1	1
Sea Train	4	4	1	1	1	1
TSSE Mothership	4	4	10	10	2	8
TSSE MOLA	88	79	1	1	1	1
Orca	11	10	-	-	-	-
T-AK	11	10	10	10	2	8
T-AKR	8	7	10	10	2	8
T-AKR	19	17	10	10	2	8
Expeditionary Fast Transport (EPF)	14	11	2	2	2	2

Ship	***Total***	***Available***	***Cruise/Ballistic Missile Salvo (per Asset)***			
			Land	***Surface***	***Air***	***Subsurface***
LCU	100	80	1	1	1	1
Expeditionary Transfer Dock (ESD)	2	2	10	10	2	8
Expeditionary Sea Base (ESB)	3	3	10	10	2	8
Sentry USV	-	-	2	2	2	2
Sea Hunter (MDUSV)	-	-	2	2	2	2

Cruise/ballistic missile salvo sizes were estimated or assumed based on asset self-defense capability and size.

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APPENDIX C. DEMAND SIGNAL AND COST FORMULATION

The demand signal formulation considered force logistics, consumptions rate, location, and cost. The types of supply we deemed to be most important to the warfighter in a contested environment were fuel, stores, and ordnance. A planning factor for each force domain such as ground, maritime, and air was determined while implementing a distribution and considered variation in the consumption rate. To integrate with our network model, we would need to place each asset in a specific location (defined latitude/ longitude). Lastly, the cost per ton of supplies and the cost of units themselves were instrumental in providing valuable insight on the cost benefit analysis for the proposed logistics system architecture.

A. GROUND DEMAND SIGNAL

1. Forces

For this research, the ground units consist of an Army and Marine component. The army component is divided into the following divisions: armored, infantry, light infantry, airborne, and air assault (DoA 1997). The Marine components are made up of the following: Marine expeditionary force (MEF), Marine expeditionary brigade (MEB) and Marine expeditionary unit (MEU).

We chose to associate a uniform distribution with each ground unit. *Probability Methods for Cost Uncertainty Analysis* describes a random variable to have a uniform distribution when the probability density function (PDF) and cumulative density function (CDF) are (Garvey, Book, and Covert 2016, 89–90):

$$PDF: f_x(x) = \frac{1}{b-a} \quad ,if \quad a \le x \le b$$

$$CDF: F_x(x) = \begin{cases} 0 & ,if \quad x < a \\ \frac{1}{b-a}\left(x-a\right) & ,if \quad a \le x \le b \\ 1 & ,if \quad x \ge b \end{cases} .$$

In a uniform distribution, it is equally likely that any value between the minimum (*a*) and maximum (*b*) will be selected. Each unit was bounded and simulated using @Risk in Excel. This platform enabled the user to capture variation in the unit size after conducting 10,000 iterations of the Monte Carlo simulation. Of note, for both ground and maritime forces, @Risk was used to determine all static values used for each unit and its various supply consumption rate. Following is a description of each force and the distribution utilized to determine the number of personnel assigned to the unit.

a. Armored

Armored divisions are heavily armed units originally designed for large scale attacks, equipped with M1 Abram series tanks, M2/M3 Bradley series infantry vehicles, M109 howitzers and other heavy vehicles and munitions (CBO 2016). The distribution allocated to this unit was:

$$X \sim Unif\left(10000, 15000\right),$$

where at least 10,000 and not more than 15,000 personnel are assigned to the unit.

b. Infantry

Infantry divisions are designed to be deployable in a short period of time; they are largely based on foot, with some transportation capability. Due to this division’s lack of heavily armored vehicles, infantry divisions are largely a supported unit, meaning they can call in for fire support and artillery strikes when required (CBO 2016). The distribution allocated to this unit was:

$$X \sim Unif\left(10000, 15000\right).$$

c. Light Infantry

A light infantry division has similar capabilities to a conventional infantry division explained above, except it is smaller in size (Mohr 1984). The distribution allocated to this unit was:

$$X \sim Unif\left(6000,12000\right).$$

d. Airborne

Airborne units are traditionally smaller and composed of personnel with specialized training. They are trained in parachuting from aircrafts to conduct missions such as forcible entry operations which involve gaining access to an enemy's terrain that cannot be reached via other transportation methods (CBO 2016). The distribution allocated to this unit was (Thompson 2010):

$$X \sim Unif\left(4000,8000\right).$$

e. Air Assault

An air assault unit has similar capabilities to an airborne unit. The distribution allocated to this unit was (Global Security n.d.-a):

$$X \sim Unif\left(4000,6600\right).$$

f. Marine Expeditionary Force

A MEF is the largest of the Marine task forces. It includes a Marine Division (MARDIV), Marine air wing (MAW, and Marine logistics group (MLG) and is composed of approximately 50,000 personnel, 4,000 vehicles, and 168 fixed-wing aircraft. A MEF carries enough supply to be self-sustained for approximately 60 days (Dayne Nix, class notes, 2019). The distribution allocated to this unit was (CBO 2016):

$$X \sim Unif\left(35000,50000\right).$$

g. Marine Expeditionary Brigade

A MEB is a crises response force that is composed of an infantry regiment, a Marine aircraft group (MAG), and a combat logistics regiment (CLR). They include approximately 17,000 personnel, 700 vehicles, and are self-sustained for up to 30 days (Dayne Nix, class notes, 2019). The distribution allocated to this unit was:

$$X \sim Unif\left(14000,17000\right).$$

h. *Marine Expeditionary Units*

A MEU is the forward deployed Marine expeditionary task force that is made up of a ground combat element, air squadron, and combat logistic battalion (Dayne Nix, class notes, 2019). It consists of approximately 2,200 personnel, 100 vehicles, and are self-sustained for up to 15 days. The distribution allocated to this unit was:

$$X \sim Unif\left(1980,2420\right).$$

i. *Anti-Ship Mobile Missile Batteries*

According to the "Global War 2030" scenario, there are 40 anti-ship mobile missile batteries located throughout the Pacific AO (Jeffrey Kline, class notes, 2019). These batteries can be manned by various ground forces throughout the AO, and are assumed to be outfitted with the Naval Strike Missile (NSM), which weighs approximately 900 lbs.

j. *Mobile Air Defense Sites*

According to the "Global War 2030" scenario, there are 15 mobile air defense sites located throughout the Pacific AO (Jeffrey Kline, class notes, 2019). These sites can be manned by various ground forces throughout the AO and are comprised of Terminal High Altitude Area Defense (THAAD) and Patriot Advanced Capability-3 (PAC-3) sites. These sites have individual warheads with a yield of approximately 2,000 lbs.

k. *C4ISR Mobile Sites*

According to the "Global War 2030" scenario, there are 30 C4ISR mobile sites located throughout the Pacific AO (Jeffrey Kline, class notes, 2019). These sites can be manned by various ground forces throughout the AO and are assumed to not draw an additional demand signal due to manning demand signals already included within the Army brigades.

2. Logistics

The planning factors for logistics consumption for ground units per person were estimated based on FM 55-15 (DoA 1997). Each class of logistics is described in Table 24.

Table 24. Class of Supply Definitions. Adapted from DoA (1997).

Class of supplies	***Definition***
Class I	Subsistence
A-Ration	Air (in-flight rations)
B-Ration	Ground support material
T-Ration	Industrial supplies
MRE	Meal, ready-to-eat
LRP	Long range Patrol
R/CW	Ration, cold weather
HCP	Health and comfort pack
Class II	Clothing, individual equipment, tents, tools, and other supplies
Class III	Petroleum, oil, lubricants, and fuel products.
Class IV	Construction/barrier material.
Class V	Ammunition.
Class VI	Personal demand (exchange) items.
Class VII	Major end items (tanks, vehicles, generators, radios, etc.)
Class VIII	Medical supplies
Class IX	Repair parts
Class X	Material for nonmilitary programs

For this research, we classified Classes I, II, IV, VI and water as stores; Class III as fuel; and Class V as ordnance. We also categorized the type of operational tempo as an assault and sustainment. The assault planning factor per person accounts for mobility; that is, if warfighters are fatigued due to the heavy strain their gear, they cannot effectively engage the enemy for a long period of time. The sustainment factor enables warfighters to carry more logistics, as they have planned for a longer period of conflict without direct action.

The planning factors outlined by the FM 55-15 by class of supplies is shown in Table 25, Table 26, and Table 27.

Table 25. Class I–IV, and VI Planning Factors. Adapted from DoA (1997).

Class of Supply	***Planning Factor lb/man/day***	
Class I	A-Ration	2.549
	B-Ration	1.278
	T-Ration	2.575
	MRE	1.57
	LRP	1.25
	R/CW	2.75
	HCP 1	0.77
	HCP 2	0.055
Class II	-	3.17
Class III	-	0.51
Class IV	-	8.5
Class VI	temperate	2.06
	tropic/arid	3.4
	artic	1.75

Table 26. Water Planning Factor. Adapted from DoA (1997).

Water (gal/ man/day)	***Temperate***	***Arctic***	***Tropic***	***Arid***
Company	3.9	4.4	5.7	5.9
Battalion	6.6	7.2	8.5	8.7
Brigade	7	7.6	8.9	11.1
Division	7	7.6	8.9	11.9
Above Division	7.8	8.4	9.9	18.4

Table 27. Class V Planning Factor. Adapted from DoA (1997).

Type of Division	***Class V (Ston/ day)***	***Planning Factor Ston/man/day***
Armored	1452	0.097
Infantry	1442	0.096
Light	651	0.065
Airborne	677	0.085
Air Assault	842	0.140

For the following calculations, we associated a triangular distribution with each logistics element. *Probability Methods for Cost Uncertainty Analysis* describes a random variable as having a triangular distribution when the probability density function (PDF) and cumulative density function (CDF) are as follows (Garvey, Book, and Covert 2016):

$$PDF: f_x(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(m-a)} & ,if \quad a \le x \le m \\ \dfrac{2(b-x)}{(b-a)(b-m)} & ,if \quad m \le x \le b \end{cases}$$

$$CDF: F_X(x) = \begin{cases} 0 & ,if \quad x < a \\ \dfrac{(x-a)^2}{(b-a)(b-m)} & ,if \quad a \le x < m \\ 1-\dfrac{(b-x)^2}{(b-a)(b-m)} & ,if \quad m \le x < b \\ 1 & ,if \quad x \ge b \end{cases}.$$

The triangular distribution is a bounded approach, where one inputs specific range values for the specified random variables: minimum (*a*), most likely (*m*), and maximum (*b*). Each logistics element planning factor (per person) was simulated using this method.

3. Modeling and Simulation for Ground Logistics

To develop a planning factor to capture variation, we first associated each element with a triangular distribution. The range for the distribution was set at +/- 25% of the values shown in the planning factor tables. The data input process is depicted in Figure 68.

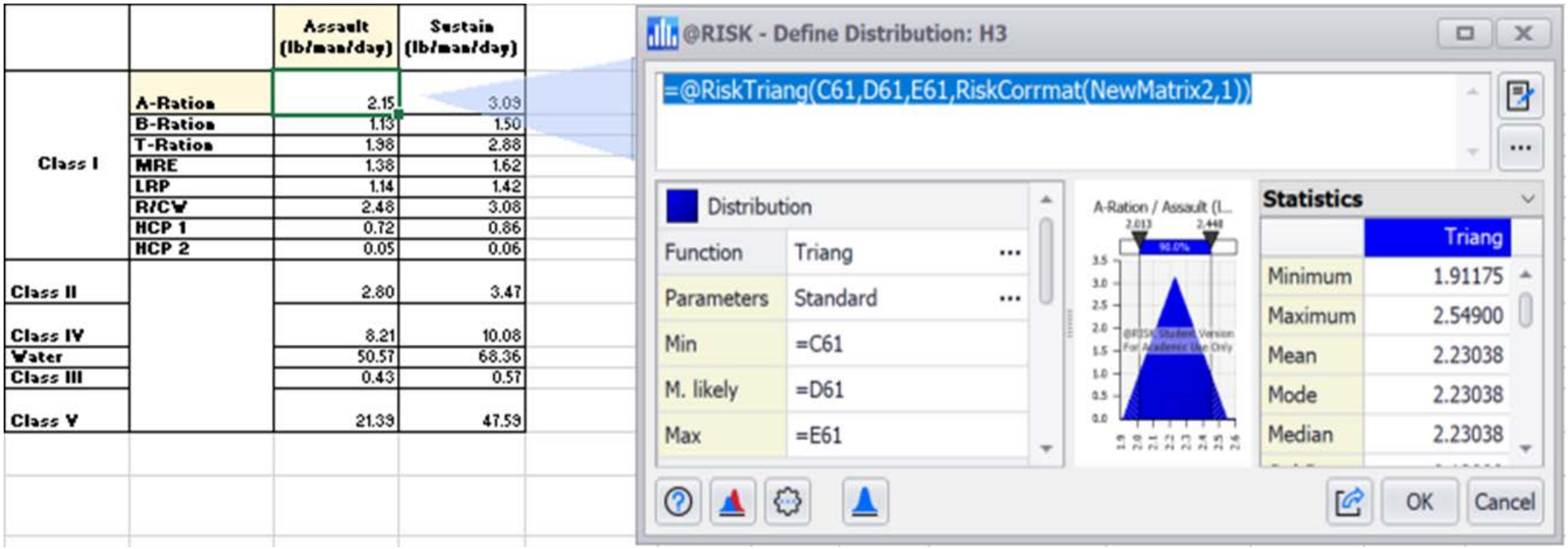

Figure 68. Inputting Distributions to Elements

Upon associating each element with a triangular distribution, we then summed all of the "stores," which include class I,II,III,V, and water variables as shown in Table 28. These values made up the total required supplies per person in each category of operation.

Table 28. Summation of Logistics

	Assault (lb/man/ day)	***Sustain (lb/ man/day)***
Stores	SUM (class I, class II, water)	SUM (class I, class II, water)
Fuel	Class III	Class III
Ordnance	Class V	Class V
Total	SUM (stores, fuel, ordnance)	SUM (stores, fuel, ordnance)

With the per person supply demand established, the next step was to account for variations in unit sizes. As mentioned in the ground forces section, each ground element had an associated uniform distribution, which was then used in the Monte Carlo simulation to assign a unit size. Finally, the unit size was multiplied by the per person supply demand to establish a per unit, daily supply demand estimate as illustrated in Figure 69.

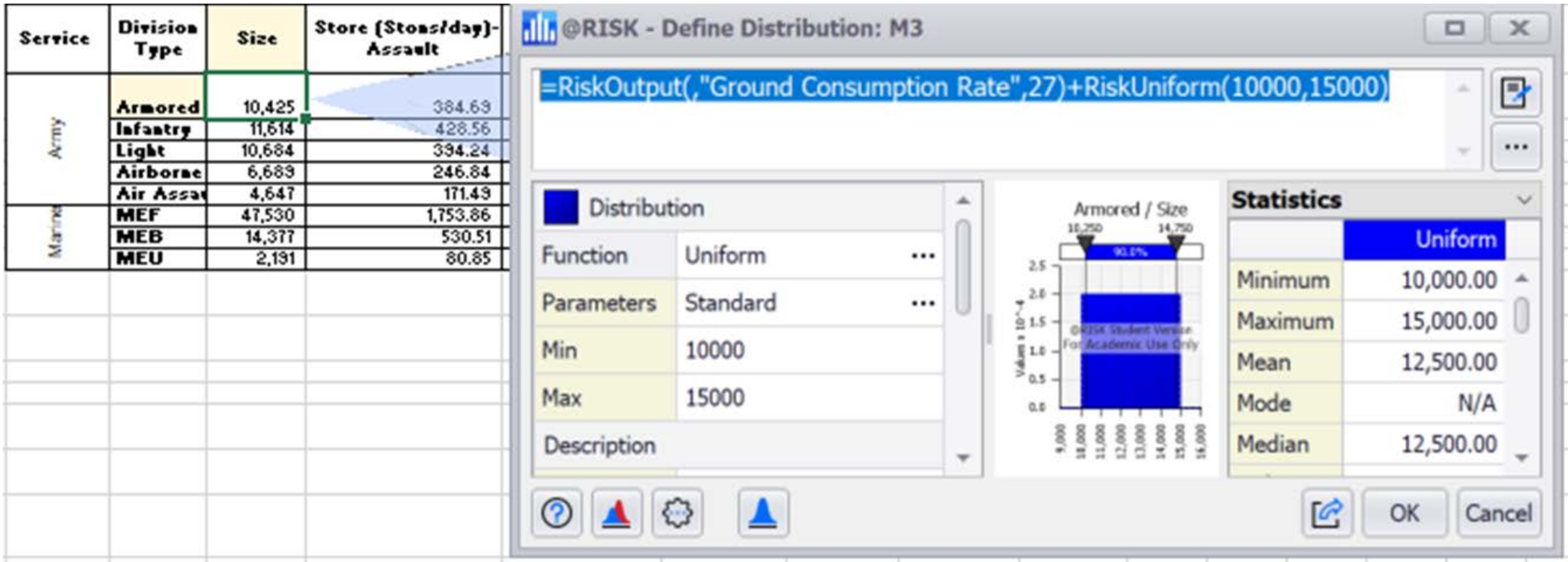

Figure 69. Ground Element Logistics

We conducted 10,000 simulations, and organized the average results in Table 29 and Table 30. These planning factor results were then used as inputs for the ground elements located in the AO demand signal.

Table 29. Logistics per Person Results

Class of Supplies		Assault (lb/man/day)	Sustain (lb/man/day)
Class I	A-Ration	2.11	2.98
	B-Ration	1.09	1.46
	T-Ration	2.39	2.70
	MRE	1.30	1.66
	LRP	1.14	1.33
	R/CW	2.29	3.00
	HCP 1	0.71	0.93
	HCP 2	0.05	0.06
Class II		2.83	3.40
Class IV		8.25	9.27
Water		55.93	70.23
Class III		0.47	0.60
Class V		15.84	54.72

Table 30. Ground Element Simulation Results

Service	Division Type	Size	Store (Stons/day) Assault	Store (Stons/day) Sustain	Fuel (Bbl/day) Assault	Fuel (Bbl/day) Sustain	Ordnance (Stons/day) Assault	Ordnance (Stons/day) Sustain
Army	Armored	14449.36	564.05	701.00	27.32	34.86	114.47	395.34
	Infantry	11015.29	430.00	534.40	20.83	26.58	87.27	301.38
	Light	10467.01	408.60	507.80	19.79	25.25	82.92	286.38
	Airborne	7448.18	290.75	361.34	14.08	17.97	59.01	203.78
	Air Assault	4667.64	182.21	226.45	8.83	11.26	36.98	127.71
Marine	MEF	40974.53	1599.51	1987.86	77.48	98.86	324.61	1121.08
	MEB	16729.56	653.07	811.63	31.63	40.37	132.54	457.73
	MEU	2095.06	81.78	101.64	3.96	5.05	16.60	57.32

B. MARITIME DEMAND SIGNAL

1. Forces

The maritime force was divided into four groups: carrier strike group (CSG), expeditionary strike group (ESG), surface action group (SAG), and independent deployers. A CSG is normally made up of nuclear capable aircraft carrier (CVN), Destroyers (DDG), Cruisers (CG), and a large tanker. For this research, it is assumed that the tankers could be detached at any moment to provide logistics to other units in the AO. An ESG is made up of large-deck amphibious surface combatants, DDGs, and CGs. In a SAG any combination of DDGs, CG's, frigates (FFGs), and littoral combat ships (LCS) is possible, and the most senior officer of the SAG would normally take command of the group. Lastly, an independent deployer could be any one surface combatant that has a robust self-defense capability to include submarines (SSNs). Below is a description of the maritime forces used in this research.

a. Carrier Strike Group

(1) CVN

A CVN is a platform that provide a variety of aerial capabilities and is commanded by Strike Group Commander, usually a Rear Admiral (O-7). It is comprised of multi-role fighter aircraft, airborne command and control assets, and helicopters, and is made up of approximately 5,000 personnel. The CVN gives the U.S. the capable of launching a variety of aerial strikes on enemy combatants in areas in the world where the U.S. does not have air bases.

(2) CG

A CG is a multi-mission platform with a robust air defense capability that is commanded by a Captain (O-6). They are capable of helicopter operations, have a Vertical Launch System (VLS), and other offensive and defense weaponry. The VLS system is operated by Aegis which enables a CG to provide sensor coverage and missile strikes on enemy combatants or in the defense of other units.

(3) DDG

A DDG is very similar to a CG. However, they are commanded by a Commander (O-5), have less firepower and air defense sensor coverage. They also have Aegis and VLS.

b. Expeditionary Strike Group

(1) Amphibious Assault Ships (LHD/LHA)

The LHD/LHA provide the Marines with the capability of ship-to shore movement via aircraft and landing craft such as Landing Craft, Air Cushion (LCAC) and Landing Craft Utility (LCU) vehicles. They are the largest of the U.S. Navy's amphibious ships and are capable of transporting MEU's and MEB's (DON n.d.).

(2) Amphibious Transport Dock (LPD/LPD-17)

The LPD/LPD-17 embarks and transports Marine units via aircraft, such as vertical take-off and landing aircraft (MV-22) and landing crafts such LCAC and Amphibious Assault Vehicles (AAV). These capabilities support a variety of missions such as expeditionary warfare, special operations, and air operations (DON n.d.).

(3) Dock Landing Ship (LSD)

The LSD provide embarkation and transport to Marines to conduct amphibious assault operations. They are capable launching LCACs and aircraft in support of expeditionary missions (DON n.d.).

c. Surface Action Group

(1) Perry Class Frigate (FFG)

The FFG is a multi-mission capable platform. It can perform undersea warfare (USW), aircraft operations, and anti-air warfare (AAW) missions (Pike 2000).

(2) LCS

The LCS is a modular, mission-focused platform that can operate near shore. It is outfitted with specific mission packages to conduct operation that include aircraft operations, mine countermeasure, anti-submarine warfare, or surface warfare. The mission package also included the requisite armament, sensors, and personnel required to meet the specified mission assigned (DON n.d.).

d. Independent Deployer (SSN)

SSN's are nuclear powered platforms designed to locate and destroy enemy surface and subsurface threats. They are multi-mission capable to include special operations, Intelligence, Surveillance and Reconnaissance (ISR), and escort support to the CSG (DON n.d.).

2. Logistics

The planning factors for logistics (fuel, ordnance, and stores) for the above-mentioned assets were inspired by the Naval Warfare Publication (NWP) *Sustainment at Sea NWP 4-01.2*. The NWP outlines nominal planning factors to support a CSG and ESG at the strategic, operation, and tactical logistic levels (DON 2007a).

The levels of logistics are defined by the NWP as:

> 1. **Strategic.** Strategic level logistics relate to deploying and sustaining forces as part of the implementation of national military strategy. Acquisition, transportation of material and personnel, and the levels of readiness of prepositioned material are meticulously planned. In the larger scheme, sustainability also includes the industrial base and the capacity to develop and produce military equipment, weapons, and systems in support of a long-term contingency or wartime operations.
>
> 2. **Operational.** Operational level logistics includes the management, protection, coordination, and provisioning of material to supported forces using an established network of support sites, activities, and theater transportation. It provides the link between the strategic logistic capability and the tactical.
>
> 3. **Tactical.** Tactical level logistics directly support the strike group (SG). It is derived from the organic capabilities of ships and from other elements, including shore based logistical assets and the CLF ships operating under the Military Sealift Command (MSC) Naval Fleet Auxiliary Force (NFAF) program and shore based logistic activities. Support activities at this level include maintenance, materiel trans-shipment, fueling, repair, engineering support, personnel support, and transportation. (DON 2007a, 20)

However, due to distribution restrictions on the NWP data, we developed our own estimate for this analysis. We were able to manipulate and develop a range and associate each asset's planning factor with a triangular distribution.

3. Modeling and Simulation for Maritime Logistics

An identical methodology to the ground logistics model and simulation was used in developing a planning factor suitable for our research. As an input to the triangular distribution, we used the data delineated in Table 31 and input them as shown in Figure 70.

Table 31. Maritime Triangular Distribution Inputs

Platform	***Type of Supply***	***Assault-L***	***Assault-M***	***Assault-I***	***Sustain-L***	***Sustain-M***	***Sustain-I***
CVN	Stores	35	52.5	70	35	52.5	60
	DFM	0	0	0	0	0	0
	JP-5	2500	3750	5000	2500	3500	4500
	Ordnance	100	150	200	0	75	110
CG	Stores	0.5	0.75	1	0.5	0.75	1
	DFM	400	900	1200	300	700	850
	JP-5	0	25	45	0	15	25
	Ordnance	1	3	6	0	1.5	3.5
DDG	Stores	0.5	0.75	1	0.5	0.75	1
	DFM	600	900	1200	500	800	1000
	JP-5	8	25	45	0	15	25
	Ordnance	1	2	6	0	1	2.75
LCS	Stores	0.1	0.15	0.3	0.1	0.15	0.3
	DFM	300	450	600	200	400	500
	JP-5	20	30	40	0	15	25
	Ordnance	1	1.5	2.5	0	0.75	1.5
LHD	Stores	7	12.4	20	7	12.4	20
	DFM	900	1600	2100	700	900	1100
	JP-5	70	800	950	0	475	600
	Ordnance	20	30	40	0	10	20
LPD	Stores	3.5	5.25	6.5	3.5	5.25	6.5
	DFM	450	900	1300	400	500	600
	JP-5	10	300	450	0	175	350
	Ordnance	1	5	7	0	3	5
LSD	Stores	1	3	5	1	3	5
	DFM	200	500	850	175	300	425
	JP-5	1	75	90	0	45	65
	Ordnance	0.5	1.25	2.6	0	0.5	1.25
LPD-17	Stores	3	4.5	7	3	4.5	7
	DFM	700	1050	1300	600	900	1100

Platform	***Type of Supply***	***Assault-L***	***Assault-M***	***Assault-I***	***Sustain-L***	***Sustain-M***	***Sustain-I***
	JP-5	10	800	900	0	450	600
	Ordnance	2	5.5	7.5	0	2	5

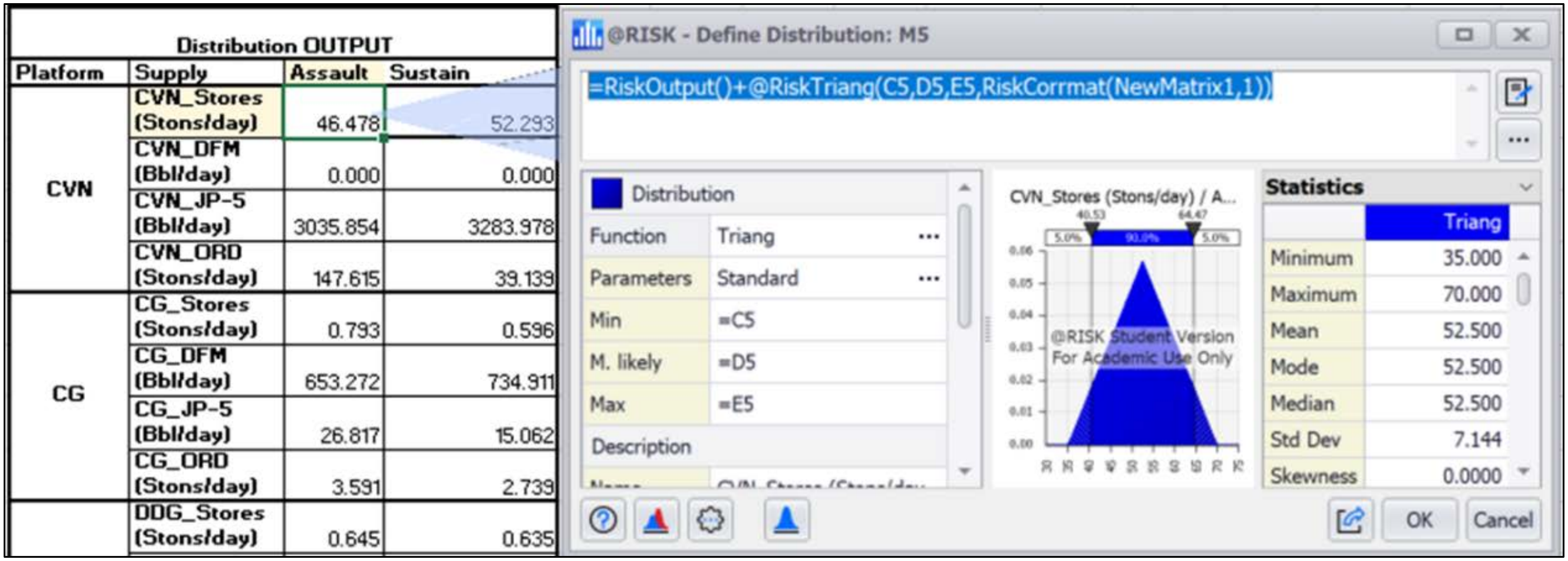

Figure 70. Maritime Model Inputs

Upon associating each random variable with their respective distribution, we conducted a Monte Carlo simulation with 10,000 iterations. The output of the model is reflected in Table 32. These values were then used as a demand signal for the logistics system in the AO.

Table 32. Maritime Model Output

Platform	***Type of Supply***	***Assault***	***Sustain***
CVN	Stores (Stons/day)	60.89	51.81
	DFM (Bbl/day)	0.00	0.00
	JP-5 (Bbl/day)	3760.97	3541.34
	Ordnance (Stons/day)	150.47	21.46
CG	Stores (Stons/day)	0.62	0.83
	DFM (Bbl/day)	1045.21	315.16
	JP-5 (Bbl/day)	28.55	22.21
	Ordnance (Stons/day)	4.39	1.75
DDG	Stores (Stons/day)	0.70	0.79
	DFM (Bbl/day)	935.83	858.33
	JP-5 (Bbl/day)	33.64	13.84
	Ordnance (Stons/day)	2.53	1.08
FFG	Stores (Stons/day)	0.70	0.75
	DFM (Bbl/day)	700.00	600.00
	JP-5 (Bbl/day)	25.00	13.00
	Ordnance (Stons/day)	2.00	1.00
SSN	Stores (Stons/day)	0.15	0.15
	DFM (Bbl/day)	7.00	4.00
	JP-5 (Bbl/day)	0	0
	Ordnance (Stons/day)	2.00	1.00
LCS	Stores (Stons/day)	0.23	0.14
	DFM (Bbl/day)	380.85	461.79
	JP-5 (Bbl/day)	30.72	21.37
	Ordnance (Stons/day)	1.35	0.78
LHD	Stores (Stons/day)	15.76	10.45
	DFM (Bbl/day)	1286.65	875.55
	JP-5 (Bbl/day)	645.45	359.89
	Ordnance (Stons/day)	28.86	12.45
LPD	Stores (Stons/day)	5.95	5.85
	DFM (Bbl/day)	1125.42	549.63
	JP-5 (Bbl/day)	329.41	88.14
	Ordnance (Stons/day)	4.68	3.75

Platform	Type of Supply	Assault	Sustain
LSD	Stores (Stons/day)	3.73	1.93
	DFM (Bbl/day)	582.80	252.93
	JP-5 (Bbl/day)	77.26	44.88
	Ordnance (Stons/day)	1.03	0.14
LPD-17	Stores (Stons/day)	5.40	4.86
	DFM (Bbl/day)	989.63	1051.13
	JP-5 (Bbl/day)	291.17	209.77
	Ordnance (Stons/day)	5.13	3.02

C. AIR FORCES DEMAND SIGNAL

1. Forces

The air forces were divided into four separate groups: fighters, bombers, patrol aircraft and tankers. The number of sorties expected for fighters was estimated to be two per day during an assault phase and one per day during sustainment. The bombers, patrol aircraft and tankers were estimated to conduct one sortie per day for both assault and sustainment phases due to their fuel capacity and/or mission sets.

a. Fighters

(1) F-15

The McDonnell Douglas F-15 Eagle is an all-weather tactical fighter aircraft utilized by the United States Air Force (USAF). It is primarily known for his ability to achieve air superiority as a fighter.

(2) F-16

The General Dynamics F-16 Fighting Falcon is a multirole fighter aircraft utilized by the United States Army (USA). It was designed as an air superiority day fighter and eventually evolved into a successful all-weather multirole aircraft.

(3) F-18

The McDonnel Douglas F/A-18 Hornet is an all-weather, carrier-capable, multirole combat jet designed to operate as both a fighter and attack aircraft. It is the primary fighter aircraft for the United States Navy (USN) but is being phased out by the F-35 Lightning II.

(4) F-22

The Lockheed Martin F-22 Raptor is an all-weather, stealth tactical fighter developed for the USAF. It is the preeminent fighter aircraft in the Air Force arsenal.

(5) F-35

Currently serving as an all-weather stealth multirole combat aircraft, the Lockheed Martin F-35 Lightning II is the newest aircraft in the U.S. arsenal and is employed by the United States Marine Corps (USMC) and the USN. It is intended to perform both air superiority and strike missions while also providing electronic warfare, intelligence, surveillance, and reconnaissance capabilities.

b. Bombers

(1) B-1

The Rockwell B-1 Lancer is a supersonic variable-sweep wing, heavy bomber utilized by the USAF. Commonly referred to as the “Bone” it is one of three strategic bombers in the USAF fleet along with the B-2 Spirit and B-52 Stratofortress (Boeing n.d.).

(2) B-2

The Northrop Grumman B-2 Spirit known as the “Stealth Bomber” is a heavy strategic bomber with low observable stealth technology designed for penetrating dense anti-aircraft defenses. Its flying wing design makes it easily distinguishable from most aircraft in the sky (Northrop Grumman n.d.).

(3) B-21

The Northrop Grumman B-21 Raider is also a heavy bomber currently under development for the USAF and will be an upgrade to the B-2.

c. Patrol Aircraft

(1) P-8

The Boeing P-8 Poseidon is a modified Boeing 737 developed for the USN to conduct anti-submarine warfare (ASW), anti-surface warfare (ASuW), and shipping interdiction roles. It has a range of 1,381 miles and a top speed of 564 mph (Boeing n.d.). Its loadouts can include, but are not limited to, sonobuoys and Harpoon missiles.

(2) E-8C

The Northrop Grumman E-8 Joint Surveillance Target Attack Radar System (STARS) utilized by the USAF is an airborne ground surveillance, battle management and command and control aircraft. It can track ground vehicles, some aircraft, collects imagery, and relays tactical pictures to ground and air theater commanders. It has a similar range as the P-8 Poseidon and reaches a top speed of 587 mph (Northrop Grumman n.d.).

d. Tankers (KC-46)

The Boeing KC-46 Pegasus is a military aerial refueling and strategic military transport aircraft developed from the 767-jet airliner (Boeing n.d.). The USAF recently decided to replace older Boeing KC-135 Stratotankers with the KC-46 Pegasus.

2. Logistics

The estimated demand signal for fighter aircraft was determined utilizing the previously defined demand signal for a CVN in terms of JP-5 and ordnance. It was estimated that a CVN carries approximately 70 aircraft, and from there our team determined the amount of JP-5 in bbl/day and ordnance in short-tons/day for an individual fighter aircraft. Those values are listed in Table 33.

Table 33. Fighter Aircraft Demand Signal

Platform	Type of Supply	Assault-L	Assault-M	Assault-I	Sustain-L	Sustain-M	Sustain-I
CVN	JP-5 (bbl/day)	2500	3750	0	2500	3500	4500
	ORD (stons)	100	150	0	0	75	110
		Assault Average			Sustain Average		
	JP-5 (bbl/day)	2083.333333			3500		
	ORD (stons)	83.33333333			61.66666667		
		Assault Average per Aircraft*			Sustain Average per Aircraft*		
	JP-5 (bbl/day)	29.76190476			50		
	ORD (stons)	1.19047619			0.880952381		

We formulated rough estimates for the fuel and payload capacities of the bombers, patrol aircraft and tanker. The B-21 is under current development and limited information is available regarding its fuel and payload capacities. Therefore, the team estimated the demand signal for the B-21 to be the exact same as that of the B-2. The estimated demand signal per aircraft per day during sustainment and assault phases is listed in Table 34.

Table 34. Air Forces Model Output

Air Forces	***Supply Type***	***Sustain***	***Assault***
F-15	Fuel (bbl/day)	50	59.52
	Ordnance (stons/day)	0.88	2.38
F-16	Fuel (bbl/day)	50	59.52
	Ordnance (stons/day)	0.88	2.380
F-18	Fuel (bbl/day)	50	59.52
	Ordnance (stons/day)	0.88	2.38
F-22	Fuel (bbl/day)	50	59.52
	Ordnance (stons/day)	0.88	2.38
F-35	Fuel (bbl/day)	50	59.52
	Ordnance (stons/day)	0.88	2.38
B-1	Fuel (bbl/day)	414.98	829.97
	Ordnance (stons/day)	5.36	37.5
B-2	Fuel (bbl/day)	261.25	522.50

Air Forces	***Supply Type***	***Sustain***	***Assault***
	Ordnance (stons/day)	2.86	20
B-21	Fuel (bbl/day)	261.25	522.50
	Ordnance (stons/day)	2.86	20
P-8	Fuel (bbl/day)	32.85	32.85
	Ordnance (stons/day)	0.75	1.5
E-8C	Fuel (bbl/day)	50	29.76
	Ordnance (stons/day)	0	0.4
KC Tanker	Fuel (bbl/day)	664.22	664.22
	Ordnance (stons/day)	0	0

D. TOTAL DEMAND SIGNAL

To determine the total demand signal, we first reviewed the "Global War 2030" scenario to determine the location of the assets (Jeffrey Kline, class notes, 2019). The main nodes in which logistics would be transferred to would consist of: Busan, South Korea; Yokosuka, Japan; Sasebo, Japan; Okinawa, Japan; Clark Air Force Base (AFB) located in the Philippines; Singapore; Darwin, Australia; Guam; a point 300 nm East of Guam; and a point 50 nm West of Guam. The 300 nm East of Guam and 50 nm West of Guam locations correlated to the George Washington and Reagan Strike Groups annotated in the "Global War 2030" scenario (Jeffrey Kline, class notes, 2019). By allocating each surface asset or ground force unit to one of these locations, we then determined the total demand signal during sustainment and assault phases for stores, in short-tons/day, DFM and JP-5, in bbls/day, and ordnance, in short-tons/day. Table 35 lists the force disposition within the Pacific AO.

Table 35. Force Disposition

		Pusan, South Korea	Yokosuka, Japan	Sasebo, Japan	Okinawa, Japan	Clark AFB, Philippines	Singapore, Singapore	Darwin, Australia	Guam	300 nm East of Guam	50 nm West of Guam
Assets	**Total Available**	-	-	-	-	-	-	-	-	-	-
Maritime Forces	-	-	-	-	-	-	-	-	-	-	-
SSN	13				5				8		
CVN	2								1	1	
CG	2								1	1	
DDG	15		3			3			6	1	2
LCS	11						8				3
FFG	4		4								
JHSV	3				3						
LHA/LHD	0										
LPD~	0										
LSD	0										
Air Forces	0	-	-	-	-	-	-	-	-	-	-
F-15	0										
F-16	40	40									
F-18	0										
F-22	60		25		10				25		
F-35	70		20	5	20	5		5	15		
B-1	6								6		
B-2	4								4		
B-21	4								4		
P-8	48						24		24		
E-8C	4								4		
KC Tanker	50	5	5	5	5	10	10	5	5		
Ground Forces	0	-	-	-	-	-	-	-	-	-	-
Anti-ship Mobile Missile Batteries	40			5	10	20	5				
Mobile Air Defense Sites	15		1	2	2	8	2				
C4ISR Mobile Sites	30		2	2	2	20	4				
MEB	4			1	1	1			1		
MEU	8	1		3		1	1		2		
Army Brigade*	2	1						1			

Our team, however, did have to interpolate on the total and type of composition of ground forces throughout the Pacific AO. It was estimated that a total equivalent of two MEFs along with the equivalent of two Army brigades would be located within the AOs. The two MEFs were further broken down into a total of four MEBs and 8 MEUs. The Army brigades were estimated to generate a demand signal that was averaged among infantry, light, and airborne units. The total demand signal utilized in our model is annotated in Table 36.

Table 36. Total Demand Signal

	Pusan, South Korea	Yokosuka, Japan	Sasebo, Japan	Okinawa, Japan	Clark AFB, Philippines	Singapore, Singapore	Darwin, Australia	Guam	300 nm East of Guam	50 nm West of Guam
Supplies	-	-	-	-	-	-	-	-	-	-
Sustain	-	-	-	-	-	-	-	-	-	-
Stores (stons/day)	569	11	1117	813	923	102	468	1546	514	6
DFM (bbl/day)	14	3168	20	40	921	19	12	2346	792	608
JP-5 (bbl/day)	5335	6251	3591	4841	7539	9031	3583	13581	651	1018
Ordnance (stons)	356	48	467	497	482	25	268	594	4	2
Assault	-	-	-	-	-	-	-	-	-	-
Stores (stons/day)	458	1404	898	654	2135	5549	376	4259	1107	2984
DFM (bbl/day)	11	3403	22	52	688	2954	9	1571	376	1554
JP-5 (bbl/day)	5713	6118	3640	5123	6972	7579	3628	16672	847	65
Ordnance (stons)	188	1437	207	233	1526	2349	88	4362	1472	1732

E. SYSTEM COST

1. Ship Cost Methodology

To facilitate a cost-benefit analysis regarding the choice of certain architectures, and provide valuable insight to decision makers, we chose to associate costs for each unit and tonnage of supplies. Each unit, both logistics and combatants, were considered in the cost breakdown shown in Table 37. While researching the unit cost for each unit, we converted the procurement price from the specified Constant Year (CY) dollars to today's CY to account for inflation. Mislick and Nussbaum (2015) describe CY dollars as, "the purchasing power or value of the dollar in the specified constant fiscal year" (88). Therefore, the cost would reflect how much the price would be at today's (2020) currency valuation. However, no learning curves were associated with the costs below. Using Unit theory for learning curves incorporates a decrease in unit cost due to learning in the production process (Mislick and Nussbaum 2015). That is, if there is a 90% learning curve associated with the production process, that is linked to a 10% decrease in production cost each time the number of units is doubled (Mislick and Nussbaum 2015)

Table 37. Ship Cost Data

Ship	***COST ($M)***	***CY(XX)***	***Inflation Factor***	***COST (CY20$M)***
CVN[a]	5,200.00	CY97	1.46	7,592.00
DDG-51[b]	1,185.53	CY05	1.31	1,554.95
CG[c]	1,282.00	CY02	1.39	1,780.83
LCS[d]	420.20	CY07	1.24	520.54
LHD[e]	1,400.00	CY10	1.18	1,655.36
LPD[f]	1,326.10	CY06	1.27	1,687.06
LSD[g]	257.50	CY01	1.40	360.55
LPD-17[h]	1,326.10	CY06	1.27	1,687.06
T-AOE[i]	365.80	CY98	1.46	532.93
T-AKE[j]	455.00	CY07	1.24	563.65
T-AE[k]	333.33	CY01	1.40	466.73
T-AFS[l]	333.33	CY01	1.40	466.73
T-AO[m]	530.00	CY20	1.00	530.00

Ship	***COST ($M)***	***CY(XX)***	***Inflation Factor***	***COST (CY20$M)***
MPF[n]	1,750.00	CY05	1.31	2,295.30
T-5 Tanker[o]	17.34	CY73	4.61	79.96
JHSV[p]	186.92	CY08	1.21	226.12
OSV[q]	4.00	CY20	1.00	4.00
MOLA[r]	8.75	CY20	1.00	8.75
Mothership[s]	240.00	CY20	1.00	240.00
Sea Train (4)[t]	80.00	CY20	1.00	80.00
LMSR[u]	308.32	CY97	1.46	450.15
LCU[v]	13.42	CY18	1.04	13.95
ESB[w]**/ESD**[x]	500.00	CY19	1.02	510.00
Orca[y]	10.75	CY19	1.02	0.97

Information Sources: [a](FI 2005); [b](DOD 2006); [c](FI 2002); [d](DOD 2006); [e](FI 2010); [f](DOD 2006) Assumed same cost as LPD-17; [g](FI 2001); [h](DOD 2006); [i](FI 2000); [j](DOD 2011); [k](St. Laurent 2003); [l](DOD 2006); [m](O'Rourke 2018); [n](Button et al. 2005); [o](Staats 1973); [p](DOD 2010); [q](Atlantic Shipping n.d.).; [r](Alexander et al. 2020); [s](DiPatrizio 2014) Based off Blue Marlin cargo ship; [t](Macias 2018); [u](Cekala et al. 1997) Based off Sea Hunter; [v](Eckstein 2018); [w](Paolino 2019); [x](*Defense Industry Daily* 2015); [y](Werner 2019) Cost averaged between four USVs.

To convert the CY dollars, we used the Naval Center for Cost Analysis (NCCA) Joint Inflation Calculator (JIC) (NCCA 2020). The JIC is an Excel document with the inflation indices associated to the services, specific categories of acquisition programs, and year, as shown in Figure 71. We then used the "General Inflation Index" to convert the price of each ship from the year it was procured to today's currency valuation. The "Inflation Index" column in Table 37 was provided by the JIC and was used to convert from CYXX to CY20. The inflation index was then multiplied by the ships cost in CYXX.

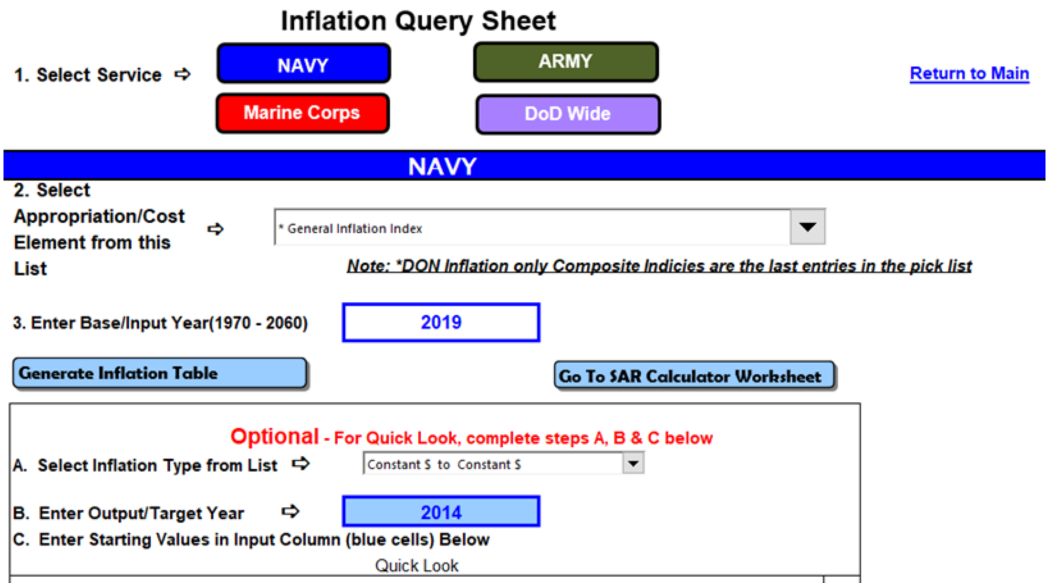

Figure 71. JIC Calculator. Source: NCCA (2020).

2. Supply Cost Methodology

Each logistics platform is associated with a specific cargo capacity, which is then multiplied by the cost per ton of supply lost if the enemy was successful in targeting, engaging, and killing the logistics platform. Therefore, adding the cost of supplies and the cost of the individual assets lost due to enemy action, could provide powerful insight for decision makers in weighing alternative logistic system architectures.

In creating the data point for this analysis, we first began with stores and fuel, to consider JP-5 (Jet Fuel-5) and DFM (Diesel Fuel Marine). The data for fuel and stores was supplied by the Defense Logistics Agency (DLA) and Naval Supply Systems Command as shown in Table 38.

Table 38. Fuel and Stores Cost. Adapted from Norquist (2018); NAVSUP (n.d.).

Supplies/Fuel	***Cost ($)***
JP-5[a] (per/bbl)	126.42
DFM[a] (per/bbl)	126.00
Stores (per/Ston)[b]	2,007.02

However, to create an average cost per tonnage of supplies, we took the given values above and converted them from barrels (bbls) to tons as shown in the following calculation,

$$JP-5:\frac{126.42\,dollars}{bbl}\times\frac{7.33bbl}{1ton}=\frac{926.66\,dollars}{ton}.$$

This same calculation was conducted for DFM and resulted in $923.58. We then average JP-5 and DFM to simplify model inputs to just one average fuel cost which was $925.12. The average cost per ton for fuel and stores is reflected in Table 39.

Table 39. Average Fuel and Stores Cost per Ton

Supplies	***Cost ($)***
Fuel (per ton)	925.12
Stores (per Ston)	2,007.02

The cost per tonnage of ordnance required extrapolation and regression analysis. Thomson and Mayo (1991) describe and analyze the expenditure and cost of ordnance through World War II. Values taken from historic cost and stock data shown in Figure 72 and Figure 73 served as inputs to Table 40 which summarizes ordnance cost data in CY20 dollars and estimates tonnage in stock.

TABLE 11—EXPENDITURES FOR HEAVY FIELD ARTILLERY AMMUNITION, JANUARY 1944–AUGUST 1945

Period	Amount
1944	
January	$10,312,000
February	12,327,000
March	17,888,000
April	24,708,000
May	26,643,000
June	32,999,000
July	32,938,000
August	36,515,000
September	40,534,000
October	43,006,000
November	53,120,000
December	53,931,000
1945	
January	65,289,000
February	67,939,000
March	77,038,000
April	82,573,000
May	78,073,000
June	53,065,000
July	37,189,000
August	16,535,000

Figure 72. WWII Heavy Artillery Cost

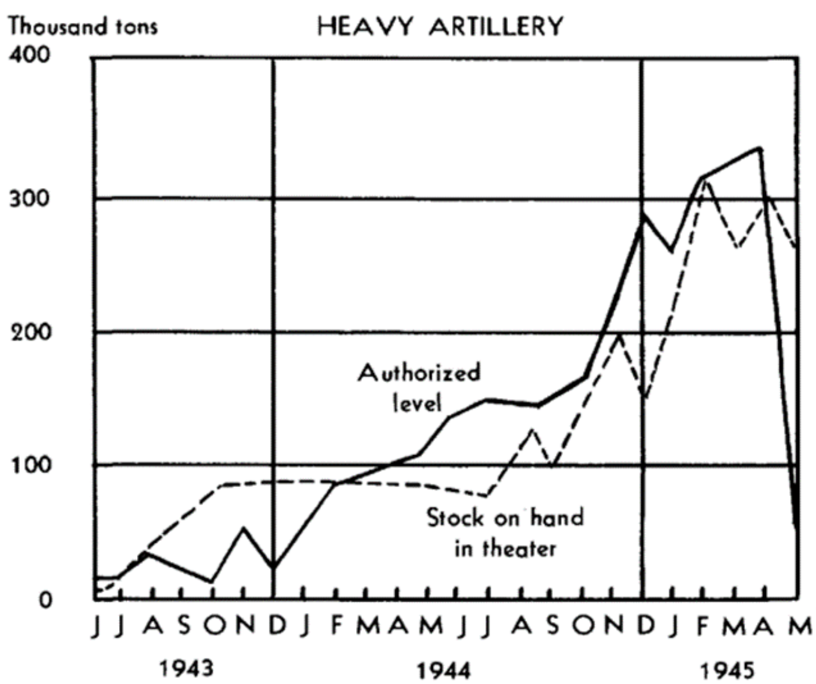

Figure 73. WWII Stock on Hand

Table 40. Ordnance Cost Data

Month	***Cost CY44/CY45***	***Inflation Factor (1970)***	***Cost CY20($)***	***Heavy Artillery (kilotons)***
Jan	10,312,000.00	5.2960	54,612,352.00	90
Feb	12,327,000.00	5.2960	65,283,792.00	90
Mar	17,888,000.00	5.2960	94,734,848.00	92
Apr	24,708,000.00	5.2960	130,853,568.00	89
May	26,643,000.00	5.2960	141,101,328.00	87
Jun	32,999,000.00	5.2960	174,762,704.00	84
Jul	32,939,000.00	5.2960	174,444,944.00	80
Aug	36,515,000.00	5.2960	193,383,440.00	101
Sep	40,534,000.00	5.2960	214,668,064.00	110
Oct	43,006,000.00	5.2960	227,759,776.00	123
Nov	53,120,000.00	5.2960	281,323,520.00	190
Dec	53,931,000.00	5.2960	285,618,576.00	150
Jan	65,289,000.00	5.2960	345,770,544.00	200
Feb	67,939,000.00	5.2960	359,804,944.00	260
Mar	77,038,000.00	5.2960	407,993,248.00	270
Apr	82,573,000.00	5.2960	437,306,608.00	295

Upon determining the expenditure and cost associated per month in 1944–1945, we then converted the cost using the JIC. However, 1944–1945 inflation indices could not be found, so an approximated inflation index of 5.296 from 1970 was used, therefore, these values are gross assumptions. These values were then used in an Excel linear regression model.

Figure 74 shows the linear regression model, with the associated equation that was used to determine the cost of ordnance per ton. However, the units of the artillery were in kilo tons, therefore, we needed to convert it to tons by dividing it by 1000.

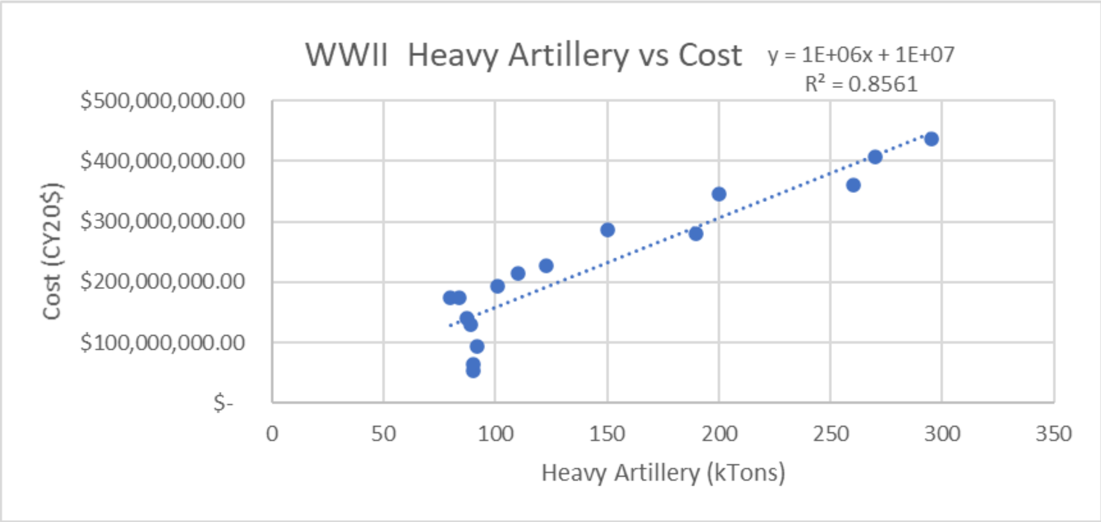

Figure 74. WWII Heavy Artillery Cost Regression

Table 41 shows the output of the cost per tonnage of logistics for each category. We average the ordnance, fuel, stores to have an average cost per tonnage of supplies to equate to $5,252.60. This data will become increasingly valuable when analyzing and determining which architecture is cost effective.

Table 41. Logistics Cost per Ton

Supply Type	***Cost ($/Ston))***
Ordnance	12,825.68
Fuel	925.12
Stores	2,007.02
Average	**5,252.60**

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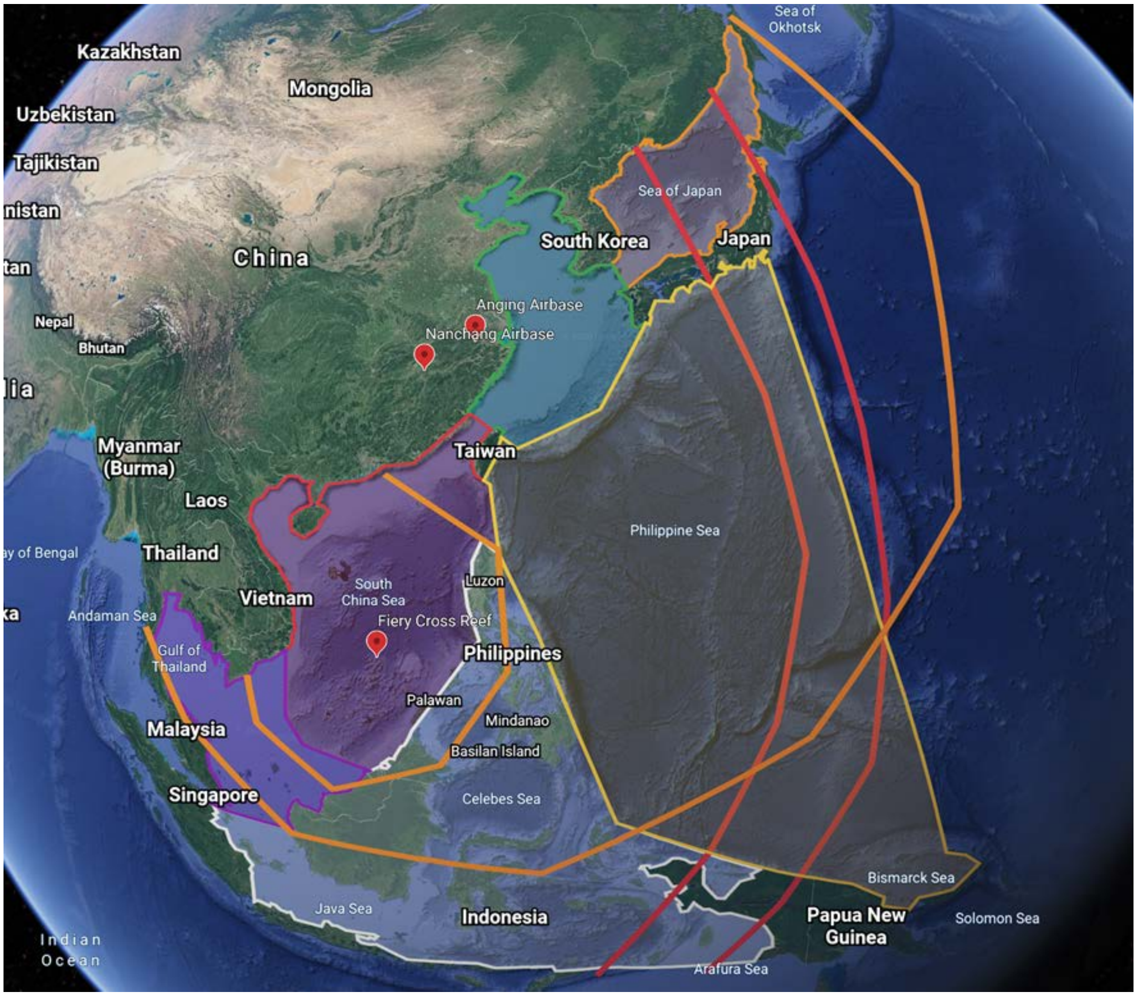
APPENDIX D. PACIFIC THREAT REGION

Our team deferred to the Technology Team's expertise and experience with operations within the Pacific Area of Operations (AO) to derive a regional breakdown of the Pacific AO. This would later assist in the determination of threat densities in which our transit routes would pass through. The regions are listed in Table 42 along with the approximate square nautical miles. Indonesia does consider approximately 1,909 square nautical miles due to land, but all other regions only consider water as part of the area

Table 42. Pacific AO Regional Breakdown

Region	***Approximate Area (nm^2)***
Sea of Japan	284,000
East China Sea	320,000
South China Sea (North)	672,000
South China Sea (South)	321,000
Philippine Sea	2,331,000
Indonesia	1,091,000

Figure 75 was developed to illustrate these regions. The Sea of Japan was outlined and shaded in orange, East China Sea green, South China Sea (North) red, South China Sea (South) purple, Philippine Sea yellow, and Indonesia white. Figure 75 also depicts enemy weapons range arcs. The red arc closest to mainland China is an approximated range marker for the DF-21 ballistic missile and the red arc just a little further from mainland China delineates the DF-26 ballistic missile range. These were determined by referencing the "Global War 2030" scenario (Jeffrey Kline, class notes, 2019). Also depicted in Figure 75 are range rings for the J-20 stealth fighter, stationed out of Fiery Cross Reef, and the H-6 bomber stationed out of Anging and Nanchange Airbases. These assets pose the greatest air threat to logistics in terms of range and payloads. The combat range of the J-20 stealth fighter is 1,000 km with an additional 180 km range from the YJ-83 ASCM and the combat range for the H-6 bomber is 3,000 km with an additional 400 km range from the YJ-12 ASCM (Jeffrey Kline, class notes, 2019).



Original map obtained from Google Earth, 2020.

Figure 75. Pacific AO Regional Breakdown with Enemy Weapons Ranges

APPENDIX E. CHINESE ORDER OF BATTLE

To determine the threat densities and lethality of the People's Liberation Army Navy (PLAN) operating within the Pacific AO, we compiled data and provided the number and location of PLAN assets within the various regions, as well as those assets outside the Pacific AO. We listed the types of weapons and payload each asset carried and annotated if the asset carried any additional, smaller assets, such as a helicopter, that could add to the asset's lethality or search and detect capability. This data was estimates based on our own operational experience and compiled after consulting the "Global War 2030" scenario (Jeffrey Kline, class notes, 2019). The compiled data is listed in Table 44, Table 45, Table 46, Table 47, and Table 48. Availability assumptions were made based solely on our operational experience and are listed in Table 43. This data helped provide a reasonable estimate to the maximum number of assets the Chinese would have available at any given time.

Table 43. PLAN Asset Availability

Asset	***Availability (%)***
Aircraft Carriers	75
Submarines	90
Surface Combatants	80
Amphibs	90
Fighter Aircraft	75
Patrol Aircraft	75
Bombers	75
Transport/Strategic Lift Aircraft	80
UAVs	90

Table 44. PLAN Maritime Force Disposition

Asset	Total	Available*	Sea of Japan	East China Sea	Philippine Sea	South China Sea (North)	South China Sea (South)	Indonesia	Elsewhere
Aircraft Carriers									
Liaoning	1	0							
Shan Dong	1	0							
Type 002	5	5		1	1	2	1		
Submarines	-	-	-	-	-	-	-	-	-
SSBN (Type 94)	4	4		1	2				1
SSN (Type 95)	6	5		1	1	2		1	
SSN (Type 93)	6	5		1	2	1	1		
SSK (Type 041 Yuan)	30	27		8	10	6		3	
SSK (Type 039G Song)	8	7	2	2		3			
SSK (Kilo 636)	5	5				1	2	2	
Surface Combatants	-	-	-	-	-	-	-	-	-
DDG (Sovermenny-modified)	2	2		2					
DDG (Type 52D Luyang III Class)	4	3		1		2			
DDG (Type 52C Luyang II Class)	2	2				1	1		
DDG (Type 52B Luyang II Class)	2	2				1	1		
FFG (Type 054 A Jiangkai II Class)	20	16		4	1	4	2	2	3
FFG (Type 053 Jiangwei I Class)	10	8		4		4			
FFG (type 53 Jianghu V Class)	5	4		2		2			
Corvettes (Type 056 Jiangdao)	20	16		6		8	2		
PGGF (Huobei Class)	60	48		9		20	7	6	6
Older PTG	25	20		2		12	6		
Amphibs	-	-	-	-	-	-	-	-	-
LHD (Type 081 Class)	1	1				1			
LPD (Type 071 Yuzhao Class)	5	5				5			
LST (Yuting II Class)	25	23				23			

Table 45. PLAN Air Force Disposition

Asset	Total	Available*	Sea of Japan	East China Sea	Philippine Sea	South China Sea (North)	South China Sea (South)	Indonesia	Elsewhere
Fighter Aircraft	-	-	-	-	-	-	-	-	-
Su-33 Flanker	200	150		40		73	12	10	15
FC-1 Fierce Dragon	100	75		24		30	6		15
J-10 Vigorous Dragon	300	225		75		100	16	4	30
J-11 Shenyang	100	75		20		35	5		15
J-20 Chengdu	25	19		6		10	3		
Patrol Aircraft	-	-	-	-	-	-	-	-	-
Y-8FQ MMA Shanxhi	60	45		10	6	10	5	7	7
Bombers	-	-	-	-	-	-	-	-	-
H-6K Xian	20	15		4	4	6	1		
H-20 Xian	25	19		4	4	10	1		
Transport / Strategic Lift Aircraft	-	-	-	-	-	-	-	-	-
Y-8/Y-9 Shaanxi	80	64		15		40	9		
Y-20 Xi'an	20	16		6		8	2		
UAVs	-	-	-	-	-	-	-	-	-
Soaring Dragon	160	144	10		100			34	
Pterodactyl UCAV	100	90	10	10	30	10	10	20	
Zond	224	202	10	30	30	72	30	30	
Zond UCAV	300	270	40	10	100	10	10	100	
Dark Sword UCAV	30	27				27			
CH-4	300	270	40	10	100	10	10	100	
CH-5	100	90	10	10	30	10	10	20	

Table 46. PLAN Maritime Force Weapons Loadout and Additional Assets

Asset		SSM	#	Range (km)	Range (nm)		SAM	#	Range (km)	Range (nm)		Torpedo	#	Range (km)	Range (nm)		OAP	#	Weapon	#	Range (km)	Range (nm)
Aircraft Carriers	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Liao ning							HHQ-10	54	9	5												
Submarines	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SSBN (Type 94)		JL-2	12	7200	4000							Yu-4B		15	8							
SSN (Type 95)		CJ-10	12	1500	810							Yu-4B		15	8							
SSN (Type 93)		CJ-10 YJ-18	12 12	1500 537	810 290							Yu-4B		15	8							
SSK (Type 041 Yuan)		YJ-82		33.3	18							Yu-4B		15	8							
SSK (Type 039G Song)		YJ-82		33.3	18							Yu-4B		15	8							
SSK (Kilo 636)		SS-N-27B	6	300	162							TEST71-ME	12	23.2	13							
Surface Combatants	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DDG (Sovermenny-modified)		YJ-12	8	500	270		HHQ-16	48	40	22		Yu-6	4	45	24		KA-28	1	OAMB Bomb	2	-	
DDG (Type 52D Luyang III Class)		YJ-18	16	537	290		HHQ-9A HHQ-10	48 24	150 9	81 5		VLS accomodates an anti submarine missile					Z-9C	2	YJ-7	2	25	13.5
DDG (Type 52C Luyang II Class)		YJ-62	8	400	216		HHQ-9A	48	150	81		Yu-7 / Yu-11	6	14	8		Z-9C	1	YJ-7	2	25	13.5
DDG (Type 52B Luyang II Class)		YJ-83	16	180	97		SA-N-7	48	42.6	23		Yu-7	6	14	8		Z-9C	1	YJ-7	2	25	13.5
FFG (Type 054 A Jiangkai II Class)		YJ-83	8	180	97		HHQ-16	32	40	22		Yu-7	6	14	8		Z-9C	1	YJ-7	2	25	13.5
FFG (Type 053 Jiangwei I Class)		YJ-83K	8	180	97		HHQ-10	8	9	5		None					Z-9C	1	YJ-7	2	25	13.5
FFG (type 53 Jianghu V Class)		YJ-83	8	180	97		None					None					None					
Corvettes (Type 056 Jiangdao)		YJ-83	4	180	97		HHQ-10	8	9	5		Yu-7	6	14	8		Z-9C	1	YJ-7	2	25	13.5
PGGF (Houbei Class)		YJ-83	8	180	97																	
Older PTG																						
Amphibs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
LHD (Type 081 Class)		None					HHQ-10	16	9	5								30				
LPD (Type 071 Yuzhao Class)		None					None										Z-8 Super Frelon	4	YJ-83K	1	180	97
LST (Yuting II Class)		None					None										Z-8 Super Frelon	2	YJ-83K	1	180	97

Table 47. PLAN Aircraft Carrier Loadout

Asset		SSM	#	Range (km)	Range (nm)		SAM	#	Range (km)	Range (nm)		Torpedo	#	Range (km)	Range (nm)		OAP	#	Weapon	#	Range (km)	Range (nm)
Aircraft Carried																						
Liaoning / Shandong																						
J-15	24	YJ-83K	8	180	97		YJ-91	10	120	65		KH-41	1	250	135		Fighter					
Z-18	6																ASW Helos					
Z-18J	4																AWACS Helos					
Z-9C	2																SAR					
Future Type 002																						
J-31	40																					
J-20	-	YJ-83	8	180	97																	
AWACS																						

Table 48. PLAN Air Force Weapons Loadout and Additional Assets

Asset		SSM	#	Range (km)	Range (nm)		SAM	#	Range (km)	Range (nm)		Torpedo	#	Range (km)	Range (nm)		OAP	#	Weapon	#	Range (km)	Range (nm)
Fighter Aircraft		**ASM**	**Max #**	**Range (km)**			**ASM**	**Max #**	**Range (km)**			**ASM**	**Max #**	**Range (km)**	-	-	-	-	-	-	-	-
Su-33 Flanker		KH-31A	10	103	56		KH-41	1	250	135		KH-25MP	12	60	32							
FC-1 Fierce Dragon		YJ-83	4	180	97		YJ-12	1	400	216												
J-10 Vigorous Dragon		YJ-8K	10	50	27		YJ-83	10	180	97												
J-11 Shenyang		Bombs and Rockets		-																		
J-20 Chengdu		YJ-83	8	180	97																	
Patrol Aircraft	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y-8FQ MMA Shanxhi		None																				
Bombers	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H-6K Xian		YJ-12	4	400	216		DF-21	1	3000	1620												
H-20 Xian		YJ-12	6	400	216		DF-21	2	3000	1620												
Transport / Strategic Lift Aircraft	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y-8/Y-9 Shaanxi																						
Y-20 Xian																						
UAVs	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Soaring Dragon																						
Pterodactyl UCAV		AKD-10	4	8	4																	
Zond																						
Zond UCAV		None																				
Dark Sword UCAV		None																				
CH-4		AR-1	4	8	4																	
CH-5		AR-1	16	8	4																	

To enable incorporation of this data into our model, we then simplified it as shown in Table 49. These models served as input valued to our modeling efforts when considering force-on-force interaction.

Table 49. Simplified Chinese Order of Battle Inputs for Modeling

Characteristics		Area	Submarines	Patrol Aircraft	DDGs	CGs	FFGs and Smaller
	Sea of Japan	284000	2	0	0	0	0
	East China Sea	320000	13	10	3	0	27
	Philippine Sea	2331000	15	6	0	0	1
	South China Sea (Nortl	672000	13	10	4	0	50
	South China Sea (Soutl	321000	3	5	2	0	15
	Indonesia	1091000	6	7	0	0	8

APPENDIX F. RADAR CROSS-SECTION REDUCTION

A logistics asset's radar cross-section (RCS) affects the probability of detection by a radar system, which increases the susceptibility of the asset. RCS is effectively the size of a target as viewed by a radar system. It is a function of the physical size, reflectance, and retrodirectivity of an object. Reflectance is a function of the surface materials of a target which determine how much energy is absorbed and how much is reflected. Retrodirectivity refers to electromagnetic radiation that the target reflects directly back to the radar system that transmitted it. Detection by a radar system relies on a target's retrodirectivity. In other words, reflectance deals with how much energy is reflected and retrodirectivity deals with the direction the energy is reflected. Decreasing either or both reflectance and retrodirectivity reduces the probability of detection by a radar system. It is worth analyzing the effect of implementing RCS reduction measures on logistics assets if increased survivability of a particular asset is desired. RCS reduction

> has become intimately associated with the term "stealth." Major contributors to radar cross section include the body, hull, or fuselage of the object; extensions such as wings, fins, sails, or mast; protuberances such as pods (sensor or weapon), nacelles, external weapons (gun barrels), or ordnance (such as bombs and missiles); propellers, engine inlets, or exhaust ducts; and sensor apertures (including the cockpit of manned vehicles) and antennas. (Harney 2013, vol 6, 367)

The United States Navy currently utilizes a variety of radar absorbent materials (RAM) and radar absorbing structures (RAS) to minimize the RCS of its assets. RAMs affect the reflectance aspect of RCS and are

> non-conducting, low dielectric constant materials are essentially transparent at radar frequencies, while highly conductive materials act like metals and strongly reflect electromagnetic energy at radar frequencies. (Harney 2013, vol 6, 383)

RAMs must have low enough conductivity levels to allow radar energy to penetrate the material, but high enough to prevent significant amounts of radar energy from escaping. "Materials that satisfy these criteria include ferrites, carbon, salts of retinyl Schiff bases, and small-particulate metal powders" (Harney 2013, vol 6, 383). Ferrites are ceramic materials, carbon composites consist of graphite fibers embedded in an organic matrix, salts of retinyl Schiff bases can be incorporated into other materials to make coatings or tiles, and an “iron ball” is a coating consisting of small iron particles. In conclusion, utilizing these types of materials via direct incorporation to the structure of a logistics asset, incorporation into appliques, or as coating could achieve reductions to 10% of the original reflectivity.

RAS is a combination of absorption characteristics of RAM with the absorption characteristics of reflecting structures. Geometric structures, such as acute wedges, require radar energy to reflect multiple times within the structures prior to exist, resulting in a significant overall attenuation to the radar energy that is available to return to the radar receiver. Figure 76 illustrates the path of radar energy when it enters wedge-shaped cavities. This structure will reduce the reflectance of the surface to the fourth power, so you can see how drastically you can reduce the RCS of an asset by implementing RAS.

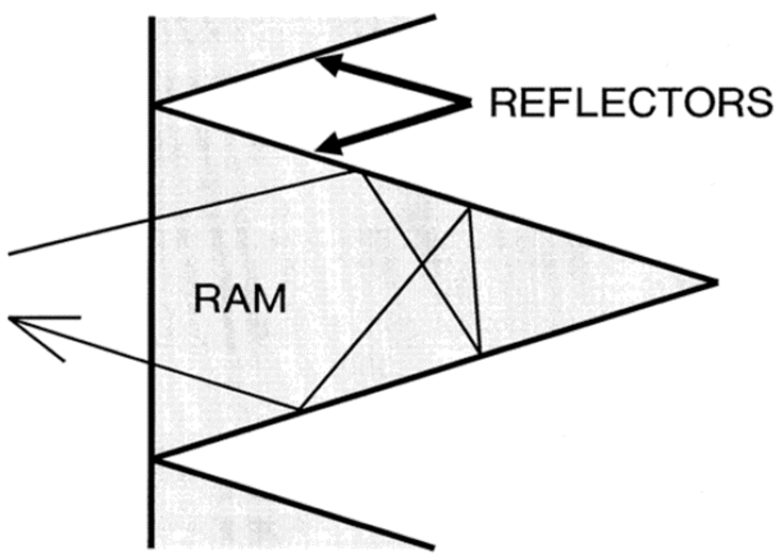


Figure 76. Multiple Reflections in Wedge-Shaped Cavities. Source: Harney (2013, vol. 6, 385).

Another RAS utilized are bent ducts preventing straight line paths from one end to the other. RAM is also used in conjunction with this as well to achieve significant overall attenuation of radar energy. This too results in a very low output intensity minimizing the probability of detection to enemy radar. Figure 77 shows a depiction of such a structure.

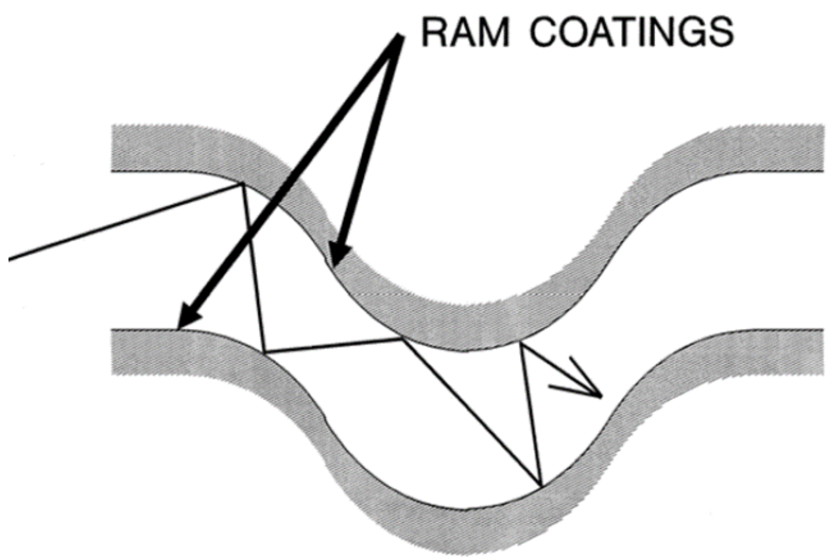


Figure 77. A Sinuous Duct Radar-Absorbing Structure. Source: Harney (2013, vol. 6, 385).

Another RCS reduction measure utilized in today's military waveguide-below-cutoff structures placed on intakes and exhausts. This is a structure that consist of large openings filled with many smaller short waveguide structures that have cutoff frequencies below with electromagnetic radiation cannot propagate and results in reflection. An alternative to this would be the use of screens, which are not quite as effective.

RCS reduction can also be achieved without using RAM or RAS by simply designing the platform in a manner that results in radar energy to reflect in directions away from the radar observing angle. Figure 78 illustrates geometric RCS reduction; it is this method that should be utilized to the maximum extent possible.

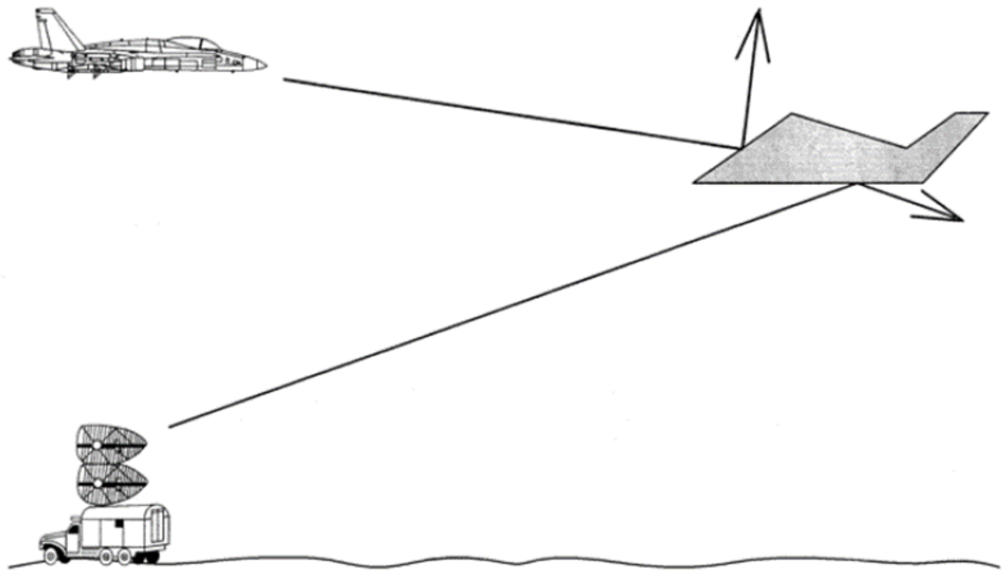


Figure 78. Geometric RCS Reduction. Source: Harney (2013, vol. 6, 377).

One example of geometric RCS reduction currently employed in the U.S. fleet is the DDG1000, *Zumwalt*-class Destroyer. It is an advanced stealth warship whose unique RCS reduction measures reduce its 610-foot long and 80-foot wide signature to that of a small fishing boat (Patterson and Lendon 2014). The key characteristic of the DDG1000 that gives such a drastic RCS reduction is its tumblehome hull-form and composite superstructure.

The hull-form features angled sides that slope inwards from the water, instead of widening, towards the ship's centerline. This allows for both an RCS reduction as well as lower observability (Global Security n.d.-b).

The superstructure utilizes both shaping and material (such as carbon fiber and balsa wood) to reduce RCS and encloses all radar apertures and communication antennas (Jacob 2014). The structure is also designed with a specialized foam core which absorbs selective radio frequencies (Lundquist 2012). The material cost of this type of superstructure is significant. For this reason, the Navy sought to reduce cost on the third destroyer of this class by utilizing steel in place of the composite (LaGrone 2013).

The LPD-17, *San Antonio*-class amphibious transport dock ship is also an example of a relatively new instance in where the Navy invested in RCS reduction. Some of this reduction was focused around the masts as they act as a major contributor to a ship's overall RCS signature. The LPD-17 was a functional replacement to the LPD-4, *Austin*-class; LSD-36, *Anchorage*-class; LKA-113, *Charleston*-class; and the LST-1179, *Newport*-class amphibious ships. In 1995, as part of the Navy's efforts to develop the next generation of ships' masts, an integrated process team was sponsored as a joint effort by the Officer of Naval Research, Naval Sea Systems Command, and Space and Naval Warfare Systems Command. This team was formed to design and integrate the Advanced Enclosed Mast/Sensor (AEM/S) system on the LPD-17 with the goal of proving that composite masts could be built for large warships at an affordable cost (Benson 1998). The AEM/S system uses advanced composites to produce a mast structure that encloses the existing legacy antenna systems of the ship standing at 28 meters tall and 10.7 meters in diameter (Mouritz et al. 2001). The structure utilizes composite materials that are sandwiched with frequency selective surface (FSS) layers that filter electromagnetic waves, allowing the transmission and reception at desired frequencies while rejecting threat radar signals (Doerry 2010). In a developmental design, the structure was hexagonal in shape with 10-degree angled sides (widest at the middle) for the top and bottom halves. The top half comprised the composite sandwich FSS materials with integrated communications infrastructure. The lower half was made with RAS comprised of a carbon reflective layer sandwiched between the structural material laminate and a balsa core, as illustrated in Figure 79. The result was a significant improvement to signal management with a mast structure to reduce the overall RCS of the ship.

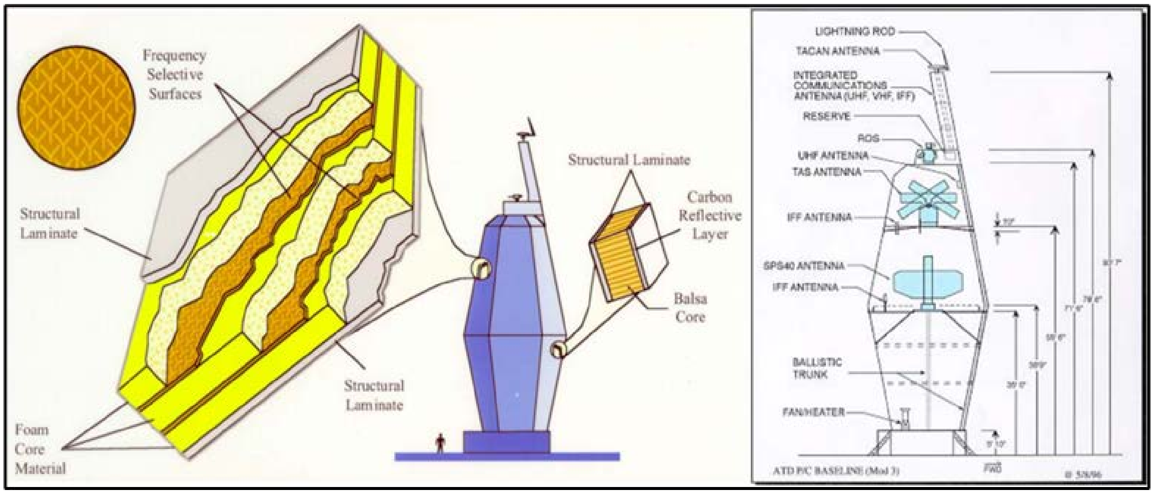


Figure 79. Illustration of an AEM/S Mast. Source: Solitario (2003).

In comparison to conventional material mast structures, the composite mast structure design studies have shown that a weight reduction of 20–50% can be achieved. In terms of cost, the fabrication of composite material is significantly higher in contract to traditional steel or aluminum structures, as illustrated in Figure 80. The other benefit to this design is that the enclosed structure protects radars and communications antennas from weather exposure and provides all-weather access for repair. This results in a significant reduction to repair, maintenance, and replacements costs as well as lowering the risk of failure. Overall, this design aids in reducing the ship's overall RCS signature, minimizes corrosion, improves fatigue performance, and improves the performance of all sensors located on the structure by reducing electrical blockage.

Weight and Cost Comparison for Composite *versus* Metallic Ship Structures

Item	*Comparison*	*Wt savings for composites*	*Fabrication cost ($/lb)*[a]		*Component cost ($composite/$metal)*[b]
			Steel or aluminium	*Composites*	
deckhouses	steel	35–45%	4–6	5–8	0·8
masts	aluminum	20–50%	9–12	20–30	1·5
foundations	steel	up to 60%	10–40	20–40	0·5

[a] Assumes composites in full production.
[b] Based on average weight and cost savings.

Figure 80. Cost of Utilizing Composite Materials in Shipbuilding. Source: Critchfield, Judy, and Kurzweil (1994).

Sensitivity analysis on RCS was conducted using the survivability model developed in this capstone project. As an example, a vessel on the sea route from Palau to Manila was modelled to illustrate the impact of different RCS values on the probability of detection by radar-equipped aircraft or ships. Generally, as RCS increases, the detection range increases to a maximum limited by the radar horizon. Figure 81 illustrates how the search sweep width of a radar-equipped aircraft varies for targets with varying RCS. The aircraft was assumed to be flying at 3,000 meters altitude against a target height of ~30 meters. At high RCS values, the sweep width was limited by the radar horizon of ~450 km. As RCS decreased, sweep width decreased to a minimum of 50 km for 1 m2 RCS.

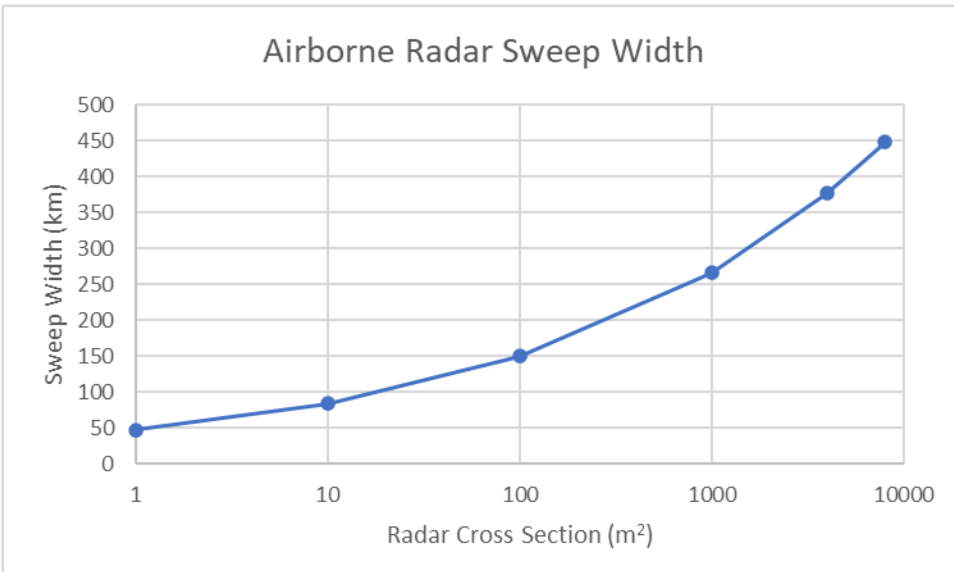


Figure 81. Sweep Width for Different RCS Values

The radar detection ranges were fed into the detection model which is based on random search theory to produce the probability of detection (P_D) curve shown in Figure 82. For a one-hour search period of the relevant AO, the P_D ranged from 2% to 18% for different RCS values. As RCS decreased, the probability of detection decreased and if the vessel went undetected, it was not engaged, hence leading to higher survivability.

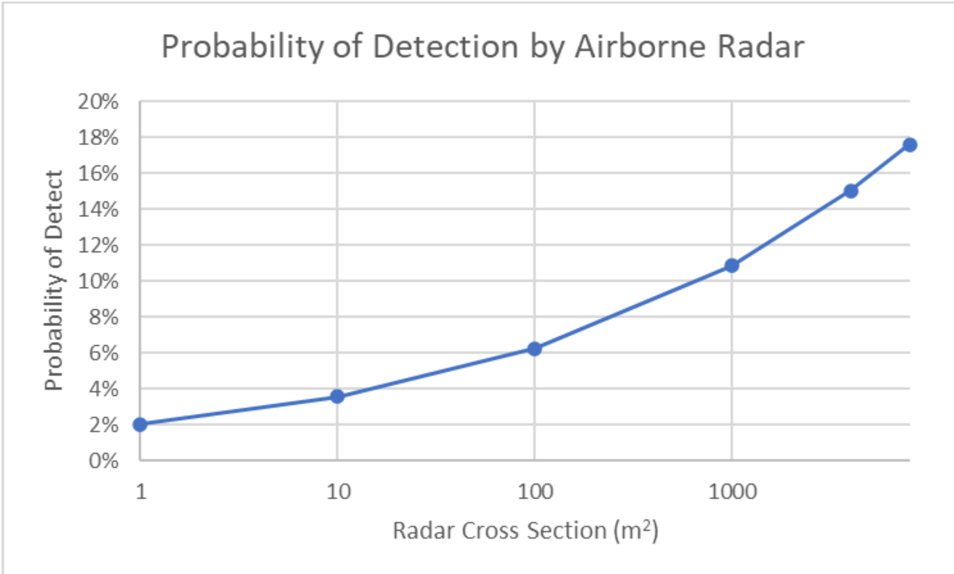


Figure 82. Probability of Detection for Different RCS Values

The routes in this capstone study were all longer than a one-hour transit due to their distances and the transit speeds of the ships studied. For instance, the route from Palau to Manila was 976 nautical miles long which took 27 hours to complete for the 35-knot JHSV—the fastest vessel studied. As a result, even with a low 2% P_D per hour, the vessels were all eventually detected and engaged. Therefore, the RCS changes did not have a major impact on survivability for these routes. However, for short routes with shorter transit times, the difference in P_D did have a significant impact. Figure 83 illustrates these results. For an 1,800 nautical mile route with nominal cruise missile threats, survivability increased slightly from ~63% to ~69%. Significantly, the improvement only became apparent when RCS was decreased to very low values. Survivability was largely determined by the single-shot probability of kill of the weapon system. On the other hand, for a 100 nautical mile route with the same threat density, decreasing RCS increased survivability from ~75% to ~95%.

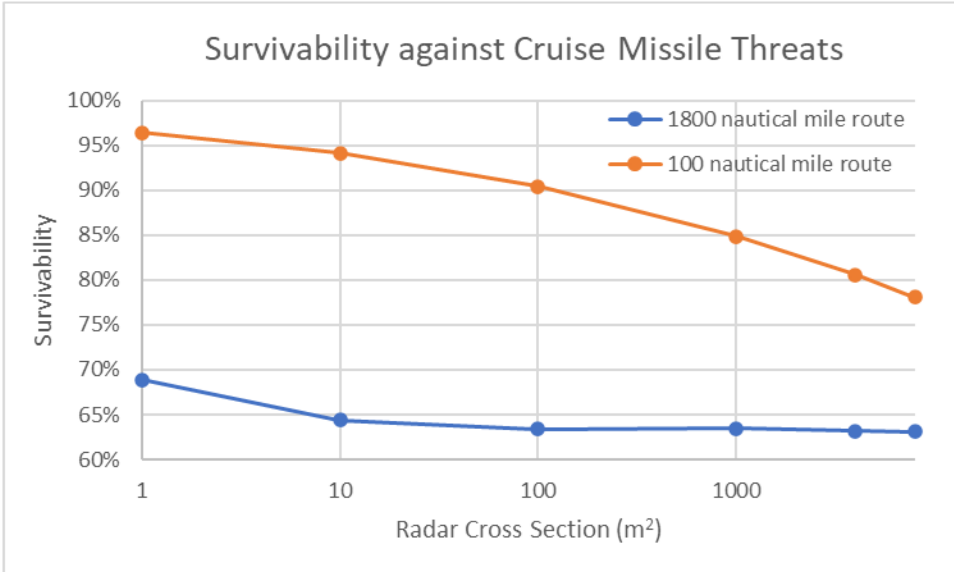


Figure 83. Survivability for Different RCS Values

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APPENDIX G. ACOUSTIC NOISE REDUCTION

The logistics assets' associated noise levels translate to a level of susceptibility to the threat, and, in particular, to enemy submarine attack. Therefore, it is worth analyzing the feasibility of implementing noise level reduction measures on assets. The United States Navy currently utilizes the prairie-masker air system on combatants to make them less susceptible to threat detection and attack by preventing the classification or identification of a ship by its acoustic signature.

The prairie air system reduces cavitation around propeller tips by emitting air through tiny holes at the edges of each propeller blade as depicted in Figure 84. Cavitation occurs because of the propeller speed, and when ships are traversing at higher speeds, higher levels of cavitation occur. The air emitting from this system reduces the pressure drop and makes it less likely to have explosive vaporization or bubble formation occur. The result of the prairie air system is a production of low-level white noise, which is much more difficult to detect than cavitation.

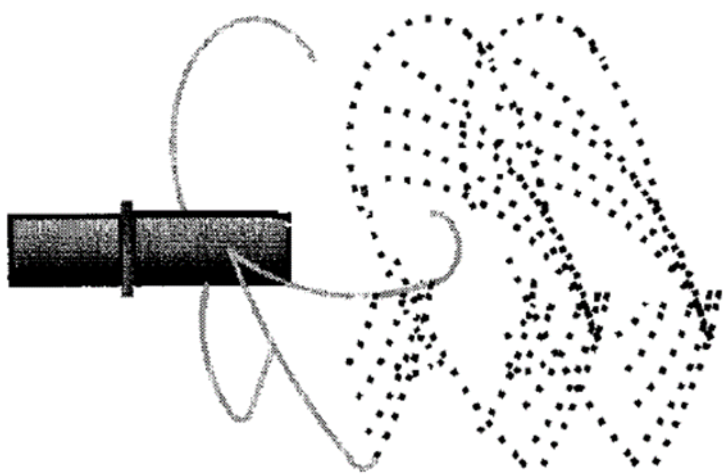

Figure 84. Prairie Air System for Reducing Propeller Noise. Source: Harney (2013, vol. 6, 403).

It is also worth stating that the pump-jet propulsion systems, like those on the LCS and Virginia-class fast-attack submarines, would not require this system as it does not use propellers. This system propels the vessel forward by creating a jet of water. This pump-jet propulsion system "produces less cavitation…which means an even lower acoustic signature"; a worthwhile consideration when it comes to reducing an asset's acoustic signature (Globe Composite n.d., par. 5).

The masker air system reduces the radiated noise of a vessel by emitting air bubbles around the hull as illustrated in Figure 85. These air bubbles strongly attenuate the acoustic noise that is being emitting from the ship. The result is that any acoustic emission coming from inside the ship travels a much shorter distance, decreasing the enemy's detection range from acoustic sensors (Harney 2013).

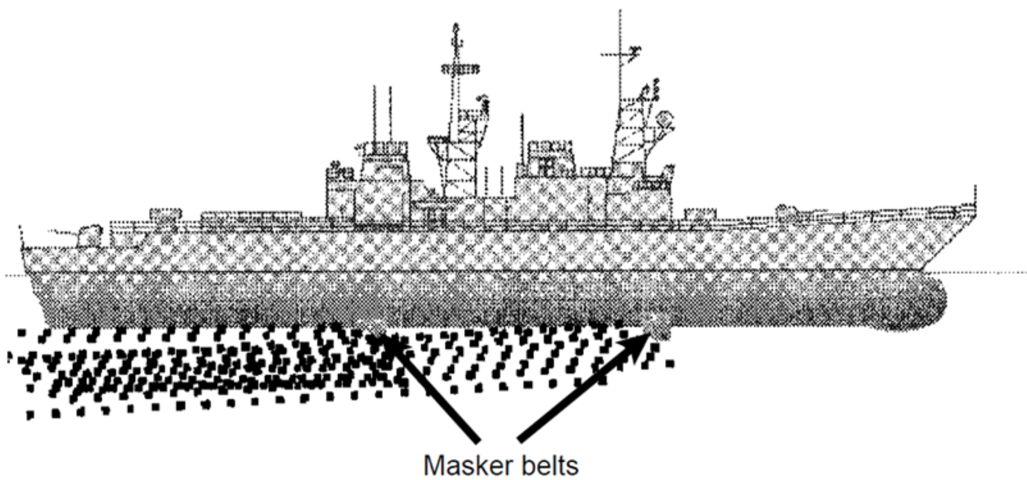

Figure 85. Masker Air System for Reducing Radiated Noise. Source: Harney (2013, vol. 6, 404).

We conducted sensitivity analysis on the noise levels of Blue logistic vessels using the survivability model developed in this study. Of the twenty vessels considered in the study, the quietest is the Orca (90 dB) and the loudest is the T-AOE (147 dB). Consequently, the sensitivity analysis considered a range of 90 to 147 dB noise level. Based on the study's sonar model, for a route with a nominal noise environment, a vessel emitting 147 dB of noise can be detected at 30 nautical miles (nm). As the noise level decreases, the detection range decreases at an exponential rate: 6 nm at 140 dB, 0.6 nm at 130 dB. The relationship between noise levels and detection range is illustrated in Figure 86 and Figure 87.

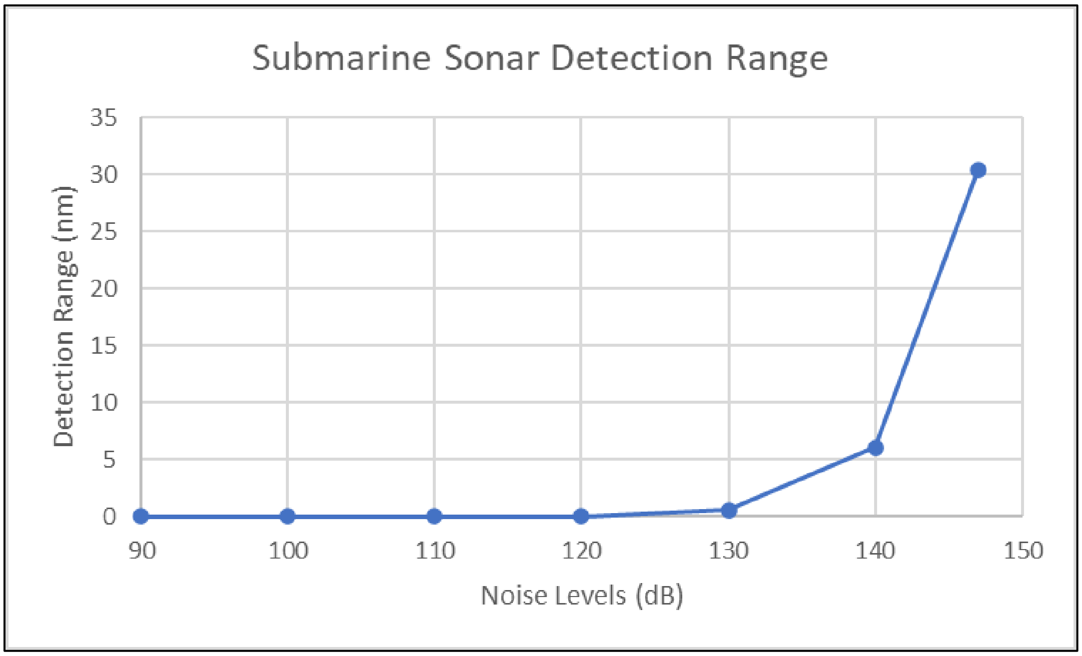

Figure 86. Sonar Detection Ranges for Different Noise Values

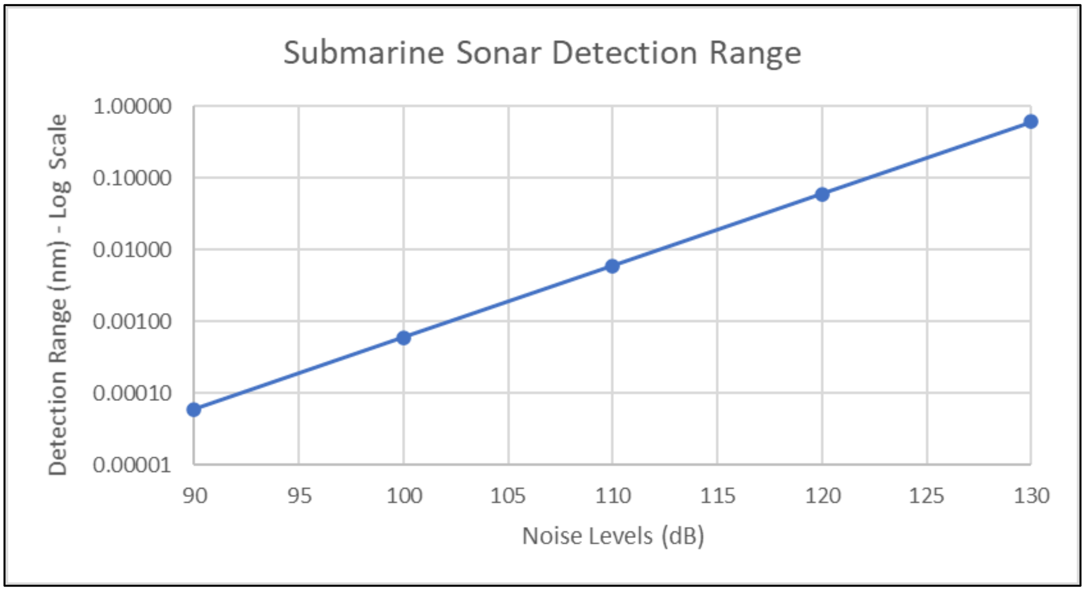

Figure 87. Sonar Detection Ranges for Different Noise Values (Logarithmic Scale)

The sonar detection ranges were applied to random search theory to derive a probability of detection (P_D) by Red submarines. As noise levels decrease, the P_D decreases. The P_D is also a function of the number of Red submarines. Higher numbers of Red submarines increase the P_D. For instance, the journey from Palau to Singapore crosses regions with a greater number of Red submarines than the journey from Palau to Manila, resulting in a higher P_D. Figure 88 and Figure 89 illustrate the relationship between the P_D per hour rate by Red submarines and the noise levels of Blue logistics vessels. It also shows the difference in P_D between the Palau-Manila and Palau-Singapore routes. For a one-hour search period, the P_D rate ranges from 0.00001% to 18% per hour as noise levels increase from 90 dB to 147 dB.

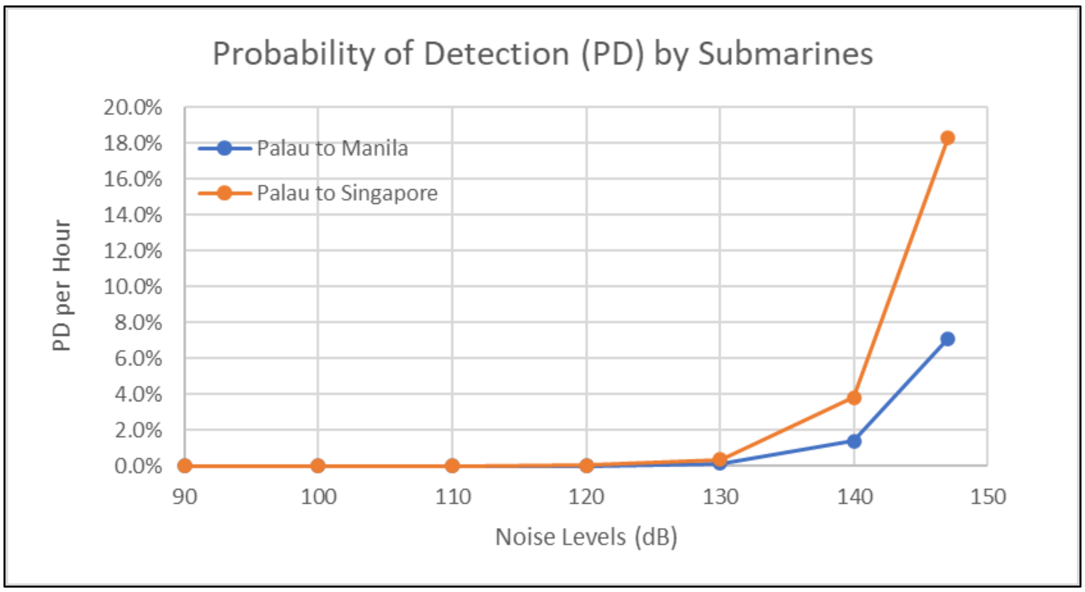

Figure 88. Probability of Detection for Different Noise Levels

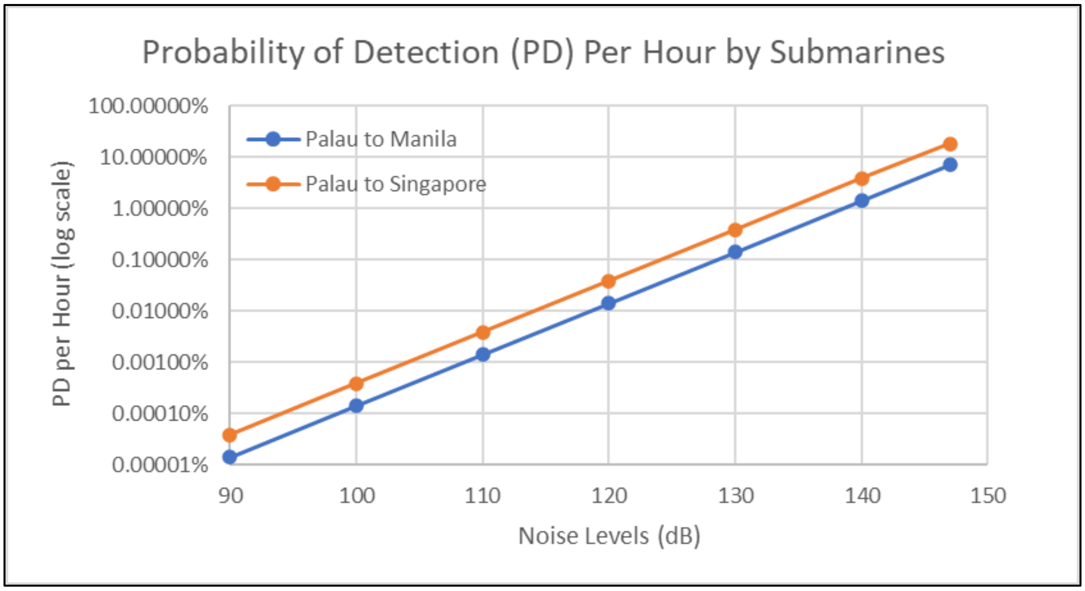

Figure 89. Probability of Detection for Different Noise Levels (Logarithmic Scale)

The overall P_D based on the journey time is calculated from the P_D per hour rate. Of note, a long journey time can result in a significant overall P_D leading to engagement by Red submarines and thus low survivability rates. For instance, the relatively low P_D per hour rate of 7% for a 147 dB T-AOE on the 27-hour Palau-Manila route still translates to a poor 35% survivability rate against Red submarines.

For the study's threat environment, especially the route lengths and the assumption of Red submarine numbers, decreasing the noise level of Blue vessels has a significant impact on survivability rate. For the Palau-Manila route, once the noise level of the Blue vessels drops below 120 dB, the sonar detection range drops to 0.06 nm, the P_D rate drops to 0.014% per hour and the survivability rate approaches 100%. The survivability rates against submarines for this route and for the Palau-Singapore route are shown in Figure 90.

While sharing a similar underlying modelling logic, sonar has much shorter detection ranges than radar. Consequently, noise reduction has a more significant impact on P_D and survivability than RCS reduction. That said, the model does not factor for the real-world possibility of pairing off-board sensors with Red submarines.

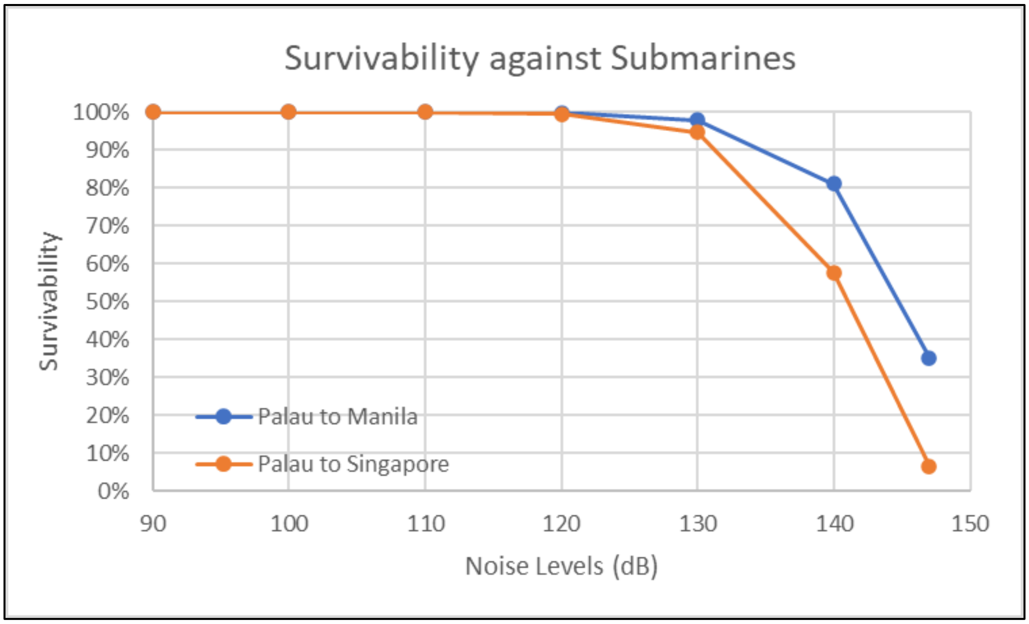

Figure 90. Survivability Rates for Different Noise Values

A 2016 thesis at the Naval Postgraduate School focused on the evaluation of LCS, a ship equipped with prairie and masker air systems, for open-ocean anti-submarine warfare. The noise reduction noted in that research was -10 dB for each system (Valerio et al. 2016). Therefore, when incorporating nose reduction values into our model, we utilized a total noise level reduction of -20 dB to simulate concurrent use of both systems to analyze the effect on logistics survivability.

APPENDIX H. BETWEENNESS CENTRALITY: TOP-TEN NODES

Table 50 shows the top ten nodes by betweenness centrality that were identified during our network analysis.

Table 50. Top Ten Nodes by Betweenness Centrality

Node	***Value***	***Node***	***Value***	***Node***	***Value***
Uncontested		***LCS***		***JHSV***	
Singapore	0.192	Singapore	0.189	Palau	0.432
Manila	0.179	Guam	0.158	Guam	0.384
Guam	0.089	Manila	0.158	Puerto Princesa	0.279
Palau	0.079	Okinawa	0.105	Bandar Seri Begawan	0.263
Cebu	0.047	Darwin	0.079	Kwajalein	0.258
Zuoying	0.047	Diego Garcia	0.068	Cebu	0.226
Puerto Princesa	0.047	Cebu	0.063	Yokusuka	0.221
Okinawa	0.042	Palau	0.058	Singapore	0.205
Yokusuka	0.026	Yokusuka	0.053	Diego Garcia	0.205
Darwin	0.021	Puerto Princesa	0.053	Darwin	0.189
T-AOE		***T-AO***		***T-AKE***	
Palau	0.411	Guam	0.268	Palau	0.326
Guam	0.374	Singapore	0.216	Guam	0.311
Puerto Princesa	0.284	Diego Garcia	0.216	Singapore	0.216
Cebu	0.274	Darwin	0.174	Diego Garcia	0.216
Kwajalein	0.247	Kwajalein	0.158	Puerto Princesa	0.195
Bandar Seri Begawan	0.247	Manila	0.153	Kwajalein	0.184
Singapore	0.226	Bandar Seri Begawan	0.132	Darwin	0.174
Diego Garcia	0.226	Yokusuka	0.126	Cebu	0.163

Node	Value	Node	Value	Node	Value
Yokusuka	0.216	Puerto Princesa	0.111	Yokusuka	0.142
Darwin	0.184	Okinawa	0.068	Bandar Seri Begawan	0.132
LHA		***LSD***		***LPD***	
Guam	0.268	Guam	0.237	Guam	0.242
Singapore	0.216	Singapore	0.205	Singapore	0.200
Diego Garcia	0.216	Diego Garcia	0.163	Diego Garcia	0.163
Palau	0.200	Manila	0.142	Bandar Seri Begawan	0.153
Darwin	0.174	Palau	0.132	Puerto Princesa	0.147
Kwajalein	0.158	Kwajalein	0.126	Kwajalein	0.126
Bandar Seri Begawan	0.132	Cebu	0.121	Darwin	0.121
Yokusuka	0.126	Darwin	0.116	Yokusuka	0.095
Manila	0.111	Yokusuka	0.095	Manila	0.084
Puerto Princesa	0.111	Okinawa	0.063	Okinawa	0.079
OSV		***SEATRAIN***		***MOTHERSHIP***	
Guam	0.226	Singapore	0.237	Singapore	0.263
Singapore	0.221	Bandar Seri Begawan	0.216	Guam	0.216
Diego Garcia	0.179	Guam	0.179	Diego Garcia	0.216
Bandar Seri Begawan	0.174	Manila	0.116	Bandar Seri Begawan	0.184
Puerto Princesa	0.116	Diego Garcia	0.116	Puerto Princesa	0.163
Kwajalein	0.111	Puerto Princesa	0.111	Palau	0.147
Manila	0.105	Cebu	0.084	Okinawa	0.132
Darwin	0.105	Okinawa	0.074	Darwin	0.132
Yokusuka	0.079	Yokusuka	0.068	Manila	0.111
Zuoying	0.053	Kwajalein	0.058	Kwajalein	0.105
MOLA		***T-AK***		***T-AKR***	
Bandar Seri Begawan	0.242	Guam	0.268	Guam	0.268
Okinawa	0.184	Singapore	0.216	Singapore	0.216

Node	***Value***	***Node***	***Value***	***Node***	***Value***
Puerto Princesa	0.184	Diego Garcia	0.216	Diego Garcia	0.216
Palau	0.168	Palau	0.179	Palau	0.179
Singapore	0.163	Darwin	0.174	Darwin	0.174
Manila	0.105	Kwajalein	0.158	Kwajalein	0.158
Phuket	0.074	Bandar Seri Begawan	0.132	Bandar Seri Begawan	0.132
Darwin	0.042	Yokusuka	0.126	Yokusuka	0.126
Cam Ranh Bay	0.042	Puerto Princesa	0.105	Puerto Princesa	0.111
Cebu	0.037	Cebu	0.095	Manila	0.089
T-AKR(RORO)		***LCU***		***ESB***	
Guam	0.268	Singapore	0.226	Guam	0.268
Palau	0.221	Manila	0.179	Singapore	0.216
Singapore	0.216	Guam	0.147	Diego Garcia	0.216
Diego Garcia	0.216	Okinawa	0.111	Palau	0.179
Darwin	0.174	Puerto Princesa	0.089	Darwin	0.174
Kwajalein	0.158	Darwin	0.084	Puerto Princesa	0.163
Bandar Seri Begawan	0.132	Cebu	0.058	Kwajalein	0.158
Yokusuka	0.126	Palau	0.032	Bandar Seri Begawan	0.132
Puerto Princesa	0.105	Yokusuka	0.032	Yokusuka	0.126
Manila	0.068	Phuket	0.026	Manila	0.105
ESD		***ORCA***			
Guam	0.268	Palau	0.189		
Singapore	0.216	Bandar Seri Begawan	0.184		
Diego Garcia	0.216	Cebu	0.126		
Palau	0.179	Manila	0.100		
Darwin	0.174	Phuket	0.100		
Puerto Princesa	0.163	Puerto Princesa	0.089		
Kwajalein	0.158	Okinawa	0.079		
Bandar Seri Begawan	0.132	Singapore	0.068		

Node	***Value***	***Node***	***Value***	***Node***	***Value***
Yokusuka	0.126	Zuoying	0.047		
Manila	0.105	Sasebo	0.037		

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