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MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING ANALYSIS CAPSTONE PROJECT REPORT

DISTRIBUTED SURFACE FORCE

by

Team Alpha
Cohort 20

June 2014

Project Advisor: Gary O. Langford

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After employing the systems engineering process tailored to the problem to understand requirements and alternatives, a single mission SSC adapted to anti-surface warfare (ASUW) emerged as the solution. The SSC is conceptually employed in an armada composed of existing naval forces, which provide a protective shield against a multi-threat enemy force. The Armada is nominally composed of Arleigh Burke-class destroyers, Littoral Combat Ships and SSCs. The SSC'As capabilities include eight anti-ship cruise missiles with a range of 90 nautical miles, speed greater than 25 knots, and organic detection and classification range of at least 60 nautical miles.

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ABSTRACT

Large naval surface combatants are potentially held at risk by adversarial anti-access aerial denial (A2AD) weapon systems. To mitigate that risk we propose a distributed surface force concept, which relies on a cost-effective small surface combatant (SSC) capable of augmenting current forces in the 2025–2030 timeframe. We show that dispensing offensive and defensive power onto numerous smaller platforms has several advantages, including a more resilient force structure, greater number of ships, and fiscal cost savings.

After employing the systems engineering process tailored to the problem to understand requirements and alternatives, a single mission SSC adapted to anti-surface warfare (ASUW) emerged as the solution. The SSC is conceptually employed in an armada composed of existing naval forces, which provide a protective shield against a multi-threat enemy force. The Armada is nominally composed of Arleigh Burke-class destroyers, littoral combat ships and SSCs. The SSC's capabilities include eight anti-ship cruise missiles with a range of 90 nautical miles, speed greater than 25 knots, and organic detection and classification range of at least 60 nautical miles.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	anti-air warfare
AIP	air independent propulsion
AoA	analysis of alternatives
AOR	area of responsibility
ARPA	automatic radar plotting aid
ASBM	anti-ship ballistic missile
ASCM	anti-ship cruise missile
ASUW	anti-surface warfare
ASW	anti-submarine warfare
A2AD	anti-access area denial
BDA	battle damage assessment
CAIV	cost as an independent variable
CBO	Congressional Budget Office
CES	cost element structure
CG	guided missile cruiser
CLA	constraints, limitations, and assumptions
CN3	communication navigation network nodes
CNO	Chief of Naval Operations
COCOM	combatant commander
CONOPS	concept of operations
CONUS	contiguous United States
COTS	commercial off the shelf
CPA	closest point of approach
CRUDES	short name for cruiser or destroyer platform (usually Aegis)
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CSG	carrier strike group
CSL	combat ship for the littorals
CVN	nuclear-powered aircraft carrier
C4I	command, control, communications, computers, and intelligence

DARPA	Defense Advanced Projects Research Agency
DD	destroyer
DDG	guided missile destroyer
DOD	Department of Defense
DoN	Department of Navy
DOE	design of experiments
DOTMLPF	doctrine, organization, training, materiel, leadership and education, personnel, and facilities
DRM	design reference mission
DSO	Defense Science Organization National Laboratories (Singapore)
DSTA	Defense Science and Technology Agency (Singapore)
DT&E	developmental testing and evaluation
EEZ	economic exclusion zone
EM	electro-magnetic
EMCON	emissions control
ESG	expeditionary strike group
ESM	electronic support measures
FAC	fast attack craft
FFBD	functional flow block diagram
FFG	guided missile frigate
FMC	fast missile craft
GPS	Global Positioning System
HF	high frequency
HVU	high value unit
IIR	imaging infrared
IO	information operations
ISR	intelligence, surveillance, and reconnaissance
JC4I	joint command, control, communications, computer and intelligence
JHSV	Joint High Speed Vessel
KEPD	kinetic energy penetrator and destroyer
LAN	local area network

LCC	life cycle cost
LCCE	life cycle cost estimate
LCS	Littoral Combat Ship
LOS	line of sight
LRASM	long range anti-ship missile
MBDA	Mantra BAE Dynamics Alenia
MEKO	Mehrzweck-Kombination
MOE	measure of effectiveness
MOP	measure of performance
M&S	modeling and simulation
NATO	North Atlantic Treaty Organization
NAVSEA	Naval Sea Systems Command
NMS	national military strategy
NPS	Naval Postgraduate School
NSM	naval strike missile
NSS	national security strategy
OASuW	offensive anti-surface warfare
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
OSD	Office of the Secretary of Defense
OTH	over the horizon
O&S	operations and support
PACOM	Pacific Command
PHM	guided missile patrol combatant (Hydrofoil)
PLA	People’s Liberation Army
PLAAF	People’s Liberation Army Air Force
PLAN	People’s Liberation Army Navy
PM	program manager
PTG	guided missile patrol craft
QDR	quadrennial defense review
RAM	rolling airframe missile
RAS	replenishment at sea

RDT&E	research, development, test and evaluation
RF	radio frequency
R&D	research and development
SAF	Singapore Armed Forces
SAG	surface action group
SAR	selected acquisition report
SATCOM	satellite communication
SCS	South China Sea
SE	systems engineering
SEA	systems engineering analysis
SES	surface effect ship
SHF	super-high frequency
SIGINT	signal intelligence
SIMIO	Simulation Modeling framework based on Intelligent Objects
SLOC	sea lines of communication
SOF	special operations force
SOM	Strait of Malacca
SSBN	nuclear powered ballistic missile submarine
SSC	small surface combatant
SSGN	nuclear powered guided missile submarine
SSM	surface to surface missile
SSN	nuclear powered attack submarine
ST	Singapore Technologies
T-AKE	Lewis and Clarke class
TDSI	Temasek Defense Systems Institute
TRL	technology readiness level
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UHF	ultra-high frequency
UN	United Nations
UNREP	underway replenishment
USN	United States Navy

USV	unmanned surface vehicle
USW	undersea warfare
UUV	unmanned undersea vehicle
VLS	vertical launch system
WBS	work breakdown structure

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EXECUTIVE SUMMARY

The United States Defense Department's fiscal constraints dictate investment in force structure which must be cost effective and add major capability to remain relevant for the foreseeable future. As stated in the 2014 Quadrennial Defense Review:

> We must ensure the that the fleet is capable of operating in every region and across the full spectrum of conflict. No new negotiations beyond 32 Littoral Combat Ships (LCS) will go forward, and the Navy will submit alternative proposals to procure a capable and lethal small surface combatant. (Hagel 2014)

This statement makes relevant the system's engineering analysis (SEA) cohort 20 team A (SEA-20A) distributed surface force capstone project as an opportunity to conduct an unbiased study to provide the Navy with a small surface combatant solution well-adapted to its needs. This project's goal is to deliver a high-level design for a small surface combatant (SSC) capable of serving as a credible deterrent to aggression well-adapted to projecting power inside an anti-area access denial (A2AD) environment.

The team's formal tasking statement via the systems engineering analysis chair is shown below:

> Design a fleet system of systems and concept of operations for cost effective small surface combatants in a range of missions to augment naval operations or conduct specified tasking in the 2025–2030 timeframe and beyond. Consider requirements for these ships to execute naval missions across the kill chain spectrum. Consider new ship requirements, flotilla size, operating areas, bandwidth and connectivity, logistics, and basing support in forward areas or from CONUS bases. Generate requirements for unmanned and manned platforms to be used by flotilla ships and ensure each strike platform can execute its own kill chain regardless of the EM environment. Specifically, analyze alternatives to employ unmanned/manned systems from flotilla ships to support their missions, including consideration of a common type aerial platform with a configurable payload package. Consider the current LCS fleet structure and funded programs as the baseline system of systems and for developing concepts of operations. Ensure all systems identified within the solution set are at a Technology Readiness Level of 8 or higher. Next, develop alternative architectures for platforms, manning, command and control, intelligence collection/dissemination and consumption, communication

and network connectivity, and operational procedures. Address the costs and effectiveness your alternatives.

Designing the SSC for combat in the South China Sea, Persian Gulf, and Straits of Malacca, where possible adversaries employ effective anti-access area denial (A2AD) weapon systems, is a challenging task. This assignment is made less difficult by utilizing the SEA integrated project team's broad expertise, which includes United States naval officers with expertise in surface warfare, air warfare, and undersea warfare combined with Singaporean civilian and military officers. Additionally, the product is enhanced by using the system engineering's (SE) guiding principles.

The SE process was used to analyze the problem posed in the tasking statement, to understand the problems posed in the tasking statement, to understand system requirements, to construct alternatives, and to produce recommendations. A tailored SE process model was developed, incorporating clear phases with iterative loops shown in the Figure 1. This process model contains a logical progression beginning with the initial tasking statement and leading to a system recommendation.

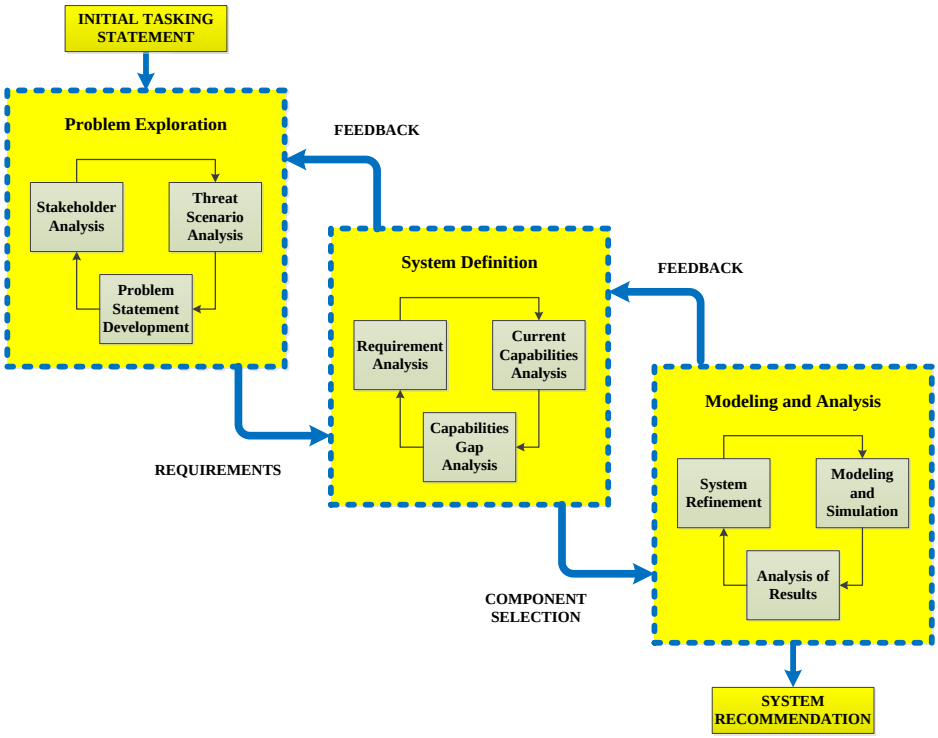

Figure 1. SEA-20A revised systems engineering process diagram.

Through the iterative process of modeling and analysis, a concept of operations (CONOPS) employs a SSC flotilla in a heterogeneous squadron the team calls the armada. The armada is a scalable concept where capability gaps of a single mission SSC are mitigated by the existing force structure. For example, the CONOPS employs an armada composed of fifteen SSCs, two Littoral Combat Ships (LCS) equipped with the anti-submarine warfare module, and two Arleigh Burke-class destroyers providing air defense for the group inside an A2AD environment. This 19-ship formation was capable of taking on and defeating an enemy force composed of 10 missile boats, four destroyers, two frigates, five submarines, and one aircraft while sustaining only marginal losses.

The team derived the most important SSC characteristics. These requirements include an organic 60 nautical mile detection and classification range capability, eight 90 nautical mile ASCMs with a minimum salvo size of two, and speed greater than 25 knots. Note that the detection and classification range is dependent on possible manned and unmanned sensor platforms launched from each SSC. Combat effectiveness did not significantly increase above 25 knots, but may provide the SSC a favorable firing position prior to engagement. The SSC networking capability was not a significant facture due to the close ship proximity resulting from geographic features in the modeling scenarios.

To find these requirements, several scenarios were considered relevant to evaluate the effectiveness of the small surface combatant and the associated armada. These scenarios include the Spratly Islands in the South China Sea, the Strait of Malacca, and the Persian Gulf. Of these three scenarios, the Spratly Islands provide the most challenging conditions and was selected to provide the tactical situations for the modeling and simulation effort. The South China Sea challenges include high merchant and commercial traffic density, a combination of shallow and deep waters, a proximity to A2AD weapons systems, and a multitude of natural landmasses that inhibit free movement.

A large number of factors may affect the performance of the SSC in a combat engagement. These factors include ship speed, missile capacity and range, sensor range, ship draft, fuel capacity, endurance, crew size, and armada group size. In order to determine the SSC capabilities that provide the most significance to the armada's combat effectiveness, multiple simulations of each possible factor combination were conducted and a regression analysis was performed. To evaluate these SSC factor's effectiveness of in a surface on surface engagement, the simulations were first restricted to just the surface combatant portion of the tactical situation. The single most significant factor that improved the armada's combat effectiveness was the SSC's detection and classification range. For the scenario the enemy was assumed to have a 50 nm sensor range. As seen in the Figure 2, the armada's effectiveness improved greatly when the U.S. sensor range exceeded that of the adversary. When the U.S. force's sensor range was approximately five nautical miles greater than the enemy's sensor range, the combat effectiveness improved to the point where the average number of U.S. casualties was less than one, while all of the enemy combatants were destroyed. *From this analysis, the single most important factor for the survival of a SSC is the ability to fire effectively at the enemy first.*

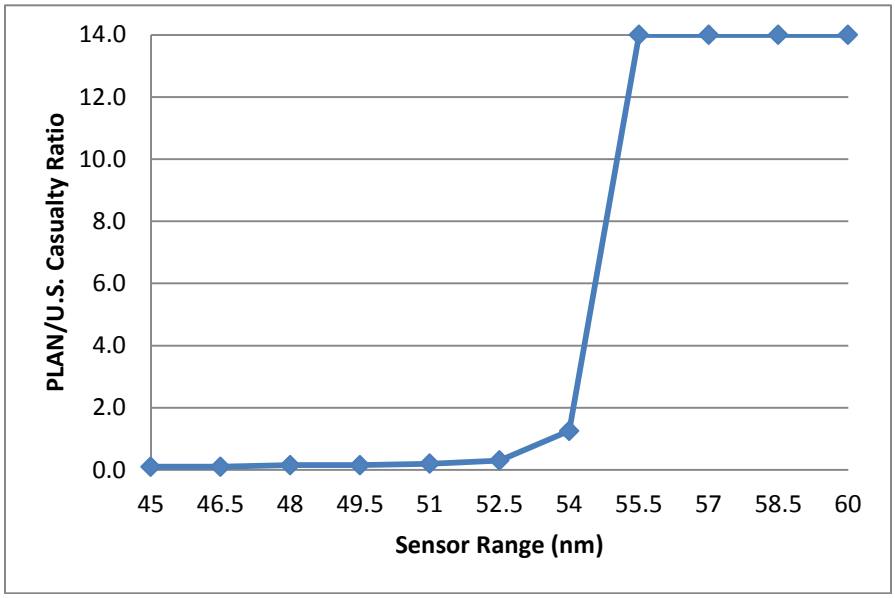

Figure 2. Refined casualty ratio versus sensor range plot.

To better understand the armada's effectiveness and risk inside the A2AD environment, the full threat envelope was introduced by adding submarines and then aircraft to the tactical simulations. Initially, no antisubmarine capabilities are modeled within the U.S. armada. The results of this model can be seen in Figure 3. The addition of one PLAN submarine engaged in an ASUW role results in a significant loss of U.S. warships. Additional PLAN submarines result in a further increase in U.S. warships lost. *The major takeaway from this analysis is that the armada is vulnerable to submarine attack if no ASW capability is included in the force mix.*

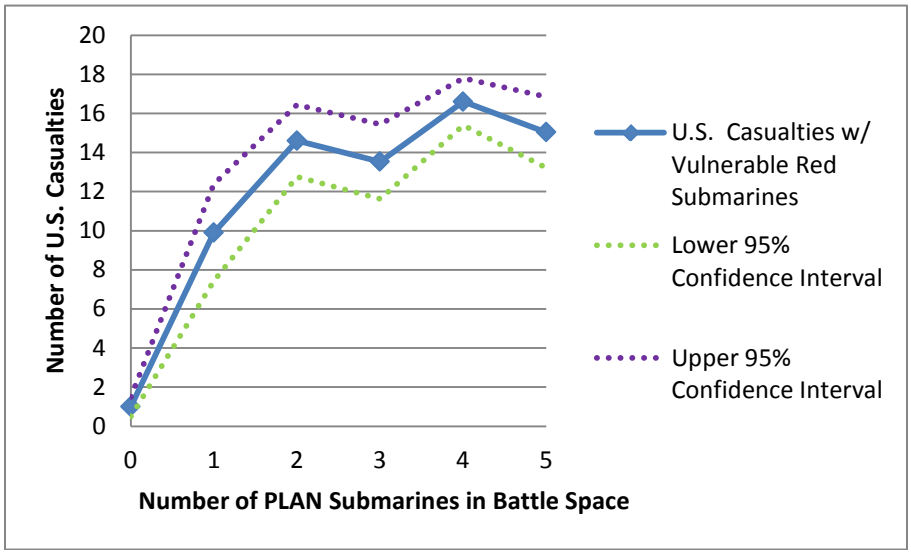

Figure 3. Impact of PLAN submarines with no U.S. ASW capabilities.

The impact of enemy submarines on the survivability of the armada reveals a capability gap that must be addressed. One feasible solution is adding ASW capabilities to the armada with the LCS's ASW mission module. PLAN submarines were again added to the scenario one at a time, but in this second iteration, the LCS is equipped with an ASW capability. The armada's survivability is drastically improved as shown in Figure 4. While U.S. casualties do increase when the first PLAN submarine is introduced, the number of U.S. casualties does not increase rapidly when additional submarines are added.

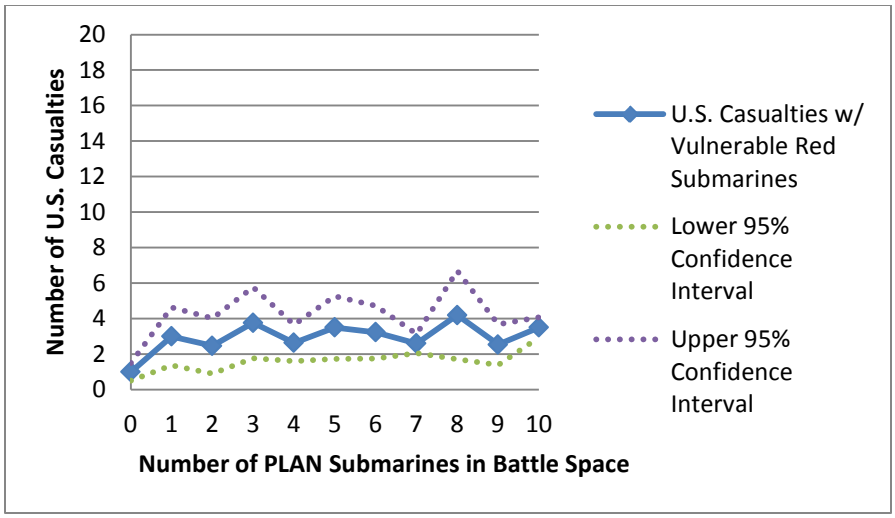

Figure 4. Impact of PLAN submarines with some U.S. ASW capabilities.

As with submarines, PLAN air threat was assessed by adding one aircraft at a time to determine the impact on the survivability of an armada without the DDG's air defense capabilities. Aircraft were modeled as H6 bombers with four ASCMs and an unlimited number of sorties. The results can be seen in Figure 5.

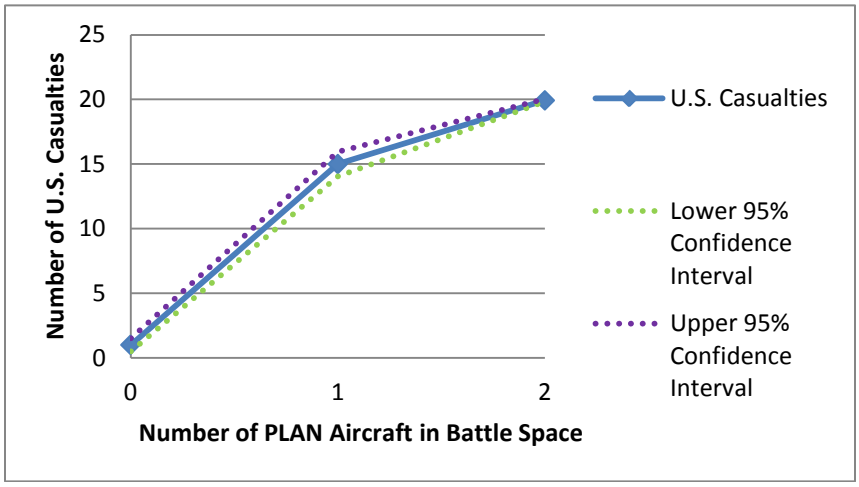

Figure 5. Impact of PLAN aircraft.

These results reveal the devastating impact enemy aircraft have on the armada equipped with no air defense. Two dedicated aircraft operating without a threat can destroy the armada in fewer than four sorties. Although it describes a worst case situation, this simulation does identify a capability gap that may be addressed by adding AAW assets to the armada or allocating land-based air assets to provide this protection.

The preceding analysis shows that a small combatant flotilla is vulnerable when enemy submarines and aircraft are in their operating area. The armada concept, or deploying with a mixed ship squadron to provide the tactical force some defensive capability while still dispersing offensive capabilities, is proposed to employ in a high threat environment.

Despite this work's simulation focus on the South China Sea, there are potential threats from ASCMs and ASBM in various locations throughout the world. Operating inside these A2AD threat areas requires a new concept for the logistics train and equipment. Establishing a new replenishment method capable of sustaining the fleet inside an A2AD environment was created. The new method involves the use of small fuel ferries to shuttle fuel from T-AKEs outside the A2AD environment to warships inside the A2AD environment. Fuel demand was found to be the most significant logistic requirement in both combat evolutions and "peace time" steaming. In order to understand and apply this concept the calculations for fuel capacity and burn rate were conducted.

Fuel capacities for the fuel transports, the fuel ferry and the T-AKE, were established and calculated through research into the various classes of ships. While there are better ships for refueling due to a higher capacity, they lacked the ability to transport dry stores and ammunition in sufficient quantities in addition to fuel. The T-AKE carries approximately 900,000 gallon of fuel. The fuel ferry, based on a modified JHSV design, carries 210,000 gallons. The capacity of the combatants was estimated as twenty percent of total tonnage. With these capacities, the number of logistics ships (T-AKEs and fuel ferries) required to support a group of SSCs was established. The example below is specifically for an Endurance Patrol, where green represents ships that can be supported by four fuel ferries, each with a 210,000 gallons capacity. Yellow represents ships that

can only be supported by four T-AKEs with a capacity of 900,000 gallons each and combatants requiring refueling when they reach 80% of capacity.

Tonnage	Single Ship	2 Ships	4 Ships	6 Ships	8 Ships	10 Ships	12 Ships	14 Ships	16 Ships
100									
200									
300									
400									
500									
600									
700									
800									
900									
1000									
1500									
2000									
3000									
4000									
5000									
6000									

Table 1. Combatant ship supportability refueling at 80% capacity.

One solution to overcoming patrol endurance limitations of a small combatant is to change the doctrine that dictates the minimum allowable fuel capacities remaining before refueling is required. The example below illustrates the increase in patrol time that can be gained by simply allowing the combatant ships to operate to a lower fuel reserve level. Using fifty percent capacity as the refueling point, a 1500-ton ship can operate for five days before refueling is required. By allowing the ships to operate to a lower fuel reserve level (20 percent remaining vice 50 percent remaining), the on station time of the combatant can be extended to eight days. This increase in endurance could help to significantly reduce the logistics issues presented in an A2AD environment. Figure 6 contains the fuel endurance versus ship tonnage at 15 knots.

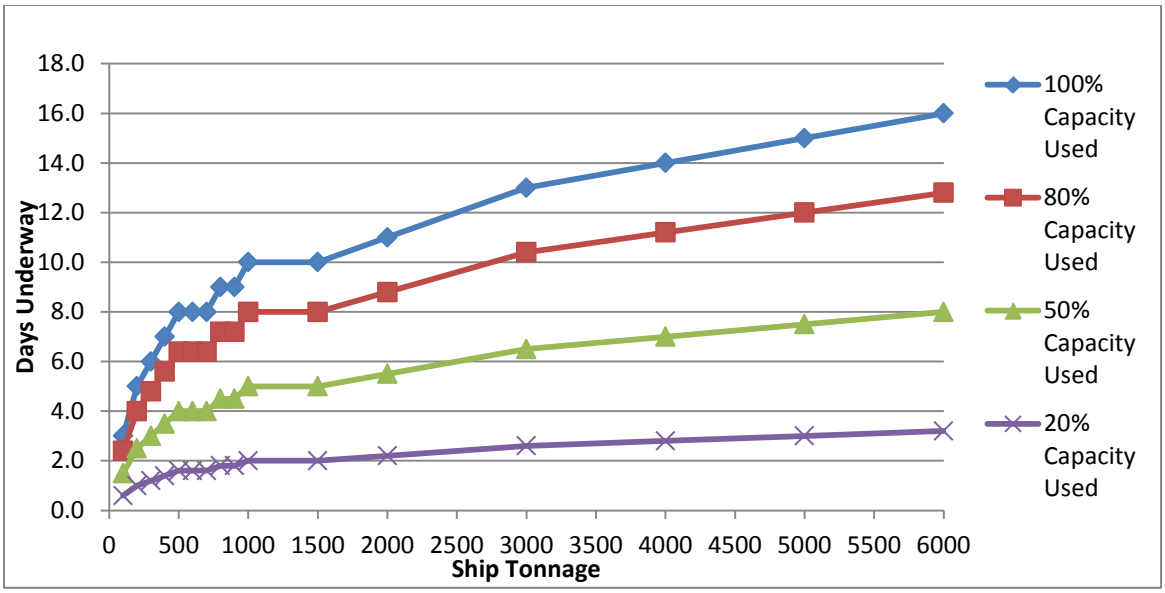

Figure 6. Fuel endurance at 15 knots versus ship tonnage.

A major component of the tasking statement is to design a cost-effective SSC capable of delivering additional capability to augment existing force structure. Using the 600-ton SSC as the lower bound and the 1500-ton SSC as the upper bound, analogous ships were selected and used to develop a linear regression based cost estimation model. Assuming the Navy would acquire 45 ships of the final desired tonnage, the model can be used to calculate the first unit cost (T_1). The final unit cost (assuming 45 ships of each tonnage are purchased) can be estimated by implementing an 85 percent learning curve into the ship production calculation. The estimated cost of each ship (based on the ship production number) can be seen in Figure 7. From the cost analysis, the 600-ton SSC was calculated to have a T_1 cost of $313 million and the 45th unit cost was determined to be approximately $138 million. For the 1500-ton SSC, the T_1 cost was estimated at $513 million and unit number 45 was estimated at $227 million. Both the 600-ton and 1500-ton SSC variants fall below current LCS acquisition cost and can effectively augment the ASUW capability of the fleet.

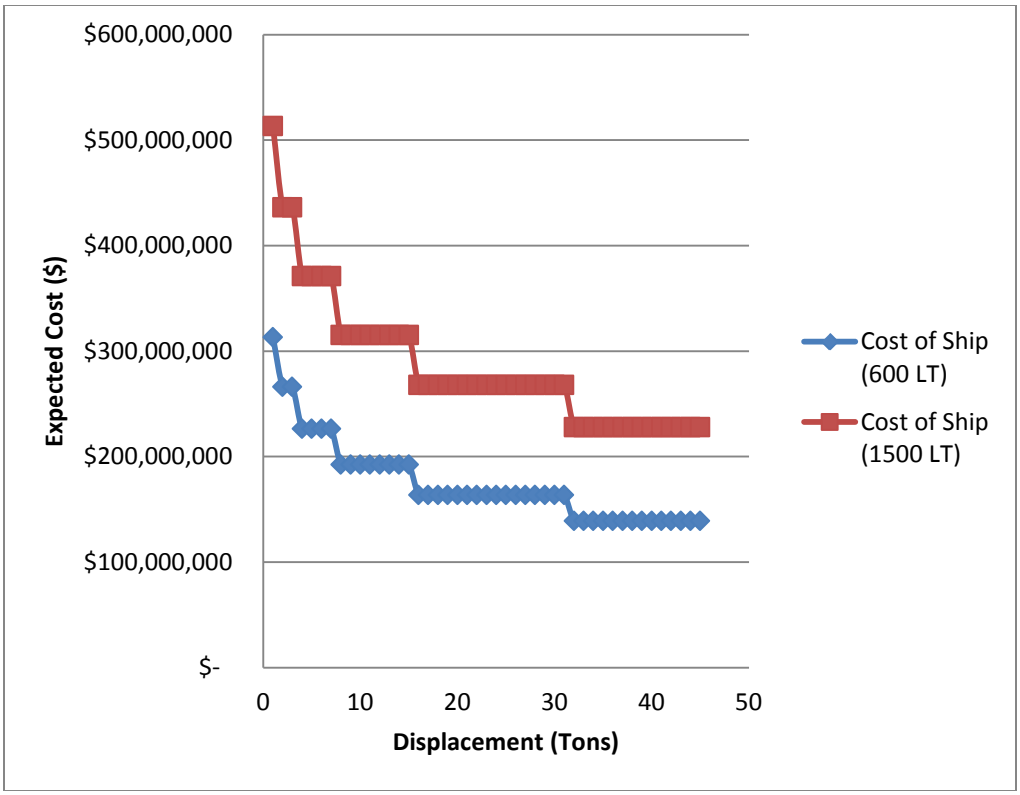

Figure 7. Expected learning curve for the construction of the SSC in FY2014$.

After using the custom built SE process model to guide the project, the research determined an effective solution that meets all of the major requirements of the tasking statement. As long as CONOPS, capabilities, sustainment and cost remain balanced with the detailed design effort requirements, a single mission SSC can be a viable platform for the navy to grow its force structure in the future and increase its offensive capability at sea.

ACKNOWLEDGMENTS

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- CAPT James Eagle, USN (ret.),
- COL Jeffrey Appleget, USA (ret.),
- Professor Daniel Nussbaum,
- Professor Fotis Papoulias,
- Mr. Imre Balogh,
- And Professor Gregory Mislick, USMC (retired).

In addition, close coordination with the Cohort 20, Team B, mutually benefited both teams and aided in shaping the solution space for both teams.

Finally, we would like to recognize the contribution of our advisor, Professor Gary Langford, in providing guidance assisting in project completion.

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I. INTRODUCTION

A. PROJECT TEAM COMPOSITION

The Systems Engineering Analysis Cohort 20, Team Alpha (SEA-20A) capstone project team is comprised of military officers and defense industry professionals from the United States and Singapore. Six of the 15 members are students in the Naval Postgraduate School (NPS) SEA curriculum, seven are Singaporean students in the Temasek Defense Systems Institute (TDSI) program, and the remaining two are U.S. students that have the honor of completing Master's degrees from both NPS and through TDSI. The six core members from the SEA curriculum began the initial background study the summer of 2013, while the TDSI students joined the team in September 2013. A list of the team members along with their respective expertise and backgrounds is provided in Table 1.

Dr. Gary O. Langford (Project Advisor) Senior Lecturer, Systems Engineering Department	**Buss, John (Project Manager)** Surface Warfare (USN)
Foo, Ceying Armour Officer (SAF)	**Ng, Yeow Chong** Satellites (ST)
Goff, John Surface Warfare (USN)	**Tan, Min Yan** Satellites (ST)
Jurgensen, Sean Surface Warfare (USN)	**Teo, Hui Fen** Ship Construction (ST)
Ling, Yu Xian Information Assurance (DSTA)	**Thompson, Chrisman** Surface Warfare (USN)
Magbanua, Rico Aviation (USN)	**Toh, Wei Quan** Armour Officer (SAF)
Moss, Andrew Surface Warfare (USN)	**Wall, Damien** Submarine Warfare (USN)
Moyer, Kyle Surface Warfare (USN)	**Wee, Toon Joo** Information Exploitation (DSO)

Table 1. SEA-20A project team personnel composition.

The team member's experience and perspectives from both the operational and academic arena are vast and varied. The Singaporeans offer skills cultivated from both their military and defense industry experience, while the U.S. naval officers bring a wide range of knowledge from the aviation, surface, and subsurface communities. Both the Singaporean and U.S. students have previous and current academic experience in a variety of engineering disciplines, and some of the U.S. officers have completed the tactical, operational, and strategic training of Joint Professional Military Education. The collaboration of the team's diverse personnel, coupled with insights provided by subject matter experts (SME) from the fleet and NPS, allowed the team to conduct a study that will help guide decision makers in developing the future naval force structure in a domain that requires distribution, innovation, efficiency, and technological superiority.

B. TASKING STATEMENT

1. Initial Tasking Statement

The following tasking statement was delivered to the team in September 2013. It was broad and encompassed the general guidelines our sponsor desired as an end state of the project.

> Design a fleet system of systems and concept of operations for cost effective small surface combatants in a range of missions to augment naval operations or conduct specified tasking in the 2025–2030 timeframe and beyond. Consider requirements for these ships to execute naval missions across the kill chain spectrum. Consider new ship requirements, flotilla size, operating areas, bandwidth and connectivity, logistics, and basing support in forward areas or from CONUS bases. Generate requirements for unmanned and manned aircraft to be used by these ships, ensuring each strike platform can execute its own kill chain regardless of the EM environment. Specifically, analyze alternatives to employ unmanned air systems from these ships to support their missions, including consideration of a common type aerial platform with a configurable payload package. Consider the current LCS fleet structure and funded programs as the baseline system of systems and for developing concepts of operations. Then develop alternative architectures for platforms, manning, command and control, intelligence collection/dissemination and consumption, communication and network connectivity, and operational procedures. Address the costs and effectiveness your alternatives (Eagle 2013).

The team took the initial tasking statement and broke it down into specific requirements including scope, mission, vision, goal and objectives as discussed in Chapter I Sections C and D. From this perspective of focusing on the holistic view of process and end-state, we developed a refined tasking statement for this project's sponsor and stakeholders.

2. Tasking Statement Development

The initial tasking statement was the starting point for the project development work. For a system's approach to identifying and solving problems, evolution of the provided tasking statement is required to open up solution space concurrently as the team was forming the necessary background knowledge required to start developing possible solutions. The initial tasking requires the small surface combatant to use unmanned air systems to support the mission set by enhancing command and control (C2) capability and over-the-horizon (OTH) targeting and sensor suites. This requirement excludes current capable manned aircraft and alternative manned/unmanned subsurface, surface or air vehicles. As a self-imposed constraint, applicable systems must be technology readiness level (TRL) 8 or higher. In not considering systems below a TRL 8, the system has the potential to be fielding in a short timeframe, while minimizing cost associated with research and development.

3. Evolved Tasking Statement

The team developed a new tasking statement providing a holistic view of the problem. In order to arrive at the new statement, the team utilized steps of problem analysis though a system's engineering perspective, which generates feedback through progress reviews, stakeholder meetings, and lessons learned. The following is the revised tasking statement approved by the project advisors and briefed during the first and second initial progress reviews:

> Design a fleet system of systems and concept of operations for cost effective small surface combatants in a range of missions to augment naval operations or conduct specified tasking in the 2025–2030 timeframe and beyond. Consider requirements for these ships to execute naval missions across the kill chain spectrum. Consider new ship requirements,

> flotilla size, operating areas, bandwidth and connectivity, logistics, and basing support in forward areas or from CONUS bases. Generate requirements for unmanned and manned platforms to be used by flotilla ships and ensure each strike platform can execute its own kill chain regardless of the EM environment. Specifically, analyze alternatives to employ unmanned/manned systems from flotilla ships to support their missions, including consideration of a common type aerial platform with a configurable payload package. Consider the current LCS fleet structure and funded programs as the baseline system of systems and for developing concepts of operations. Ensure all systems identified within the solution set can be fielded in the given timeframe. Next, develop alternative architectures for platforms, manning, command and control, intelligence collection/dissemination and consumption, communication and network connectivity, and operational procedures. Address the costs and effectiveness your alternatives.

C. SCOPE

Operational planning involves all phases from shaping the problem to supporting civil authority's security issues. A detailed discussion of operational phases is provided in Chapter III Section C.2. This study focuses on Phase II (combat: seize initiative) operations. The broad range of possible operations a SSC could be capable of conducting requires boundary conditions (i.e., no anti-submarine warfare (ASW) or anti-air warfare (AAW) capabilities) to be set in order to move forward with the analysis of the problem. For these reasons, the other operational phases and their associated mission sets were not considered. Other phases will be referred to in the discussion, but they were not developed with detailed modeling results, and therefore should be considered in the context for future development and supplementary to Phase II operations discussed in this report.

D. MISSION, VISION, GOALS, AND OBJECTIVES

Mission

The following is the team's mission statement: Utilize the diverse knowledge, research ability, and analytical capabilities of the SEA project team to evolve a resilient, forward-deployed, small surface combatant concept to serve as a credible deterrent to potential attacks in the 2025–2030 timeframe.

Vision

Reduce risk and cost while increasing effectiveness through technology and asset distribution.

Goals

- Explore varying force compositions and characteristics (such as weapon and sensor range and salvo size) using combat simulation models
- Identify SSC key performance parameters
- Develop a concept of operations for the distributed surface force

Objectives

- Recommend a specific capability set and platform requirements for further development during the Total Ship Systems Engineering Course being offered during the fall of 2014 at the Naval Postgraduate School.
- Deliver a detailed life cycle cost estimate (LCCE) for the selected alternative. Include in the cost report alternative modifications to existing designs and the associated cost with modifying current platforms. Compare the small surface combatant cost with a new frigate acquisition cost.
- Recommend a Concept of Operations (CONOPS) that describes how to employ the SSCs to aid in multi-threat scenario operations. Include a description in the CONOPS of how the SSC can be logistically supported in a high threat environment.

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II. BACKGROUND

To develop a complete understanding of the maritime status, both worldwide and within the United States, substantial background research is required to put the problem in context. If a solution set is developed that does not integrate well with the Navy's five and 30-year shipbuilding plans (O'Rourke 2014b), does not take into account the White House Guidance on 21st century global leadership (Obama and Panetta 2012) and the United States Combatant Commander posture statements to Congress for 2014 (Locklear 2014; Jacoby 2014; Kelly 2014; Austin 2014) in the context of the Unified Command Plan and Combatant Commands overview by the Congressional Research Service (Feickert 2013), the solution will not be considered relevant or sufficient. Additionally, potential adversaries are not static. Their capabilities and limitations must be projected to the 2025–2030 timeframe, with the additional knowledge of both physical and human geography that is currently happening and projected to continue.

A design of a system or a system of systems for a specific scenario or outcome is undesirable. Rather, this study seeks to develop a system of systems that can be employed in different scenarios. An effort was made to collect as much of the current and projected information as possible from open-source reference material about the U.S. Navy status. The following background information on weapons, situation, and location provide context into where the findings in this report were drawn from.

A. CURRENT PROJECTIONS OF 2025–2030 FORCE COMPOSITION

The Navy's goal as of January 2013 is to maintain a fleet of 306 ships, which was a reduction from the previous total of 313 (Department of the Navy N8 Department 2013). This 306-ship plan includes 12 SSBNs, 48 SSNs, 11 aircraft carriers, 88 cruisers and destroyers, 52 Littoral Combat Ships (LCS), 33 amphibious ships, 29 logistics and resupply ships, and Joint High Speed Vessels (JHSVs), and 23 other ships including command and support vessels (O'Rourke 2014b). Additionally, the number of LCS ships that are to be built has become a contentious subject, with indications that they may be cut in total production to 32 (Cavas 2014). Regardless of the outcome of LCS, the U.S.

Navy is projecting itself to operate with primarily multi-mission and high-cost ships in the 2025–2030 timeframe. The LCS will undoubtedly provide assistance in mine warfare, anti-submarine warfare, and surface warfare (LaGrone 2013). Although highly capable and technologically superior ships are a large part of maintaining sea dominance, the U.S. Navy needs to consider ship designs and a concept that distributes sensors and weapon reach into areas that are not accessible or are too risky to utilize the high-end force.

B. CURRENT SURFACE TO SURFACE MISSILE TECHNOLOGY

Since the end of the Cold War, the world has undergone a dramatic shift in military missions and priorities. The United States finds itself in a situation with an outdated surface-to-surface or anti-ship cruise missile (ASCM) engagement capability against a possible competitor. For example, as China continues its economic and military expansion this ASCM deficiency has moved to the forefront of military decision makers concerns as they evaluate the current and future threats. The primary issue is that "The Navy has not prioritized defeating enemy warships at sea since the collapse of the Soviet Union." (Majumdar 2014). The lack of emphasis on surface-to-surface engagements means both weapon potency and current fleet experience in deploying these weapons is called into question.

The U.S. would be limited to the dated Harpoon anti-ship missile if this engagement were to happen today. Originally developed in the 1970s, "the Harpoon missile provides the Navy and the Air Force with a common missile for air, ship, and submarine launches" (Federation of American Scientists 2014a). Although state of the art when originally deployed, the last modification to the Harpoon design occurred in 1982 with the Block 1C (Federation of American Scientists 2014a). Since the cold war, many nations have had the time to develop superior anti-ship weapons. The result has been a lessening of the comparative advantage in power projection than the U.S. has enjoyed historically. The Harpoon is an outmoded missile with an insufficient range and inadequate survivability for today's open-ocean and littoral battle spaces. The United States must consider new technology to bridge the gap between its Navy and those of its competitors. The Navy's deficiency in the ability to address these opponents could create

a significant threat to American security. At a minimum, lack of an effective ASCM restricts high-end multi-mission ships' employment to environments where the U.S. enjoys air superiority, as the U.S. possesses no weapon system that holds an adversary's surface combatants at risk.

The United States requires a deployable surface-to-surface missile to engage the enemy in a littoral combat scenario. Merely modifying or improving the Harpoon is not a viable option, even in the short term. Experts agree the Harpoon missile "does not have the range or survivability to defeat emerging surface threats" (Majumdar 2014). Additionally, the U.S. Navy has strongly reduced the number of Harpoon missiles deployed each year; the Navy's ability to effectively implement Harpoon in battle is diminished as compared to the 1980s fleet.

To address this surface missile deficiency the U.S. Navy gave authorization to begin increment two of the Offensive Anti-Surface Warfare (OASuW) program, which is a continuation of the Defense Advanced Projects Research Agency's (DARPA) Long Range Anti-Ship Missile (LRASM) (Majumdar 2014). An illustration of LRASM is shown in Figure 1.

Figure 1. LRASM anti-ship missile (from Lockheed Martin 2014).

It is important to note that LRASM is not a long-term solution. The missile "is merely a stopgap for the Navy until it can develop a more comprehensive solution in the form of OASuW Increment Two—which will be used by aircraft, surface warships, and possibly submarines." (Majumdar 2014). The "stopgap" concept makes sense from a cost effectiveness standpoint and is in-line with classic U.S. missile technology acquisitions. Lockheed estimates the cost of LRASM at about $2 Million (Aviation Week 2013) each, and for that price the Navy gets an anti-ship missile that offers a long-range (500 nm) (Defense Industry Daily 2014a) precision strike capability that can be fired out of the existing VLS system currently on Aegis cruiser or destroyer (CRUDES) ships.

LRASM is not the only viable missile technology available. Kongsberg's naval strike missile (NSM) is another potential option. The NSM is a lightweight (1000 pounds) and long range (130 nm) weapon (Defense Industry Daily 2014b). Stealth is the key feature of the NSM and was a major consideration throughout its design. To ensure difficulty for early warning radar systems and electronic support measures (ESM), the missile was designed to not include onboard radar. Additionally, the missile utilizes imaging infrared (IIR) and travels at a speed under supersonic (Defense Industry Daily 2014b). A potential barrier to the U.S. Navy purchasing NSM is that it is a new and unproven system and currently made by an overseas supplier (Norway).

In addition to NSM, Kongsberg also makes the helicopter launched Penguin anti-ship missile that is designed to operate in both littoral and open-ocean environments. The Penguin may also be useful in further missile technology studies especially since it is capable of littoral missions (Kongsberg Defence Systems 2013). A picture of the Penguin anti-ship missile is provided in Figure 2.

Figure 2. The Penguin anti-ship missile fired from a helicopter (from Penguin Place Post 8).

Other possible solutions include Mantra BAE Dynamics Alenia's (MBDA) Storm Shadow/Scalp and the Taurus kinetic energy penetrator destructor (KEPD) 350. Like the Penguin, these missiles are currently only air launched, but the Storm Shadow/Scalp missile offers long-range accuracy. The Storm Shadow/Scalp utilizes mid-course guidance through global positioning system (GPS) and an autonomous terminal guidance with an (IIR) seeker (Matra British Aerospace Dynamics Aerospatiale (MBDA) Missile Systems 2013). Images of the Storm Shadow and the Taurus KEPD are displayed in Figure 3 and Figure 4, respectively.

Figure 3. Picture of the Storm Shadow missile (from Deagel 2005).

Figure 4. Picture of the Taurus KEPD 350 MR (from Saab Group 2010).

The KEPD offers high precision in a long-range (300 km), lightweight (1400kg) (Saab Group 2010), all-weather weapon, which can conduct precision strikes on a variety of targets.

This list is not all-inclusive; there are a myriad of possibilities, especially in the long term since increment 2 is merely a stopgap. Given the high level of performance (either during operation or testing), any of these alternatives would meet or exceed the surface-to-surface missile need. This report does not provide a specific solution; rather the purpose is to demonstrate the solution space in order to give the end decision maker enough information to determine the best solution.

C. EXISTING SMALL SURFACE COMBATANTS

Before recommending a specific platform and its associated capabilities as a solution, a broad study of existing small surface combatants (SSC) currently in use or planning to be built in the near future is warranted. The inventory of existing small surface combatants was constrained to those having less than or equal the displacement of either LCS variant.

This section provides an inventory of current or near-future SSC, the associated capabilities and unique characteristics of similar ships built in the United States, and designs that could be available from the international market. The small SSC can be easily broken into two groups; multi-role and single-mission. A quick comparison chart of the characteristics of these small combatants is provided for reference in Table 2.

	Vessels	Speed (kts.)	Length (m)	Displacement (tons)
Multi-role	LCS-1 Freedom Class	45	116	3,089
	LCS-2 Independence Class	45	127	2,790
	Meko CSL	40	108	2,750
	VISBY Corvette class	40	73	640
	Gowind Combat corvette	28	107	2730
Single Mission	Ambassador Class	41	61	500
	Skjold SES	45	47	275

Table 2. Existing small surface combatant comparisons (after Saunders 2013).

The two variants of LCS are displayed in Figure 5. Both ship classes are multi-role (surface, anti-submarine, mine counter-measure, and irregular warfare) capable small surface combatants. As described in the tasking statement, the study analyzed a comparison of the two variants of the LCS.

Figure 5. The Freedom class LCS (left) and Independence class LCS (right) (from Defense Tech 2010).

Both LCS ships are comparatively armed and are capable of being equipped with modular mission modules, but the ship designs are very different. The Freedom class has a steel mono-hull and aluminum superstructure whereas the Independence class has an all-aluminum trimaran design. Both platforms are designed to perform the same mission

capability with the "plug and play" modular concept. This concept allows the LCS to adapt to the changing threat scenarios against mine counter-measure (MCM), anti-submarine warfare (ASW) and anti-surface warfare (ASW) with a focus on capabilities suited for the littoral region. However, since the completion of the LCS variant, the design has been greatly scrutinized for its mission fit, design requirements and the cost overruns of the acquisition program. The criticism is primarily based the modular concept feasibility, and problems associated quick turnaround time, lean manning, survivability and lethality of the LCS.

Three alternate multi-role SSC platforms are the MEhrzweck-KOmbination (MEKO) Combat Ship for the Littorals (CSL), Visby Class and Gowind combat corvette, which are illustrated in Figure 6.

Figure 6. Images of the MEKO (left), Gowind (middle), and Visby (right) ship classes.[1]

These ships are designed and built in foreign shipyards. Of the three alternatives, the Meko CSL is still in the design phase while the other two vessels are already commissioned. The Meko CSL specifications are very similar to those of the USN LCS. The uniqueness of the Meko design is its proven modularity with an interchangeable "plug-and-play" concept (Thomas 2007). The Meko Modular concept is shown in Figure 7.

[1] (From Pakistan Defense 2010; Defense Industry Daily 2014c; Wallpapers 2013).

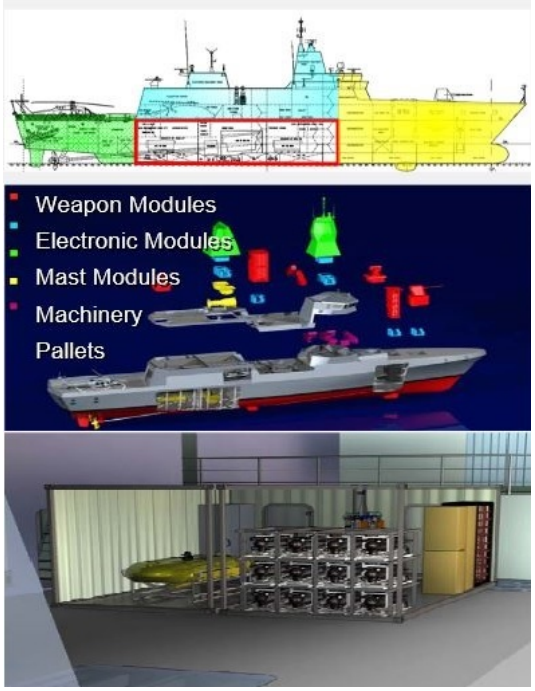

Figure 7. Pictorial description of the modular concept by Meko (from Hauschildt and Sichermann 2012).

The Visby class and Gowind combat corvette designs minimize radar cross - section, and include ASUW missiles and point defense system. Both travel at high speeds greater than 30 knots. Plans exist for the Visby class to be upgraded and to incorporate an AAW system later in its life cycle (Naval Technology 2014a). Additionally, the Visby is equipped with a sonar system capable of detecting submarines in shallow water and is constructed of an all-composite design to reduce weight (Naval Technology 2014d).

This study looked into the Norwegian Skjold surface effect ship (SES) corvette and the U.S. designed and built Ambassador MK III class missile boat. The Skjold class SES can travel up to 45 knots in rough seas and up to 60 knots in a calm sea state (Naval Technology 2014c). The low drag, freeboard design, and special radar absorbent material coating prevents SES from being easily detected. The Skjold Class SES is equipped with SSM and SAM missile and soft kill systems (Naval Technology 2014c).

The Ambassador MK III has a unique surface effect hull design. The ship design incorporates a “V” shape wave-piercing monohull and enables a 41 knots speed in calm

seas. The vessel is armed with ASUW missiles and point defense anti-air warfare (AAW) systems shown in (Naval Technology 2014a).

Figure 8. Images of the Ambassador class SSC (left) and the Skjold SES (right) (from Naval Technology 2014a).

Much like the discussion on current missile technology, the existing SSC list is also not all-inclusive. The final decision is based on several key constraints and factors which include cost, performance, timeline and even political aspects. Foreign overseas companies construct many of the ships discussed above, which creates a series of challenges in itself including the crew's equipment familiarity, the ability for the manufacturer to meet the high standards of a U.S. warship and contracting requirements for the Department of Defense (DOD). Still further considerations involve the inevitable integration of the final ship design with the proper missile system. This report does not provide a specific solution; rather the purpose is to illustrate the solution space to give the end decision makers adequate information to make well-informed decisions.

D. UNMANNED TECHNOLOGY

In developing the SSC, we looked to leverage unmanned technology as a sensor platform extension, overhead data relay in a multi-threat domain, or kinetic weapons. A SSC may reduce manpower and increase platform time on station by utilizing an unmanned platform for these simple functions. These unmanned vehicles can be launched from the distributed surface force or an external source.

Employment of air, surface, and underwater systems supplements the distributed surface concept by reducing the vulnerability of a surface unit in providing a layered-defense technique of detecting and classifying targets before entering weapons range. Additionally, unmanned systems add to the distribution, and can go into threat zones (i.e., DF-21 range) with less risk of an adversary using a high tech weapon on low-tech unmanned systems.

As a sensor extension platform, unmanned technology can dramatically increase situational awareness of the distributed surface force while improving targeting accuracy. Extending sensor range allows a ship to take advantage of its full weapon range and enhance chance of a successful first strike. An example of an unmanned sensor extension platform is the MQ-8B Firescout, shown in Figure 9.

Figure 9. Picture of the MQ-8B Firescout (from Northrup Grumman 2014).

An unmanned vehicle may function as a satellite replacement in an electro-magnetic (EM) denied spectrum. Unmanned technology could serve as an acceptable communications relay platform if a potential adversary denied satellite communication to the distributed surface force. One example of a communication relay platform is an Aerostat. The Navy is currently experimenting with this technology on ships. The Aerostat concept is shown in Figure 10.

Figure 10. Aerostat operating from USNS SWIFT (HSV 2) (from Wasserbly 2013).

Unmanned systems will benefit the SSC concept as they may provide a low-risk and cost extension of sensors and possible weapon range that supports the distributed surface force idea.

E. DISTRIBUTED SURFACE FORCE / ARMADA CONCEPT

The distributed surface concept relies on the dispersion of offensive combat power and sensors throughout units in a group to create a resilient and survivable offensive system. Each unit may be less capable as an independent unit, but be extremely effective when integrated with the distributed surface force due to dispersed offensive and sensor capability. The team markets the distributed surface concept as the armada, or a combination of SSC ships and other U.S. Navy assets, to further reinforce the notion that the force's strength remains with the group rather than the individual ship.

Each ship should be primarily designed to fight one mission to reduce cost (although the individual armada ships may have different missions) and should operate in a multi-threat environment by a systems-of-systems networked defense. By making each ship cost effective, more ships can be fielded in a shorter amount of time if needed. The

distribution over multiple platforms makes the armada more survivable and decreases the significance of losing an asset. System of systems network defense can be found in more detail in Chapter IV Section D.1, but in short means protecting armada ships from air and undersea threats with other platforms, asset distribution, and layered defense which eliminates single points of failure. This single mission strategy will allow the U.S. to acquire more ships at a lower cost and deliver a more resilient ASUW capability in the 2025–2030 timeframe.

F. ANTI-ACCESS AERIAL DENIAL WEAPON SYSTEMS

Potential adversaries are developing advanced weapons systems that may be capable of denying the United States access to maritime areas in the future. These weapon systems, which affect the U.S. Navy's ability to project power, are grouped under the term anti-area access denial (A2AD) (Krepinevich, Work and Watts 2003). The systems include diesel submarines, anti-ship cruise missiles (ASCMs), sea mines, anti-ship ballistic missiles (ASBMs) and fast attack craft. One example is the Chinese DF-21 ASBM, which is capable of targeting an U.S. aircraft carrier (United States Naval Institute 2009). Another example is the proliferation of affordable air independent propulsion (AIP) diesel submarines throughout the world. These AIP diesel submarines are capable of operating submerged in shallow water areas and are difficult to find.

A2AD systems have the ability to hold the U.S. Navy at risk by exposing vessels to a high likelihood of damage in a surface conflict. Most of these weapons are less expensive than the potential U.S. Navy targets. The distributed surface force aims to reverse that trend by focusing on cost-effective SSCs, which can access A2AD areas with less risk and increase the difficulty for an adversary to locate, target, and conduct offensive operations toward friendly forces.

G. LITTORAL/COASTAL OPERATIONS

The maritime battle space has expanded from deep-water Mahanian battles to parts of the maritime domain where maneuverability could be limited due to geographic features or water depth. In the littoral or coastal domain, a series of a small force-on-force battles could be the dominant engagement type.

According to the U.S. Navy, littoral "as it applies to naval operations… is not restricted to the limited oceanographic definition encompassing the world's coastal regions. Rather, it includes that portion of the world's land masses adjacent to the oceans with direct control of and vulnerable to the striking power of sea-based forces" (United States Navy 1994).

A generic example of the cross-section of a littoral zone is depicted in Figure 11. This illustration highlights the difficulties that deeper draft high-value units have navigating littoral areas, which severely limits their access capability. However, there is no clear line or definition where littoral starts or stops around the world. Water draft, tides, shipwrecks, territorial waters, archipelagic lanes, straits, economic exclusion zones (EEZ), and internal waters make up an elaborate series of criteria defining where ships can operate both physically and by international law. That being said, the SSC needs the capability to push as far into all of these areas when needed.

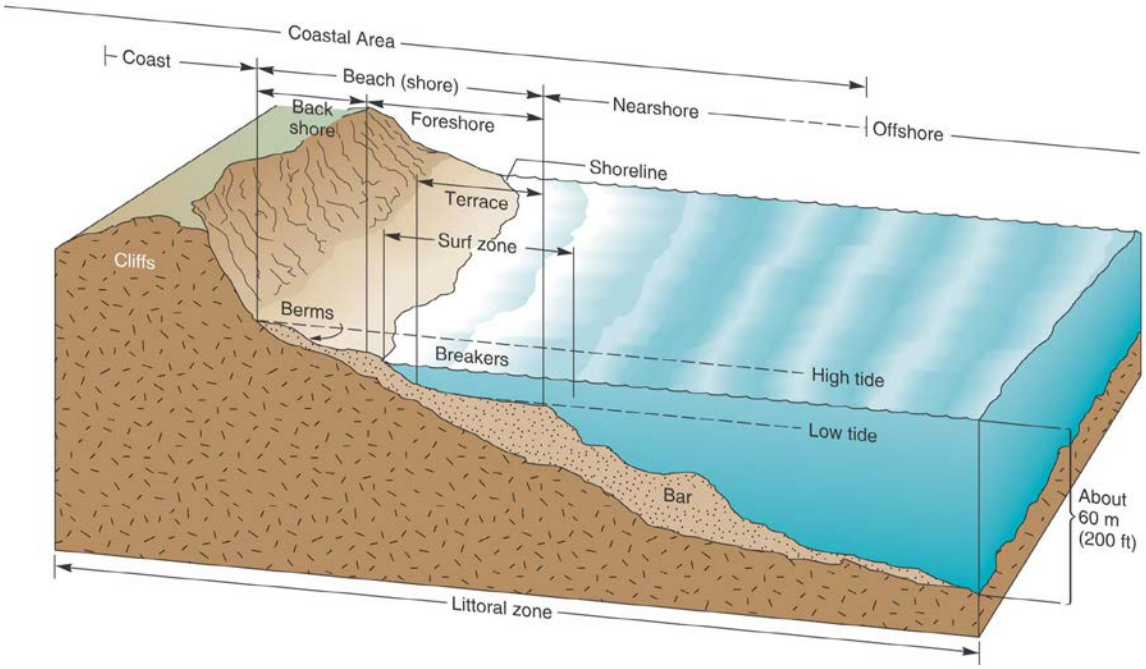

Figure 11. Littoral zone example (from Allen 2012).

III. APPLICATION OF THE SYSTEMS ENGINEERING PROCESS

The systems engineering process was used to analyze the problem posed in the tasking statement. This project's scope did not align with traditional systems engineering process models, so we developed a tailored process model. The modified model is based on the 'Waterfall' process model. The overall design resembles a 'Waterfall' process model; however there is an iterative loop for each phase rather than a return path to the beginning. Additionally, the steps do not correlate to the traditional models.

A. SYSTEMS ENGINEERING PROCESS

The systems engineering process began with an attempt to fit this project in the traditional systems engineering model. The initial process model is shown in Figure 12.

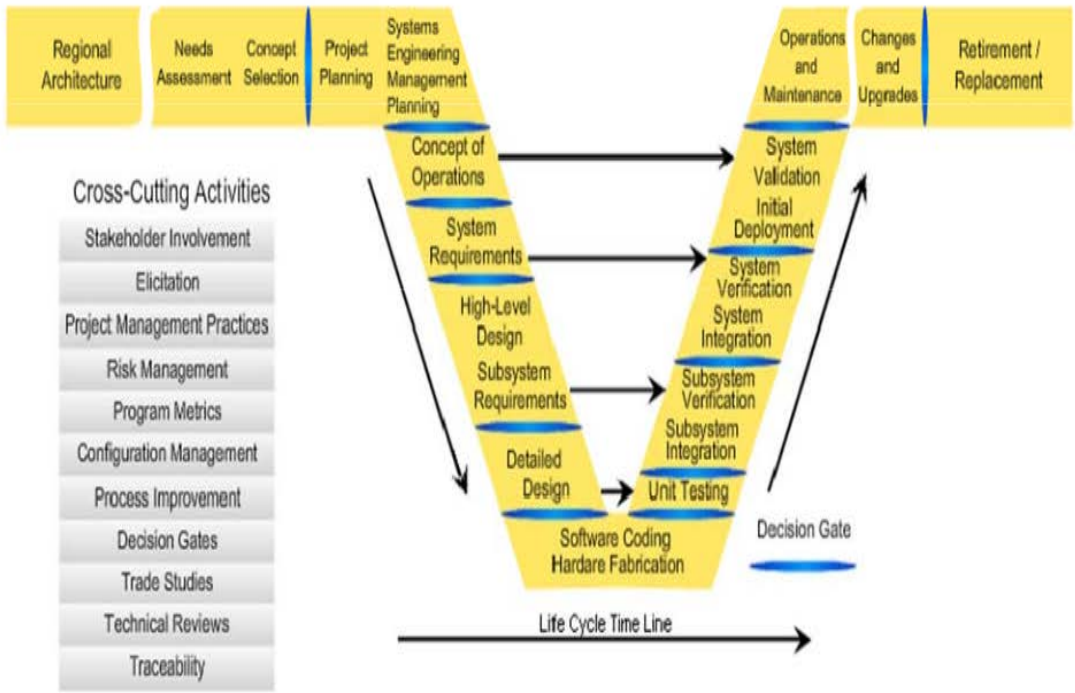

Figure 12. Sample systems engineering "V" process model (from Langford 2009).

The ultimate goal of the project is to develop a set of requirements and capabilities for the proposed system. The existing traditional model's application did not fit the scope due to this work having no requirement for detailed design. As described in the next section, a tailored SE process model was developed which focuses on the first half of the 'V' model and provides specifics to milestones to be achieved prior to entering each phase.

B. SEA-20A SYSTEMS ENGINEERING PROCESS MODEL

A SE process model was developed, incorporating clear phases with iterative loops shown in Figure 13. This process model contains a logical progression that leads to a system recommendation at the end of the SE Process. The process begins with the initial tasking statement that was presented to the team. This tasking statement enters the main component of the process. This component consists of three main phases (Problem Exploration, System Definition, and Modeling & Analysis). Each of these three phases has three sub-phases connected by a rotational cycle. The output of one phase becomes the input to the next phase; however, an iterative loop back to the previous phase is also available as shown with the feedback arrow. This feedback allows continuous refinement the original problem, if needed. The dotted lines around the phases denote open information flow into each phase. The process model is not a closed-loop process, so discoveries at any phase can lead to refinements of any other phase.

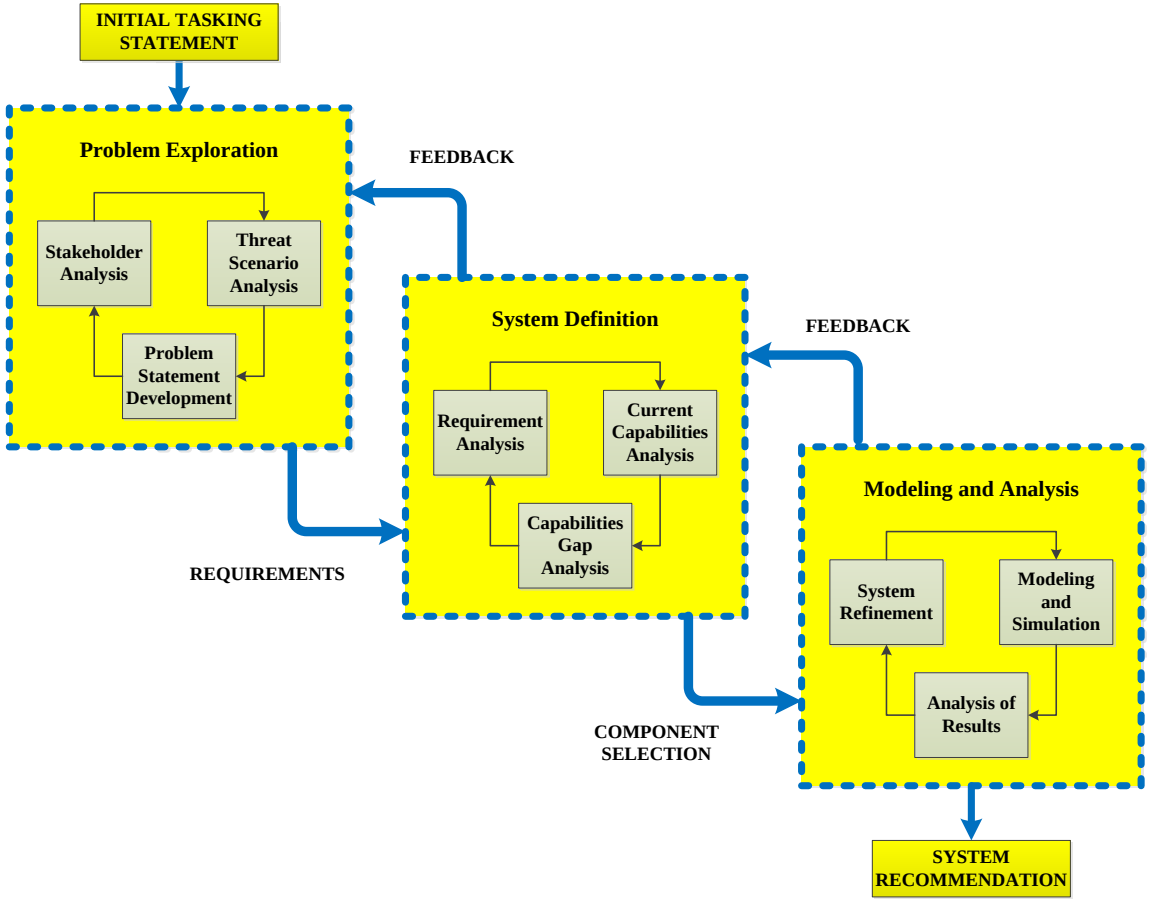

Figure 13. SEA-20A revised systems engineering process diagram.

1. Problem Exploration Phase

The first step of the SEA-20A systems engineering process model was to analyze the initial tasking statement during the *problem exploration phase*. While exploring the problem given in the initial tasking statement and conducting applicable background research, the team looked at potential stakeholders and the influence each stakeholder might have on forming the initial problem statement. After identifying various stakeholders, the team performed a needs analysis. Threat scenario analysis was conducted to scope the problem, and three scenarios were created that were representative of potential threats. After investigating the background information on the problem, looking at particular problems presented by various threats, and exploring stakeholder groups, the initial problem statement was formed. As the understanding of the problem grew, each of the tasks within the problem exploration was revisited and traceability ensured back to the initial requirements. Major discoveries in the problem exploration phase include littoral operating environment challenges, operation in an A2AD environment, and specific needs analysis for potential stakeholders. The trade space analysis, which provides problem exploration phase background and system definition phase justification, is contained in Supplemental D.

2. System Definition Phase

After forming the initial requirements, the s*ystem definition* phase of the SE process model was undertaken. During this phase, the team studied the causal relationship between stated requirements and capabilities of the small combatant ship. A rotational research cycle was conducted between capabilities and requirements to ensure the system definition was correctly understood and communicated through component selection. The rotational research cycle consisted of an iterative process in which system requirements were compared to current capabilities to identify capability gaps used to refine system requirements. This analysis refined the requirement for an effective surface-to-surface weapon and for a defensive network incorporating existing surface and air platforms to perform the sea denial mission. Boundaries discovered during this analysis included the engagement range, tonnage of each ship, draft, capability of

operating in an A2AD environment, and capability of operating with various types of units and assets. Some boundary conditions discovered during this analysis include relationships between cost and capability, size and seaworthiness, autonomy and interoperability.

The project was scoped to develop high-level system of systems design specifically capable of operating in an A2AD environment and a CONOPS for its employment. Results that are required from the modeling and analysis phase are system recommendations based on analysis of the engagements in the model. At this point in the SE process, the initial set of capabilities that helped develop the modeling and analysis phase of the project were defined.

3. Modeling and Analysis Phase

The *modeling and analysis* phase of the SE process is dependent on the component selection derived in the s*ystem definition* phase. Evaluation of component selection was modeled and tests conducted to determine if the system of systems is effective based on the requirements defined in Chapter III Section C.5. After analyzing the results, system refinement was accomplished using iterative feedback paths to previous SE phases. In doing so, the refinement allowed tasks to be revisited and thus provide further insight and a better understanding of the problem. For example early discoveries in the modeling phase led to the requirement for a "system of systems" approach to defending the distributed surface force to survive in a multi-threat environment. Additionally, the need for an air defense platform was established and included in an iteration of the model. Finally, after iterations of the SE phases and sub-phase tasks, a system recommendation was determined as an output presented in Chapter VII. Major discoveries in this SE phase included the creation of a robust logistical network to meet fuel demand requirements to support missions that lasted more than 10 days and the need for off-ship sensor platforms to extend targeting range of surface combatants.

C. NEEDS ANALYSIS

Needs analysis allows an open-minded and unbiased approach to solving the problem at hand. By studying the problem and not driving straight at an answer, the solution space is expanded as alternatives eliminated by stakeholders are included back into possible solutions. Needs analysis begins with the establishment of stakeholder wants or desires; from this the establishment of what capability or design is actually needed. Needs analysis is completed using stakeholder analysis, scenario analysis, problem definition, and identification of capabilities which all lead to the requirements generation.

1. Stakeholder Analysis

The development phase of the system engineering process enabled the team to derive potential stakeholders. The initial list of possible stakeholders is in Table 3. This list is not exhaustive, but rather a selection of organizations that could exert influence over the project or be influenced by the results.

Sponsor (OPNAV N91)	US Taxpayers	Potential Adversaries
Department of Defense	NPS Research (CRUSER)	Foreign Military Sales
Shipbuilders(contractors)	OPNAV N8/N9I/N95/N98	Commercial Shipping
NAVSEA	US State Department	United Nations
Lobby Groups	Naval Warfare Development Command	US Pacific Command
US Congress	US Fleet Forces	US Naval Personnel
Secretary of Defense	Global Economy	US Central Command

Table 3. Potential stakeholders for the distributed surface force concept.

The team used the list as a guide and determined the three most significant stakeholders in the project and further decomposed their needs to provide context into the problem presented in the tasking statement. The key stakeholders are those with the most influence in determining the next generation small surface combatant (SSC), whose needs capture the majority of needs of all stakeholders. The key stakeholders are described in Table 4. Primitive needs were developed based on views of the stakeholder and effective needs were the teams' translation of the perceived needs to actual needs.

Stakeholder	Primitive Need	Effective Need
Naval Sea Systems Command (NAVSEA)	Follow-on LCS design with more cost effective additional capability as compared to baseline LCS design	Field a next generation ASUW weapon which can be utilized by current platforms and be incorporated into a modified LCS or new ship design
US Pacific Command (PACOM)	Forward deployed forces that can project force while serving as a credible deterrence to conflict	Larger number of ships deployed to PACOM AOR with capabilities that allow the ships to operate in a A2AD environment
Office of the Chief of Naval Operations (OPNAV) N91	Develop a warship within the fiscal boundaries of the current budget that delivers capabilities that augment current force structure	Determine capabilities of the next surface combatant to meet the needs of 2025–2030

Table 4. Key stakeholder analysis.

Understanding stakeholders' perceived and effective needs can lead to a better understanding of the problem. By including this research in the SE process model, the needs of different stakeholders can be balanced with the perceived problem, which can lead to a better solution. Analysis of the stakeholders, and the needs presented by each revealed the key needs and contributed to problem definition. Ensuring specific needs are satisfied when making recommendations is also important, and those needs were considered by the SEA project team throughout the process.

2. Scenario Analysis

An analysis of the most likely scenarios the small combatant ship would encounter in the 2025–2030 timeframe was conducted. The exploration resulted in determining three scenarios in mission Phase II (seize initiative) in which the SSC would be operating. These scenarios contain different opposing force compositions that employ varying levels of sophistication in A2AD weapons. Since the South China Sea model had the most formidable opposition force, the force that produced the best results was in this model was used in the other models. These scenarios are discussed in more detail in Chapter V Section A.

The study concentrated on Phase II operations. Other phases of operations, which are listed below, were considered but deemed out of scope (Joint Chiefs of Staff 2011). Potential impact to each mission phase is explained below.

- Phase 0: Shape-provide positive influence by partner nation engagements, ensuring freedom of navigation, humanitarian assistance, disaster relief, and counter-piracy operations.
- Phase I: Deter-present credible surface threat forward deployed to potential conflict zones to decrease probability of armed conflict.
- Phase II: Seize Initiative-conduct dynamic offensive and defensive ASUW operations while halting enemy advance.
- Phase III: Dominate-contribute to joint force task force securing sea lanes of communication inside a theater of operation while denying the enemy use of the sea.
- Phase IV: Stabilize-protect economic exclusion zone, assist with humanitarian relief and provide maritime security in territorial waters.
- Phase V: Enable Civil Authority-support security concerns of civil governments.

Although the this study concentrates on Phase II, the team assumes the SSC will be employed throughout all phases and the role of SSC in other phases has been identified as an area of future exploration found in Chapter VII.

3. Problem Definition

The first attempt at shaping a problem statement came after studying stakeholders and the A2AD threat scenarios from the worldwide analysis. Three separate assumptions were evident and are explained below.

- Potential adversaries and their associated A2AD weapons have the potential to hold high-value units at risk.
- The projected 2025–2030 U.S. Navy Fleet does not have an effective counter to advanced A2AD weapons.
- The existing Harpoon missile does not have the range or survivability characteristics necessary to counter the growing A2AD threat and therefore the fleet cannot counter or deter the possible A2AD threat in the 2025–2030 timeframe.

High-value units (HVU) are susceptible to new and emerging weapons such as anti-ship ballistic missiles (ASBM), advanced diesel submarines, and advanced anti-ship cruise missiles (ASCMs). The loss of a HVU such as a CVN would be catastrophic, and therefore these vessels require expensive escorts. Employment of HVUs in an A2AD environment places those ships at risk of being lost from attack. The loss of just one high value unit will impact U.S. strategy and dramatically weaken the military force available for a conflict (United States Naval Institute 2009). If potential adversaries deny the United States the use of a CVN in a high risk A2AD environment, there is no current ship or weapon in the U.S. arsenal that can replace the sea control mission that a carrier strike group (CSG) is capable of. Directed energy weapons offer promise to blanket protection from adversarial ASBMs and ASCMs but current projections do not estimate laser weapons being effective against these fast moving threats until past the 2025–2030 timeframe (O'Rourke 2014a).

Advanced and emerging anti-access area denial (A2AD) weapons can push back existing U.S. fleet to beyond the effective operational range. The problem is at those long-transit distances the Navy will not be able to project a sufficient amount of force to be effective in shaping the battlespace, let alone in prevailing in an engagement. Having the ability to operate in the littorals, as described in Chapter IV, affords better flexibility of force employment in any of the threat scenarios the team analyzed. With a majority of

U.S. sea power concentrated into a CSG, dispersing that offensive sea power into a group of surface combatants would add resiliency to the U.S. forces in an A2AD environment.

4. Identification of Capability Gaps

The problem exploration phase revealed four major gaps in capability and technology: Logistics, offensive ASUW weapons, defensive networks in both air and undersea domains, and a resilient command and control network capable of functioning in the absence of overhead satellite coverage.

Previous coursework in an NPS class titled *Joint Campaign Analysis* uncovered a logistical dependency on large and minimally armed logistics ships to sustain a U.S. Navy fleet at sea. These large logistics ships, such as the Lewis and Clarke class (T-AKE) are extremely vulnerable to attack from multiple A2AD weapons and are ill-suited for a multi-threat hostile environment. Current logistics force structure lacks a method or platform for sustaining a naval fleet at sea without T-AKE size ships and the team has identified this critical weakness as a capability gap.

The team has judged the U.S. Navy lack of modern ASUW weapons to be a capability gap. The Harpoon missile has been outpaced by development of potential adversarial ASUW missiles such as the SS-N-27 SIZZLER (O'Rourke 2014a). Potential adversaries employ missiles with a longer range that are designed to defeat U.S. Navy defensive weapons.

With the growing program maturity of the LCS sea frame and associated mission packages, the team generated ideas on how to employ LCS in a multi-threat environment within the confines of current projected capabilities. The LCS must be equipped with the ASW mission package; otherwise the armada must include another asset with ASW capability. In addition, the LCS's point air defense system combined with electro-magnetic countermeasures does not create a robust layered defensive network and is not very well suited for an AOR with the characteristics of the 7th Fleet (Freedberg 2012). Considering the LCS as part of the system of systems solution requires a robust AAW and USW area defense capability, which the team judged to be an additional capability gap.

As referenced in Appendix A, the NPS class *Joint Command, Control, Communications, Computers and Intelligence (JC4I)* course determined a capability gap in operating in an electromagnetic spectrum-denied environment. As potential adversaries have demonstrated the capability to use anti-satellite weapons, the U.S. Navy needs to be prepared to operate without satellite GPS and communications. (The Washington Times 2007). As a result, traditional forces would lose their primary means of navigation, communication, and information sharing. Operating in an electromagnetic-denied environment is deemed to be a capability gap based on conclusions during the teams' research in the problem exploration phase and from the JC4I course conclusions.

5. Requirements Generation

The requirements generation SE development phase is derived from the problem exploration phase of the SEA-20A systems engineering process and further refined during the system definition and modeling and analysis phases. Six general requirements were discovered through analyzing the problem, and the modeling results.

a. Anti-Ship Cruise Missile Over the Horizon Advancement

Requirement statement 1.0: The system shall be capable of striking intermediate and long-range surface targets. This requirement is directly related to the ASUW capability gap, which needs to be addressed by next generation weapons. For the purpose of this work, the intermediate range is defined to be the distance to the horizon, relative to the firing platform, while long range includes distance over the horizon. The system referred to in this requirement is the ship.

b. Anti-Area Access Denial (A2AD) Resilience

Requirement statement 2.0: The system shall be capable of operating in an A2AD and electromagnetic spectrum-denied environment. This requirement ensures the ship possesses the requisite capability to operate in an electromagnetic spectrum-denied scenario, which addresses a key capability gap, combined with operations inside the A2AD threat environment.

c. Distribution of Assets, Sensors, and Weapons

Requirement statement 3.0: The offensive combat power shall be dispersed among the small surface combatant group and unmanned vehicles. A fundamental component of survivability is related to the ASUW capability creating a resilient fighting force with ability to sustain potential losses without major degradation to combat power. This requirement is derived from effective needs of stakeholders and provided tasking.

d. Forward-Deployable

Requirement Statement 4.0: The system shall be forward deployable with sufficient logistic capability to conduct offensive surface operations. The forward deployed element of the requirement is rooted in the effective need of PACOM with forces in the theater of conflict when needed. The logistics aspect of this requirement was derived during the problem exploration phase of the SE process when the team tried to apply traditional navy replenishment at-sea (RAS) platforms. This requirement addresses the A2AD logistics network capability gap.

e. Cost-Benefit Advantage in Operational Scenarios

Requirement Statement 5.0: The system shall be designed to ensure cost does not prohibit employment in a high-risk environment. This requirement is derived from two separate entities, one being the cost-effective aspect of the tasking statement and the other being the effective need of Pacific Command (PACOM) to operate in an A2AD environment. The core principle of the concept is distribution with no high-value assets, and the individual units shall be designed so the loss of any one has minimal impact in force effectiveness, loss of life, and monetary cost. This requirement illustrates the contrast between operating an armada and a CVN inside an A2AD environment.

f. System of Systems Approach

Requirement Statement 6.0: Each small surface combatant shall be interoperable and be employed as a system of systems. During the modeling and analysis phase, the team discovered a multi-threat environment requires a robust network of ASW sensors and AAW defensive platforms. In the distributed force concept, the addition and

subtraction of units, drones, and other assets shall be seamless to fit the mission set. This single mission concept is a translation away from the multi-mission concept of the Aegis ships or the modular concept of a single LCS. The flexibility of the system of systems is derived from the ability to structure the system for low cost and seamlessly integrated for the mission at hand with the ability to scale up or down by adjusting the composition of the armada to meet the threat presented.

D. FUNCTIONAL ANALYSIS

Functional analysis aids in increasing the understanding of a system by conducting a broad functional decomposition by which to understand the underlying activities occurring inside the system.

1. Decomposition

A functional decomposition seeks to draw out additional stakeholders or requirements by categorizing the functions a system will perform. This process is accomplished by identifying the components that make each function.

a. Top Level

The distributed surface force function is "to prevail in an A2AD environment." This will be accomplished by dispersing capability over a group of ships. A view is shown in Figure 14.

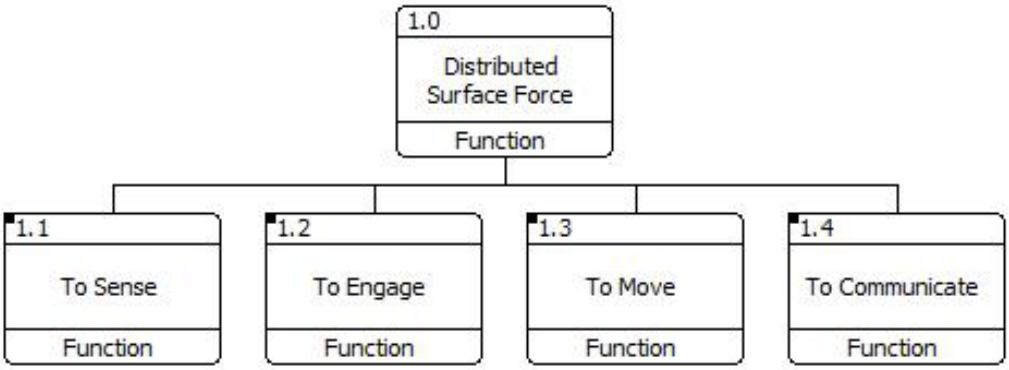

Figure 14. Top-level functional decomposition.

The top-level design is further broken down into the detailed design in the next section.

b. Detailed

(1) Function 1.1 is "to sense." This function defines the vessel's systems; utilizing both organic and off-vessel sensors, shall detect, locate, and track seaborne contacts. Information provided to system operators at a minimum shall include:

- For radar: course, speed, and bearing (both true and relative)
- For electronic warfare equipment: frequency, bearing, and signal strength

Under Function 1.1 we have three sub-functions: "to detect," "to classify," and "to track." Details for these sub-functions will be explained below and are shown in Figure 15.

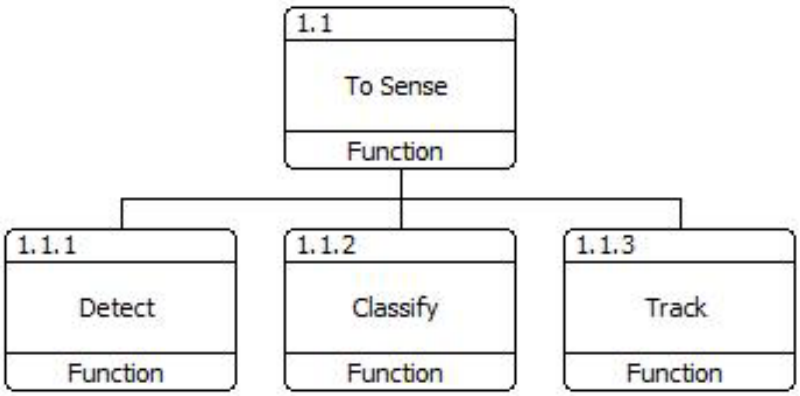

Figure 15. "To sense" sub-functional decomposition.

Function 1.1.1 is "to detect." This function defines that the system automatically receive inputs actively from own-ship and passively from off-ship radar, providing feedback to sensor operator.

Function 1.1.2 is "to classify." This function defines the radar system that provides raw radar data to the signal processing system and sensor operator to assist in classification. An electronic warfare system will assist the operator in classifying contacts through the use of database and pairing likely vessels through emitted frequencies.

Function 1.1.3 is “to track.” This function defines organic radar system’s Automatic Radar Plotting Aid (ARPA), which actively tracks the history of detected radar contacts and provides closest point of approach (CPA). Off-ship assets may provide contact position and, if capable, video images of contacts to aid operators in classification.

(2) Function 1.2 is “to engage.” This function defines the action in three sub-functions specific to a firing sequence. The system, after the target is acquired and classified as hostile, produces a fire-control solution. The fire-control solution is established from the radar system and operator inputs. The weapon system shall engage with missile or main gun to intercept the target of interest. Additional means to engage contacts will be through crew-served weapons such as machine guns, grenade launchers, and small arms. The operators using on and off-ship sensors will assess weapon effectiveness. A breakdown of function 1.2 is shown in Figure 16.

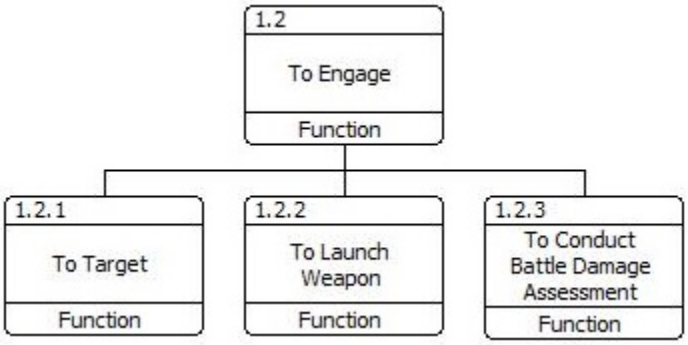

Figure 16. “To engage” sub-functional decomposition

Function 1.2.1 is “to target.” This function defines that the radar and off-ship sensors shall provide track data to the sensor operator in order to establish a fire control solution on the target of interest. Fire-control solutions will provide a fine bearing resolution on the target of interest. This information will be provided to the weapon prior to engagement.

Function 1.2.2 is “to launch weapon.” This function defines the act of the weapon leaving the ship and specifically pertains to missiles, and primarily surface-to-surface

missiles. The function may also apply to main gins, machine guns, and defensive missiles. After a fire-control solution is received from the radar system, the weapon will launch and fly towards the contact of interest. Target location is updated to the weapon for the longest duration possible.

Function 1.2.3 is “to conduct battle damage assessment (BDA).” This function defines the ability of sensors to accurately report lost contacts due to combat. BDA may pertain to on and off-ship sensors including electronics and the human eye.

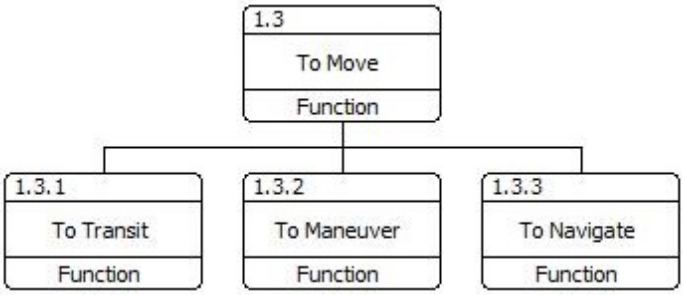

Figure 17. “To move” sub-functional decomposition.

Function 1.3 is “to move.” This function defines the ability of the vessel to travel under the control of the crew.

Function 1.3.1 is “to transit.” This function defines how the vessel operates from its initial starting point to a designated location.

Function 1.3.2 is “to maneuver.” This function defines the ability of the vessel to avoid static and moving obstacles such as ships, islands, and navigational aids. The maneuvering will be done through operator interaction.

Function 1.3.3 is “to navigate.” This function defines the ability for a vessel to know its current and projected location and plan to transit to new locations.

Function 1.4 is “to communicate.” This function defines the transmitting and receiving of data or voice information required to conduct the operations of sensing,

engaging, and moving. These communications must be effective in both network optional warfare environments and network centric environments. A breakdown of Function 1.4 is shown in Figure 18.

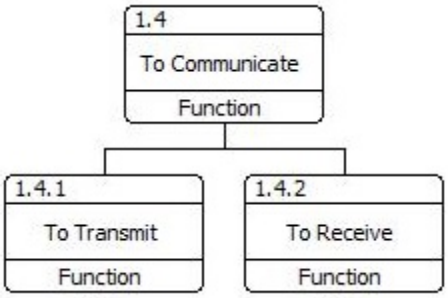

Figure 18. “To communicate” sub-functional decomposition.

Function 1.4.1 is “to transmit.” This function defines actively sending signals from the vessel these signals may be data or voice signals. This information may be sent via radio, light, visual cues, and lasers.

Function 1.4.2 is “to receive.” This function defines actively or passively obtaining radio, laser, or other electronic information and conversion to pictorial, data, or voice information. Radio, light, visual cues, and lasers must be receivable by the system.

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IV. SEA COMBAT CONCEPT OF OPERATIONS FOR THE SMALL SURFACE COMBATANT

This section will address the concept of operations (CONOPS) for the small surface combatant (SSC). The motivation for developing the CONOPS is to provide a theoretical guide of employing the small surface combatant at the 2025–2030 timeframe. The CONOPS will also help guide modeling and system design with regards to translating this work's vision and recommendations into a detailed ship design.

A. OVERVIEW

The concept of operations was developed to provide the initial foundation for employment in the full spectrum of Phase II (seize the initiative or offensive) operations. The SSC CONOPS provides a roadmap of how to successfully employ the ships in different environments against a multitude of threats from all domains. Concepts presented in the CONOPS were influenced and informed by analysis consolidated from other sections of this paper. Three different force compositions are presented in the CONOPS. An independent deployment consists of a single SSC. A Flotilla is group of more than one SSC. The armada is a force composed of SSCs mixed with other platforms. Additional details for each force composition are provided in the following sections.

B. SCOPE

As previously discussed, the focus of the CONOPS and the SSC research is Phase II operations, which are defined in Chapter III Section C.2. Although the SSC will be able to contribute in other phases, the emphasis of the analysis is on initial combatant operations. An expansion on an example set of missions the SSC might be expected to conduct during Phase II operations is provided in Table 5.

Primary Missions	Secondary Missions
Power Projection	Intelligence, Surveillance, Reconnaissance
Sea Lines of Communication Patrol	High-Value Unit Escort
Deterrence through Presence	Defend Seaport of Debarkation

Table 5. Examples of Phase II missions.

C. PURPOSE

Rather than design a multi-mission next generation frigate replacement, the project team identified an opportunity to explore a cost-effective, single-mission design of a small surface combatant. The SSC's strength lies in a distributed offensive combat power dispersed effectively among multiple ships. The SSC's offensive combat power is comprised of ASCMs. The project team proposes dispersing the number of ASCMs employed in a sea battle onto multiple surface combatants instead of one capital ship thereby increasing the resilience and survivability of the fleet's offensive combat power. An individual ship's survivability against ASUW missile attack will depend on the inherent low-radar cross-section of a small ship and EM countermeasures.

D. FOUR PILLARS OF THE SMALL SURFACE COMBATANT CONCEPT

Each of the four SSC pillars are a major foundational concept designed to provide foundational background to develop the new platform.

1. System of Systems (Armada) Concept

The CONOPS employs the SSC as a system within a larger fleet of different platforms, creating a system of systems where the capabilities of each complement the overall combat effectiveness of the fleet. The system of systems as a whole is defined to be the armada. The armada represents a formidable force capable of defeating an opposing force at sea. The strength in the armada is utilization of existing force structure, combined with the new SSC, to integrate into a force that can deter aggression and project power in any region.

In 2025–2030, the U.S. naval force structure will feature a large number of Arleigh Burke-class destroyers and approximately 30 LCSs. Assuming that a third of the

modular-designed LCSs will be equipped with ASW modules and the other two-thirds will be equipped with either the MCM or SUW module, the SSC will forego redundant force structure capability to save cost. The same philosophy applies to AAW capability, where large numbers of Arleigh Burke class destroyers are sufficient for air defense. Given this programmed force structure for 2025, the team envisioned employing the SSC in a force composed of ASW-capable LCSs and AAW-focused DDGs alongside multiple dedicated ASUW SSCs. Manned and unmanned sensor platforms such as the MQ-8B Firescout could be used to increase the ISR capability of the force. The P-8 Poseidon maritime patrol aircraft could replace or complement the ASW capability of the ASW-equipped LCS. The system of systems approach has the goal of allowing the U.S. Navy to expand its fleet size, but at a lower cost than building multi-mission ships.

One system the SSC is not inherently designed to work with is the aircraft carrier. Short-duration protection missions such as a strait escort are envisioned, but the SSC will not be well suited for extended blue-water carrier strike group (CSG) operations. The SSC could be considered an external system to the CSG system capable of interacting with but not belonging to the CSG. Sustained operations at sea for prolonged periods, as is normal operating procedure for a CSG, would stress the ship and crew beyond its designed capabilities and will not be considered a core capability of the ship.

2. Forward Basing

In order to execute the SSC's primary missions, it is essential the vessel be forward deployed in a regional theater, such as the South China Sea (SCS) or southwest Asia. As with the LCS, multiple SSCs are to be forward deployed to allow for rapid employment in response to a quickly developing situation. In a Phase II scenario, where an adversary has achieved strategic surprise with naval forces, forward-based surface forces will be able to respond to changing strategic situations faster than forces based in continental bases in the United States. In addition, this study's logistical research shows the SSC will have less endurance than an Arleigh Burke class destroyer. The research pointed to fuel capacity as the limiting factor of a SSC. We calculate a 1500-ton SSC will have approximately eight days of endurance if the ship is patrolling at a speed of 15 knots

before it reaches 20 percent fuel level. Transoceanic voyage at high speed in response to a situation is not a capability the SSC is designed to possess. Thus, forward basing complements a ship with endurance in days not weeks.

3. Cost Effectiveness

The motive for building a new follow-on ship class to the LCS is to invest in a force structure that increases the fleet size to meet peacetime demands while increasing the Navy's offensive combat power. This project team has defined cost effectiveness as delivering additional capability to the force at a unit cost less than that of the LCS. In addition, the loss through combat attrition of one SSC does not constitute a mission kill as the combat power of the group is based on resiliency of multiple SSCs operating in a group.

The ship's design should strike a balance between manpower and automation. Manpower will be objectively set at the LCS core crew level, with the threshold manpower numbers arriving through additional investment in automation. Decreased maintenance requirements of installed systems on the SSC shall be a priority of the design, so as not to cause the manpower numbers to rise in order to support maintenance requirements. Manpower, in the form of ship's crew, will be considered as the optimal number to operate at sea during combat operations and is set at prior manning levels established for U.S. Navy PHMs at 25 personnel.

4. Sustainment

A2AD weapon systems have the ability to place at risk large replenishment ships that traditionally sustain the fleet at sea. Current sustainment methods do not have the flexibility to adapt successfully to the A2AD environment. Alternative methods of sustaining the armada must be established or the armada must leave the threat area to resupply. One method to connect the supplies between large replenishment ships and high threat areas is to employ a vessel such as Joint High Speed Vessel (JHSV). If the JHSV cargo area was optimized to carry fuel instead of bulk cargo, the JHSV could be utilized as a high-speed shuttle ship from the replenishment ship to the armada. Other options for a fuel ferry include converting LCS's modular mission zone into a fuel

storage area. LCS is better adapted to combat than the current JHSV due to the LCS's self-defense capabilities. In the absence of at-sea replenishment, a robust shore supply network may be feasible provided local nations were willing to support U.S. forces operating out of host nation ports. Using ports as resupply networks will decrease on-station time, but decreased on-station time may be mitigated by maintaining a reserve force in port and simply rotating from on-station to in-port. This rotation method is a higher cost alternative because twice as many units need to be forward deployed, but may be feasible due to the low cost associated with SSCs and savings from not utilizing JHSV and LCS as shuttle ships.

Fuel conservation is included as a major policy of sustainment in the effort to decrease the demand on supplying ships. Using organic sensor platforms to perform scouting ISR functions should lessen the fuel burned on each ship. In addition, the design of the propulsion plant and hull form should incorporate features to decrease fuel burn. Doctrine changes, such as allowing the ships to burn down to 20 percent total fuel remaining as a standard operating procedure will increase time on station and utilization of each asset.

Rotational crewing will aid in sustaining the SSC at sea. Rotating crews when fatigue levels get too high will offset the fatigue level of a crew. Rather than externally scheduling the rotation of crews, at-sea or in-port rotations will increase the units' overall combat effectiveness. Additional manpower cost is offset by higher utilization of each platform.

E. TACTICAL EMPLOYMENT

Depending on the threats presented in any tactical employment scenario, the SSC gives flexibility to the decision maker by being scalable from the single unit up to a flotilla or armada. Each ship will possess the organic capability to conduct the full detect to engage sequence. The organic sensors are a combination of own-ship and unmanned or manned sensor platforms to extend ISR range. To ensure the SSC's maximum effectiveness in a multi-threat environment, the following capability parameters were discovered through analysis: organic sensor range to 60 nm, 90 nm missile ASUW

missile range, 25 knot maximum vessel speed, missile capacity of eight missiles and a salvo size of at least two missiles per engagement.

1. Independent Deployment

Although not ideal, situations may arise where only one SSC is able to respond and will have to engage an enemy's ship or ships in ASUW combat. Since each SSC possesses sensors and weapons capable of executing the entire detect to engage sequence it will be able to engage in a small-scale surface engagement. Ambush and hit and run tactics will increase the small surface combatant's survivability from the engagement. Tactics that stress firing first and not letting an enemy determine a firing solution will increase survivability. Having a sensor capability that allows detection and classification beyond the enemy's capability will aid in these offensive tactics. Finally, the ships' ASUW weapon will need to be effective and capable of inflicting a kill against enemy combatants with the first salvo.

2. Flotilla Deployment

A group of multiple SSC will form a flotilla to engage in surface-to-surface combat. If undersea and air domains are controlled by other units, the flotilla will mass the combat power of the small surface combatants. By massing the combat power, the flotilla can launch an overwhelming surface strike of ASUW missiles. A flotilla's vulnerability in this situation is protection from enemy missile salvos. The flotilla will rely only on EM countermeasures and a small ship's radar cross-section to avoid detection at over-the-horizon distances. However, a flotilla will serve as a major deterrent to potential adversaries using surface forces in offensive roles and will project power from a presence standpoint.

3. Armada Deployment

An armada deployment provides the group with capabilities to contest air, sea and undersea domains. The armada increases the SSC's survivability by employing Arleigh Burke-class destroyers in an air- and missile-defense role. The armada utilizes the LCS

equipped with the ASW module to protect the ships in the armada from undersea attack. This concept is illustrated in more detail in Figure 19.

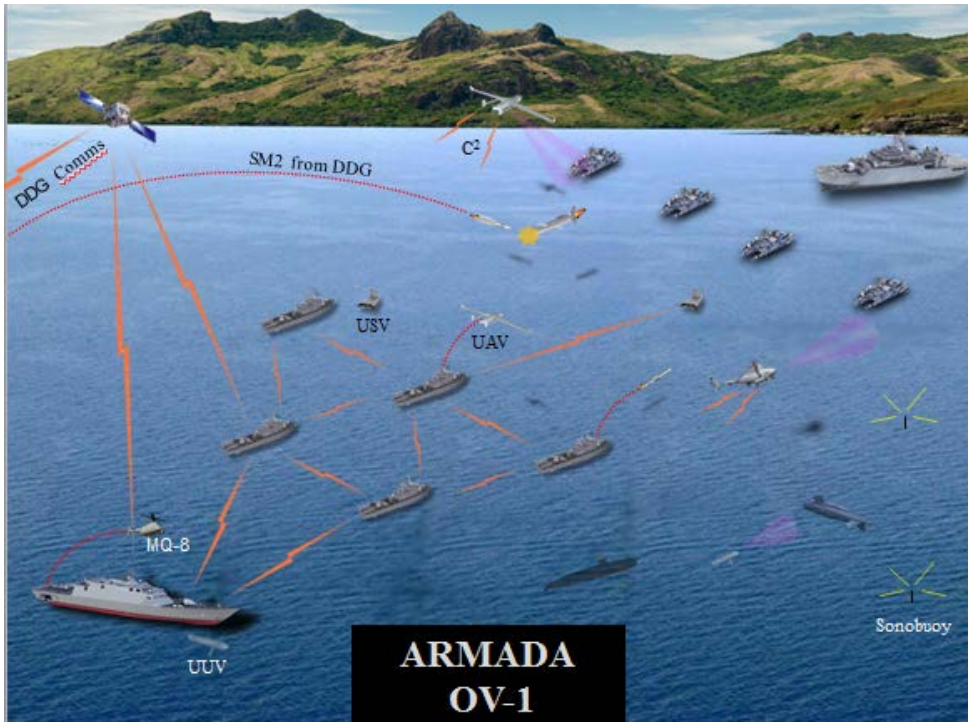

Figure 19. Operational view-1 for armada depicting the system of systems approach.

In Figure 19, we depict the armada operating in a multi-threat environment where the threats are from surface, air and undersea adversary platforms. Communication flow between the systems relies on line of sight means. The five ships in the center of the diagram are the SSCs. One of the SSCs is launching an unmanned aerial vehicle (UAV), which will be the means to extend organic sensor range in order to optimally perform the "detect to engage" sequence. Also shown is an unmanned surface vehicle (USV), which will assist with extending organic sensor range. Both the USV and UAV are assumed to be organic to the SSC.

The LCS in the bottom left corner is conducting ASW to mitigate undersea threats. Although not an organic member of the armada, BLUE force submarines may

operate in the area to aid in securing the undersea domain. P-8s and MH-60Rs may also be temporary members of the armada in order to further prosecute ASW threats. The P-8 and MH-60R are the source of the sonobuoys shown in Figure 19. A DDG functions as the armada's AAW component by intercepting an incoming enemy missile. The MQ-8B is launched from the LCS and will increase ISR of the group and the information will be distributed.

The number of platforms other than the SSC can be scaled up or down to meet the threat scenario. For example, if the air domain is highly contested more DDGs can be added to the group to boost the AAW capability. As stated previously, increasing the number of ships in the group adds to overall resiliency of the combat power and survivability of the overall group.

F. OPTIMAL CAPABILITIES OF THE ARMADA CONCEPT

To ensure the armada's maximum effectiveness while operating in a multi-threat environment, the following parameters for the small surface combatant were determined through analysis: organic sensor range at 60 nm, ASUW missile range of 90 nm, 25 knot maximum vessel speed, missile capacity of eight missiles and a salvo size of at least two missiles per engagement.

G. OPERATING ENVIRONMENTS

Whether the SSC is independently deploying, part of a flotilla or a component of the armada, the SSC may find itself in several different operating environments. Each operating environment contains challenges that distinguish the environment from other areas, but some challenges will overlap all environments.

1. Anti-Area Access Denial Environments

Any environment where an adversary seeks to deny friendly forces use of a maritime area through threats of attack from weapon systems could be considered an A2AD environment. These weapons seek to disrupt the U.S. ability to freely navigate international waters and project power while disrupting normal operations in A2AD environments. The weapon systems encountered in A2AD environments vary in

complexity from naval sea mines to anti-ship ballistic missiles (ASBMs). Current U.S. force structure depends on aircraft carriers to project power and ASBMs are designed to hold aircraft carriers at risk within the A2AD zone. A more common threat is an ASCM launched from aircraft, ships, shore batteries or submarines, which are in the inventory of most of the world's militaries. ASCMs can be employed to force withdrawal from a maritime region or even to deny its use by any surface maritime force. Advanced diesel electric submarines are becoming more common in the inventory of potential adversaries. Diesel electric submarines are difficult to find and have the ability to deal a crippling blow to friendly ships without much warning.

Also included in the A2AD weapon systems are adversarial systems designed to deny friendly forces use of the full range of the electro-magnetic (EM) spectrum. Current U.S. forces depend on network and communications through various means. Without GPS position finding or satellite-based network capabilities, U.S. forces will not be capable of operating at their designed strength. All of the above threats are included in the A2AD environment which may share geographic characteristics with the following two zones.

2. Littoral Zones, Coastal Regions and Strait Transits

Challenges associated with the littoral zones, coastal regions and strait transits typically are water depth, proximity to land, high surface contact density, and possible attack from shore-based ASUW missile batteries. Asymmetric threats from non-state actors are a major concern in littoral, coastal and straits. Contact density and proximity to land can challenge the "detect to engage" sequence as operators try to distinguish targets from radar clutter. If attacked in these areas, threat warnings may not provide the operator with much reaction time to respond to incoming threats. These areas provide some of the highest risk to U.S. Navy ships due to the unique challenges faced in these zones.

The SSC will have a draft comparable to LCS and will have access to the same water-space. The destroyer must remain in deeper water since it has a deeper draft, while extending the AAW shield over the armada. Detecting and classifying surface targets will be aided through organic UAVs and USVs employed by the group. The formation of

ships shall remain in relatively close position to aid in mutual defense of the group. If naval sea mines are present or suspected, operations in the areas will be suspended until the area can be cleared of mines.

3. Blue Water

Blue-water operations for an independent deployed SSC, flotilla group or armada are not outside the scope of possible operating environments. Although distance from land excludes frequent port visits for resupply, traditional replenishment methods can be utilized in blue-water areas. The traditional replenishment method is dependent on the assumption that the replenishment ships can be protected and are not under direct threat of attack. Endurance of the small surface combatant might be the limiting factor to blue-water operations. In addition, sea state might exclude the SSC from operating with larger surface combatants. However, the U.S. Navy has planned and executed blue-water operations frequently in the past and operating in blue water should be less challenging from a threat perspective than the littoral, coastal and strait areas.

H. COMMAND, CONTROL, COMMUNICATIONS, COMPUTERS AND INTELLIGENCE

In a normal environment, command, control, communications, computers and intelligence (C4I) will be through standard satellite communication (SATCOM): ultra-high frequency (UHF), super-high frequency (SHF) and high frequency (HF) channels. These channels present the optimal configuration of the command, control, communications, computers, and intelligence (C4I) network to enable communications between ships and to any external nodes. To be prepared for any adversarial interference with the EM spectrum or operating with emission control (EMCON) measures in place to reduce vulnerability, the SSC and the platforms operating with the SSC need to be prepared to use alternative means to communicate. Line of sight (LOS) communications and local area network (LAN) are more difficult for an adversary to interfere with and will become the C4I network path in the EM denied or EMCON environment. By having C4I flexibility the small surface combatant and the interacting platforms will still retain communications capability in any environment.

I. MAJOR RISKS ASSOCIATED WITH SMALL SURFACE COMBATANT

As the SSC matures from high-level concept to initial design several high risk factors have been identified which may threaten the SSC's effectiveness as a viable platform for the U.S. Navy.

(1) Cost Controls. If the SSC becomes too expensive to risk in a high-threat environment then the feasibility of this concept is lost. The SSC concept is designed to employ in a high-risk environment by forming the armada, which is capable of engaging potential adversaries in air, sea and undersea domains. Cost may prohibit the SSC employment if the ship design is subjected to mission creep by adding additional capabilities other than ASUW. If modularity or additional capability adds to the list of requirements provided in this study, then the SSC may lose appeal as a possible acquisition program due to cost escalation.

(2) Obsolescence. Major technological breakthroughs in the area of directed energy weapons, rail-guns, hypersonic ASCMs or ASBMs capable of targeting a SSC could render the design of the small surface combatant obsolete. A small platform inherently will have a small reserve weight capacity for future upgrades and may not be capable of sustaining several iterative designs or major midlife upgrades. Decreasing the ship's service life will aid in keeping the SSC from becoming obsolete, but may not be economically feasible.

(3) Endurance. A SSC will not have the endurance of a larger ship such as a DDG. Alternative logistical CONOPS will aid in sustaining the ship at sea, but it most likely will not be able to sustain prolonged operations with a carrier strike group or at sea. Operational planners will need to account for logistics requirements associated with a smaller combatant in order to mitigate the risk associated. The SSC cannot be shifted into the logistical model that larger surface combatants follow because that model will not fit the unique requirements associated with a smaller combatant. Increasing endurance during the design of the ship will increase size, ultimately driving up cost unless mitigating design features such as efficient hull forms or propulsion systems are incorporated into the design.

J. CONOPS TAKEAWAYS

Adding the SSC platform into the U.S. fleet will cause a paradigm shift in the way surface combatants are employed. By combining existing platforms alongside SSC into the armada, the fighting force would become more capable and resilient as a whole. The armada concept mitigates platform weaknesses by optimizing the group with platforms that are strong in every domain. The armada concept does not replace the power of a CSG; rather, the concept provides a low-risk offensive power-projection alternative, which can operate in the A2AD environment to deter aggression and inflict heavy casualties on an adversary.

V. MODELING

A. SCENARIO DEVELOPMENT

Modeling is performed to determine the optimum force structure, investigate the required capabilities which affect force effectiveness, and validate the proposed distributed surface force concept. The model scenario provides the context and defines the operational environment for the proposed force structure and design. The main aim is to enable proposed force structure and design strength and weakness discovery as well as to ascertain the opportunities and threats which the opponent may present to U.S. forces in each operational scenario, and to translate the results to a presentable format.

1. Considerations for Design of Model Scenarios

The considerations for the design of the model scenarios take the Who-What-When-Where-Why approach to set the context of the model scenario.

a. Potential Conflict Areas (Where and Why)

The U.S. military has begun to rebalance focus towards Asia-Pacific and Middle East areas as this region presents the highest concentration of U.S. interest and emerging threats. In the Asia-Pacific, U.S. economic and security interests in the region will continue to be threatened by adversaries like North Korea in the northeast region, and also the increased military aspirations of China in the East and South China Seas. Territorial disputes by China with neighboring countries in the East and South China Sea region will continue to cause suspicion and increase regional tension.

In the Middle East, political instability in various countries continues to encourage the growth of extremist organizations and rogue governments. These organizations and governments will center their naval activities in the Persian Gulf, which will have significant impact on U.S. interests in Gulf States like Kuwait, Bahrain, and Oman.

The model scenario areas of operations were centered on the Asia-Pacific and Middle East regions, which have been assessed to be the most likely areas where future naval conflicts will happen (Hagel 2014).

b. Adversary Strategies (Who and How)

This section provides the future adversary strategy estimate to create a basis for the model development, as well as scenario considerations. The future USN force will face adversaries who will employ asymmetric strategies and tactics to evade USN strengths and exploit weaknesses by:

- employing A2AD strategies to threaten the U.S. military power projection ability in the air, land, and sea domains,
- utilizing low-cost technology to achieve overmatch and cause maximum destruction,
- leveraging long-range, high-precision weapons such as ASBM/ASCMs for standoff encounters and to reduce inland strike range of carrier strike groups (CSG) and surface action groups (SAG),
- inhibiting freedom of information and communication by denying as well as disrupting the use of the electromagnetic (EM) spectrum,
- employing asymmetrical tactics utilizing manned and unmanned systems to achieve surprise and confusion and erode morale,
- dispersing and concealing Naval assets to reduce signature,
- increasing lethality as well as survivability for each naval platform, and
- evolving quickly to prevent predictability and elude response.

c. Scenario Imperatives (How)

In order to design the system with potential strategies of the future adversaries in mind, we evaluated the flotilla with varying capabilities under several threat scenarios, which provide insights for the following:

- concept of operations and capabilities to counter A2AD threats,
- impact of the adversary's long range ASBMs and ASCMs,
- impact of the adversary's asymmetrical tactics,
- impact of maritime environment operation near potential conflict areas, and

- implications for USN's role in sea-based strike and targeting operations.

2. Selected Area of Operations

The following areas of operation will provide context for the modeling effort to allow for realization of the targeted scenario imperatives.

a. Scenario One: Spratly Islands

The Spratly Islands has always been perceived as a resource rich region. With minimal exploration of the region, the estimates of the resources reserves remain high with the estimated amount of oil to be at least 28 billion barrels and approximately 900 trillion cubic feet of natural gas. In addition, the Spratly Islands region also boasts one of the busiest commercial shipping lanes and most productive fishing grounds in the world (Central Intelligence Agency 2014).

The Spratly Islands consist of dozens of uninhabited rocky outcrops, atolls, sandbanks and reefs, such as the Scarborough Shoal. These islands are of strategic importance to many countries, and have been contested by many nations throughout history. China, Vietnam, and the Philippines have recently emerged as competitors and potential combatants with interest in this region (Central Intelligence Agency 2014).

The recent People's Republic of China claim on the Spratly Island region backed by aggressive behaviour has disturbed the power balance in the region. Although the U.S. has always officially supported the peaceful rise of China as a global power, the aggressive stance by China has no doubt threatened the U.S. economic interest and the interests of allies.

In addition, the Spratly Islands lie in the southwest portion of the South China Sea (SCS) in between the U.S. and the Asiatic region. With the pivot of its focus to Asia, the U.S. military forces require allies and military bases in this area. This national strategic need further elevates the importance of the Spratly Islands region to the U.S. (Hagel 2014).

With the ever-growing military prowess and political aggression of the regional powers, the ability to counter external influence is vital so that the U.S. Navy is able to

defend and protect its interest in the region in the foreseeable future. Hence, the Spratly Islands region is chosen as one of the operational scenarios locations in which to model a distributed surface force concept.

b. Scenario Two: Malaysian Civil War/Strait of Malacca Closure

Three main factors are used to develop the sequence of events that lead to this scenario. These factors include geographical and geopolitical realities, China's intentions as a regional hegemon, and China's existing and potentially emerging capabilities in the region.

The Strait of Malacca (SOM) is bordered by the littoral states of Indonesia, Thailand, Malaysia and Singapore. It connects the Indian Ocean to the SCS. The SOM is 3.5 kilometers wide at its narrowest location at the Singapore Strait. It serves as an important as well as busy transit route for the world's energy and trade (United States Energy Information Administration 2012). Due to the SOM's depth, speed and maneuverability of large capital assets are limited. In addition, proximity to land makes potential naval assets susceptible to shore-based anti-access area denial assets such as anti-ship missiles and naval mines.

The SOM serve as important sea lines of communication (SLOC) for China. Over 90 percent by volume and 80 percent by value of PRC's foreign trade travels through the SOM. Also, 90 percent of China's imported energy transits through the SOM **(Office of Naval Intelligence 2009)**. This strait is a chokepoint that the PLAN recognizes as a strategic vulnerability and the PLAN has always been uneasy over the activities carried out by the U.S. and its allies in the area (Vavro 2008). China's intentions of projecting greater influence and being a larger stakeholder in the security of the Strait of Malacca was manifested in 2006 when then President Hu Jintao summarized China's maritime security as China's "Malacca Dilemma." The Chinese thrust into the Indian Ocean by establishing diplomatic ties for base access in Gwadar port of Pakistan, naval bases in Myanmar and the Kra Isthmus in Thailand can be regarded as a strategic move to increase her strategic depth and power projection if necessary into the critical strait **(Vavro 2012).**

As for capabilities, the South Sea fleet headquartered in Zhanjiang is responsible for China's maritime security in the SCS and the Strait of Malacca. Operating out of Zhanjiang, the PLAN's upgraded Luyang II DDGs are capable of launching newly developed YJ-62 ASCM (approximately 120nm) for over-the-horizon (OTH) targeting and strike operations. Houbei-class guided-missile patrol craft (PTG) provides alternatives to operate in the confined and shallow depths of the Strait of Malacca. The Houbei class of PTGs is capable of launching ASCMs (approx. 50nm). The operational employment of the Houbei class PTGs can be based on swarming tactics to overwhelm the opponent's sensors and create confusion. For the straits, the PLAN will most likely deploy small quiet diesel-electric submarines for surface force advanced screening and interdiction operations. The People's Liberation Army Air Force (PLAAF) has airbases located in Hainan Island which have operational range that covers the entire SOM (Office of Naval Intelligence 2009). PLAAF air assets with a networked sensor suite can increase the land-based and sea-based ASM overall operational range.

The following are the Straits of Malacca scenario narratives:

- China regards the SOM as a strategic vulnerability as she is heavily dependent on it for imported energy and goods.
- In the year 2025, Taiwanese nationalists were elected and subsequently declared independence from China and rejected the "one China" policy.
- China is subsequently forced into unlimited conflict with Taiwan and in the effort to stabilize the region, which draws the U.S. and her allies into the conflict.
- With the Chinese East Sea fleet being tied down in the East China Sea, the Chinese South fleet was tasked establish sea control in the SOM to secure SLOCs and sustain ongoing operations in the East China Sea.

This unilateral action by China to establish sea control in the Strait of Malacca has compelled the USN and her allies to engage the Chinese force in the strait and conduct sea denial operations against the PLAN.

c. Scenario Three: Persian Gulf

The Persian Gulf is another foreseeable theater of operations for the SSC force. Much like the SCS, the Persian Gulf is an area rich in natural resources with multiple

nations vying for control. Iran's seemingly excessive claims of territorial waters seek to close off the region and serve as an excuse to question any vessels transiting to or from the region (Alexander 2014). This situation has heightened tensions and provides the potential for future conflict as demand for these resources continues to grow.

Iran's claims require frequent execution of freedom of navigation operations to ensure the Strait of Hormuz stays open. (Alexander 2014). Another current mission the U.S. performs in the area is defense of oil platforms (Montgomery 2009). This defense activity can be difficult for current platforms because of the shallow water depth and deep draft of the ships. Any assets in the area are within range of Iranian shore-based missile batteries (CNN Wire Staff 2012). Additionally, the Iranian Navy and Revolutionary Guard have numerous small combatants that employ swarm tactics to pose threats to the much more capable but less maneuverable ships the U.S. Navy currently uses in the area (Williams 2013). The SSC addresses the listed issues that the U.S. Navy's current force structure faces in that operational environment.

d. Baseline Model

To focus modeling effort and resources, it was necessary to select a single scenario for the baseline model. The team chose the Spratly Islands as the baseline model development scenario based on the following considerations.

- Given the reasons highlighted in Chapter V Section A.2.a, naval conflict in the seas surrounding the Spratly Islands is the most probable. As seen in Figure 20, the following countries have territorial claims to parts of the Spratly Islands: China, Taiwan, Vietnam, Malaysia, Brunei, and the Philippines (Rodis 2011).
- Due to its proximity to mainland China, PLA assets would be able to sustain operations and exert dominance over the countries who also claim ownership. In addition, the seas surrounding the Spratly Islands are within range of PLA's ASCMs and ASBM (Office of Secretary of Defense 2013).
- The Spratly Islands area of operations consists of very little land area as most of it is covered by sea. This focus on maritime operations assists in simplifying the model and ensures any insights arising are due to the battle's naval component.

Figure 20. Spratly Islands' geography including potential adversaries (after Rodis 2011).

After accounting for these considerations, the Spratly Islands were assessed to be the most suitable scenario for the model development.

B. OPERATIONAL FORCE EMPLOYMENT MODEL

The goal of the quantitative analysis was to determine the SSC characteristics required to both maximize the survivability and combat effectiveness of the units.

1. Model Requirements

The analysis approach shall be capable of accepting various inputs (within a prescribed set of limits) for offensive and defensive capabilities. It was beneficial to possess the capability to quickly change these input values, as a range of input parameters to analyze the effectiveness of the system through modeling were required. The model shall be capable of varying the following input parameters: speed, sensor range, missile range, radar cross section, offensive weapon battery size, offensive weapon fire rate, evasion capability, and force size.

The analysis shall generate the desired outputs listed in Table 6. The most significant output required was the number of units killed during each combat engagement. A breakdown of the individual unit types lost and the timeline of casualties was included.

(1) Required Inputs	(2) Required Outputs
(3) Individual Unit Entities	(4) Adjustable Model Stopping Conditions
(5) Variable Speed	(6) Graphical Representation of Individual Units and Actions
(7) Variable Sensor Range	(8) Duration of Engagement Output
(9) Variable Weapons Range	(10) Number of Friendly Force Casualties
(11) Variable Probability of Hit	(12) Number of Enemy Force Casualties
(13) Variable Salvo Size	(14) Time Casualties Occur
(15) Variable Fire Rate	

Table 6. Summary list of model requirements.

The main analysis tool shall provide a visual depiction of events unfolding. Observing the events as they unfold will provide valuable insight on the engagement dynamics as the scenario develops.

2. Analysis Options

After reviewing the requirements and comparing the options, it was determined that discrete event simulation (DES) met all analysis requirements. DES has great generality and has potential to capture the desired details of naval combat (e.g., duration of engagement, own and adversary unit casualties, and time of detection). The main shortcoming of using computer simulation was that particular instances of simulation models can be large, time-consuming to construct, and require significant computer runtimes to achieve desired statistical accuracies.

Several DES tools exist that meet the desired analysis criteria. The two selected are described below, along with their particular strengths and weaknesses.

a. Map Aware Non-Uniform Automata

The first step in the modeling process was to determine the capabilities necessary to achieve the requirements defined during the SE process. These capabilities can be identified by performing multiple simulation runs, where many possible combinations of parameterized capabilities are evaluated to determine those parameters that are the most significant. One modeling tool that can be used to aid in the DOE analysis is Map Aware Non-Uniform Automata (MANA). MANA is an agent-based, time stepped, stochastic, map aware modeling tool (McIntosh, et al. 2007).

The first benefit of the MANA model is *map awareness*, meaning that the agents in the model move and react according to a specific preset decision process. Some modeling tools allow individual agents to move from point to point following specific waypoint guidance. MANA allows for similar guidance, yet the capability to alter individual squads based on the environment adds a touch of realism to the outcome. More specifically, each squad follows the predetermined path with a varying level of randomness, which simulates the friction of real life units in the battle space. Additionally, units can only travel over specific environments, allowing the designer of the scenario to add realistic land masses and shoal waters that inhibit travel. Units can also be programmed to maintain minimum and maximum distances from other units allowing the designer to evaluate the concept of operations and standard operating procedures that may be employed in the future fleet.

Another feature of MANA is the model's non-uniform aspect. Each individual unit or squad can be programmed with specific characteristics and limitations. This ability allows the user to alter each squad's capabilities and specific features independently of the group, which will later become invaluable in the analysis.

Finally, MANA operates each individual unit as a separate and individually complex entity. This attribute means that each unit will operate according to a specific set of loosely defined guidelines, but slight differences in the environment or conditions of two identical units can result in drastically different behavioral actions. Again, this

variability accounts for some friction in the battle space, and provides a more realistic behavioral outcome for individual units in combat.

There are many advantages of using MANA as the major modeling tool for this project. The user interface is intuitive (changing specific capabilities does not require advance programming knowledge), and significant resources are available to aid the user when specific knowledge gaps occur. Another advantage is the ease with which accurate and realistic threat regions can be constructed. Overlaying global satellite data images and manipulating the terrain to reflect these images can be completed relatively quickly and intuitively. This rapid manipulation capability is particularly important if the user intends on evaluating specific forces in multiple threat regions. Finally, the model is time-stepped, which allows the user to expeditiously run multiple scenarios in a given time frame.

There are some disadvantages to using MANA. Most specifically, targeting is limiting to agent versus agent. This limitation means that offensive units must target specific enemy units to engage rather than shooting in the general direction of an incoming fleet. Changes in technology have made this limitation more significant, as advanced missile systems under consideration utilize individual targeting technologies (shoot a missile down a general bearing and allow the missile to conduct the targeting based on priority characterization). While this capability would increase the effectiveness of an offensive unit, the inability to achieve this targeting capability level does not invalidate the model results because current weapon systems do not possess this capability. The other major disadvantage to this modeling program is the absence of robust command and control capability. Although the units are capable of communicating with each other to prevent fratricide, no capability exists to control the individual unit actions from a central command unit. As the concept of operations shows, this capability is central to the swarming concept of a small flotilla force.

Despite its shortfalls, MANA remains the model of choice to model the operational scenarios in this study as the modeling program meets all requirements listed in Chapter V Section B.1.

b. COMBAT XXI

COMBAT XXI is a simulation tool for evaluating weapons systems and tactics. It is a modeling program designed for high-resolution, entity level combat simulations, producing stochastic results based on discrete events. COMBAT XXI is capable of providing high-fidelity results of campaign-level engagements (TRADOC Analysis Center 2011). Designed for combat simulation in a joint battle space with ground forces, air mobile forces, future forces, logistics and casualty handling, considerable effort was required to modify COMBAT XXI's capability to model naval engagements. Programming skills are required in order to build a model. Because of the time investment required to make COMBAT XXI capable of modeling a naval engagement, only the force composition that produced the best results using the MANA model were tested. The preliminary work with the COMBAT XXI model produced results similar to those of the MANA model as shown in Appendix C.

3. Input and Output Parameters

As discussed previously, multiple simulation runs are required to determine the most significant factors affecting the battle outcome. Many variables can change, and determining which variables to evaluate is critical to scoping the model to one that can be achieved in the project's time horizon. Some of these factors include, but are not limited to, speed, missile capacity and range, sensor range, ship draft, fuel capacity, endurance, crew size, and armada group size. Based on the simulation program chosen for this analysis (MANA) and the desire to identify the armada system's key capabilities, the primary input parameters were force structure, unit network capability, missile range, sensor range, and salvo size. These parameters are discussed in more detail in the Chapter V Section C.3.

The MANA simulation program is capable of providing thousands of outputs including battle duration, engagement time, number of shots fired and hit, and attrition rates and times. Ultimately, the armada force structure's goal is to provide a credible (if not necessarily survivable) deterrence capability. In other words, if the chosen armada force structure is capable of inflicting substantial casualties to the adversary, the

adversary may avoid the conflict. The primary output used for most of the analysis is specific unit attrition rates. To provide a single factor of analysis, a comparison of the two side's attrition can be determined using the exchange rate in the following formula:

$$AttritionRate = \frac{ForcesLost_{US}}{ForcesLost_{Adversary}}. \qquad (1)$$

Some discussion is included that addresses the battle duration primarily for logistics rather than combat purposes.

C. INITIAL TRIAL RUNS

1. Purpose

As discussed in Chapter V Section A, evaluating the force structure in the Spratly Islands provides a worst-case scenario. Thus, determining the capability requirements to carry out combat operations effectively in this region should provide adequate capabilities for effective combat in any other realistic region. This idea is discussed in significantly more detail in Chapter V Section F. Once the capability requirements are determined, they can be applied to other scenarios to determine the force effectiveness in different threat scenarios. Another purpose of this initial model version is to determine any underlying issues that may prevent identifying the key capabilities required for success.

2. Initial Force Structure

The Spratly Islands are a group of islands (about five square kilometers in total land mass) that lie in the South China Sea about two-thirds the distance from southern Vietnam to the southern Philippines. Ownership of the islands is highly contested, as much for their political value as for the economic value they can provide (Central Intelligence Agency 2014).

In this scenario, the Chinese intend on occupying all of the islands by laying physical claim to all of the territories. Several regional countries have asked for U.S. support in preventing the People's Republic Army Navy (PLAN) from reaching their destination. The initial force structure for each side can be found in Table 7.

U.S. Forces:	10 Small Surface Combatants	PLAN Forces:	10 Missile Boats
	2 Destroyers		4 Destroyers
	2 Littoral Combat Ships		2 Frigates
	1 Submarine		5 Submarines
	4 Aircraft		1 Aircraft

Table 7. The initial force used for the combat model.

On the initial model run, only 10 small combatant ships were evaluated as a small run in order to determine any underlying issues. One of the main objectives of the armada concept is to create an affordable small combatant that, when combined with other ships, provides an effective and survivable system of ships. Air and undersea defense must be provided by external entities. This reliance makes the small surface combatant a system, and the flotilla concept a system of systems (SoS). Two Arleigh Burke class destroyers provide the air defense, as well as limited anti-submarine warfare (ASW) capabilities. Two Littoral Combat Ships (LCS) are modeled to be equipped with the ASW mission module, making them the primary providers of ASW capabilities. These LCSs also provide the primary platform for deployment of unmanned vehicles, which deliver external sensor capabilities. One submarine is assumed to be in the area providing undersea support to the flotilla group. Finally, four unmanned aircraft are assumed to be in the area providing ISR and sensor support to the flotilla.

The RED forces are primarily composed of 10 Houbei-class PTGs. Although there may be some question regarding their endurance, they do provide a feasible and capable surface-to-surface engagement capability. Four Luyang-class (or equivalent) destroyers, two Jiangkai-class frigates, five local-area submarines, and one air-to-surface missile capable aircraft comprise the rest of the PLAN battle group.

A visual context for the first model run of MANA is provided in Figure 21.

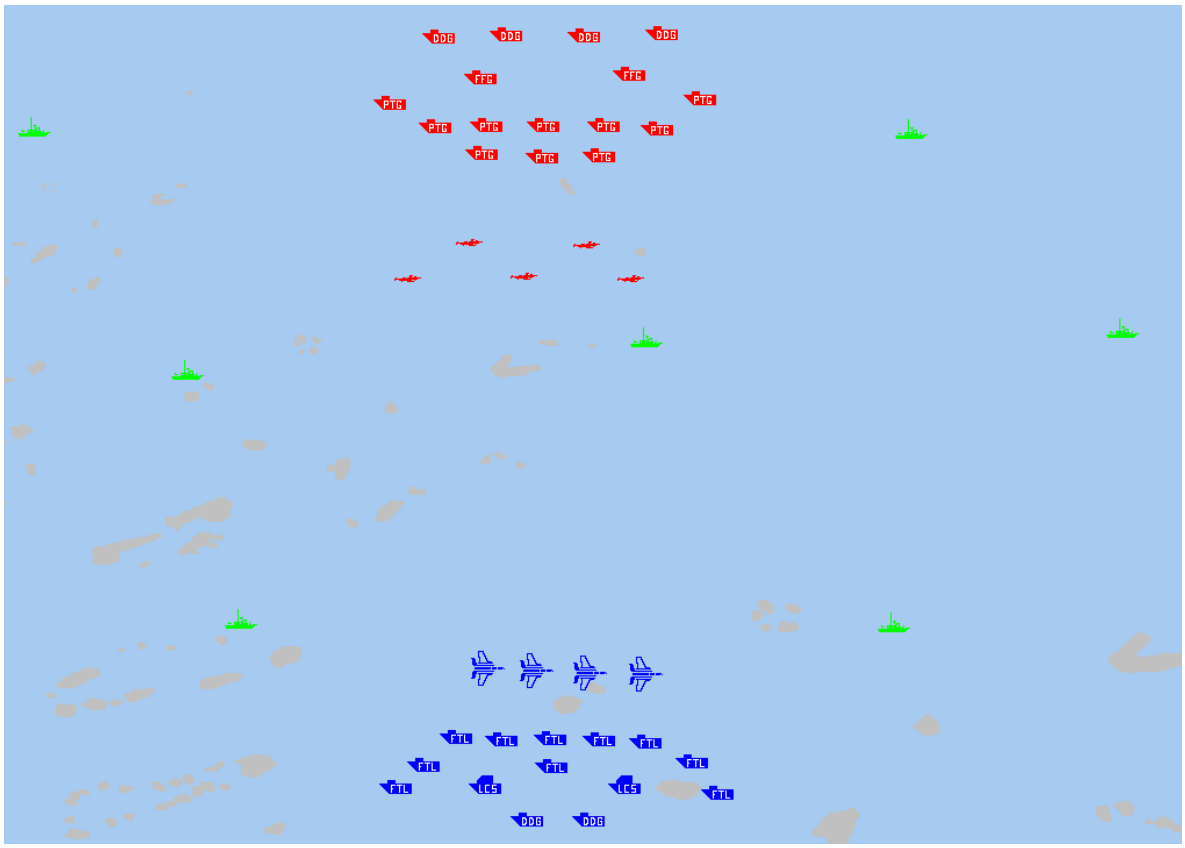

Figure 21. Screenshot of MANA model used for the initial trial run.

As shown in Figure 21, the PLAN forces (in red) start at the map's north end. This starting position represents forces from the PLAN South Sea Fleet deployed from Zhanjiang. A terrain map of the SCS is directly overlaid into the program, forcing the units to navigate around the islands and adding realism to the results. The green units scattered throughout the battle space represent commercial shipping and fishing vessels that would normally exist in the region. The green units have no offensive combat capabilities, and serve as distractors from the actual combat picture (a very low probability of detection and targeting may occur). Per the scenario, the PLAN forces travel south with the purpose of occupying the Spratly Islands. The U.S. forces loiter around the Spratly Islands and engage the PLAN forces when the U.S. forces are within weapons range (rules of engagement are not considered for this scenario).

3. Capability Variable Assumptions

As stated earlier, the capabilities that require evaluation include force structure, unit network capability, missile range, sensor range, and salvo size. These capabilities are discussed in more detail below. Although at least 30 simulations runs for each variable set are typically required for result data analysis (Ross 2009), only 10 runs were performed during this initial model trial for each variable set. The reduced number of runs might diminish the value of the results for analytical purposes such as drawing statistical inference, but is adequate to gain initial insights into the model design and required capabilities.

(1) Force Structure

The force structure is the number of individual ships in each flotilla group. Because the small SSC is by design a single-mission offensive platform, multiple SSCs and support units are required to provide both offensive and defensive capabilities. Two DDGs and two LCSs are included in all trial runs to provide this support. During this analysis portion, only 10 small combatant ships were evaluated. A more robust set of ship combinations were evaluated in subsequent model iterations, described in Chapter V Section D.

(2) Unit Network Capability

Unit network capability (a variable) defines the ability of each ship within the flotilla group to communicate with all other assets. From a real world perspective, this variable models the robustness of communications systems and the necessity to communicate in adverse environments. The two possible states for unit network capability are “on” and “off.” These states are respectively identified as one and zero in the result summary sheets. When network capability is “on,” units are assumed to be able to communicate by relaying targeting and engagement information to all other units within communication range. The method with which communication occurs is not specified, nor is it important (for this modeling) how it occurs. An in-depth analysis of communication methods, performed by the Joint C4I Capstone class on the NPS campus, can be found in Appendix A. When network capability is off, units cannot relay targeting

and engagement information to other units. This inability to communicate is meant to simulate an EM-denied environment in which no alternative communication capabilities are effectively employed. In the "off" condition, multiple ships may engage an enemy target if within sensor and weapons range.

(3) Missile Range

Missile range is the effective range of the missile being deployed from all U.S. combatant ships. The missile range is more a function of the missile type than the ship itself. For this model, two missile ranges were evaluated. On the low end, a 60 nm range is evaluated. This range was chosen because it roughly reflects the anti-ship missile range of U.S. Navy warships. More specifically, this range is similar to that of the Harpoon missile (Boeing 2014). The other alternative considered is a 90 nm range. This range is meant to simulate the range of alternative missiles either currently deployed or being designed. In particular, this range closely reflects the low end of the effective range of the naval strike missile (Naval Technology 2014b), and will adequately represent a minimum capability of the LRASM currently in development by the U.S. Navy (Defense Industry Daily 2014a).

(4) Sensor Range

Sensor range is defined as the effective detection and classification range that the SSC is capable of achieving through either organic or inorganic sensor networks. With respect to the model, the method with which this extended sensor range is achieved is less important than the fact that it can be achieved. The first sensor range scenario assumes that the detection range of the SSC's sensor network is 30 nautical miles (or 60,000 yards), and the range at which the network can positively classify a target and obtain a usable firing solution is 15 nautical miles (or 30,000 yards). These ranges are comparable to radar systems that exist on most modern naval combatants, making it the minimum expected SSC capability.

The next sensor range scenario assumes that the detection range is 45 nautical miles (or 90,000 yards), and a classification range (with all of the capabilities with respect to identification and solution development as described above) of 22.5 nautical

miles (or 45,000 yards). These sensor ranges are based less on any existing capabilities or planned systems, but serves mostly as a method of extending the range to evaluate the result's significance.

The last sensor range combination is a detection range of 90 nautical miles (or 180,000 yards), and a classification range of 45 nautical miles (or 90,000 yards). These ranges are outside the realm of feasibility for todays (or for that matter, the near term futures) shipboard radar systems. An external sensor system must be used to achieve these extended ranges. One possibility to achieve these ranges is to utilize existing unmanned platforms with inherent communications capabilities, such as unmanned aerial systems (UAS). Deploying a UAS from a platform, like the LCS, is already within the capabilities of today's Navy (United States Navy Fact File 2013c). External sensors do not, however, have to be limited to this traditional thought. Use of unmanned surface or subsurface vessels can extend significantly extend the ship's sensor range, as can rapidly deployable lighter-than-air devices and space-based technology. This study does not focus on the *how* (determining *what* required capabilities are more important is the goal).

(5) Salvo Size

The last major variable that this model evaluates is the numerical missile salvo size for the SSC. One base SSC design assumption is that it can rapidly deploy missiles, and also rapidly rearm and reengage in combat. The first variation of the model evaluates launching two missiles per salvo. The other variation evaluates launching four missiles per salvo. These two variations are based on minimizing the cost of the fire control system, as well as using canister stored and launched missile delivery systems on the small surface combatant. Should the analysis prove that varying the salvo size has a significant impact, a more detailed analysis will be conducted.

4. Limitations and Assumptions

Some limitations and assumptions are required to allow for modeling and simulation. These limitations and assumptions will remain the same throughout the modeling process to ensure comparable results are obtained.

a. Limitations

The limitations of the model are largely attributed to the limitations of the MANA program itself as well as the need to keep the model simple, yet realistic enough to draw relevant insights. The limitations of the model are listed below.

- The ships are not able to sail in battle formations, and elaborate set piece ship maneuvers cannot be modeled. Instead, the maximum distance between friendly forces is dictated by individual weights.
- The ship's sailing route is set using waypoints. The ships are not able to adapt to new situations and set new destination waypoints during the model simulation.
- Only tactical battles between the ships are modeled. Operational maneuvers such as power projection and sea basing are not modeled (Phase 0 staging and shaping operations).
- Flight path and trajectory of ASCMs are not modeled. The effective missile interception was modeled crudely by the probability of hit.
- Effect of command and control cannot be studied, as each unit is modeled to act independently of the group. This independence meant that degradation to a unit's combat effectiveness due to impairment of command and control and leadership functions cannot be successfully modeled using MANA.

b. Assumptions

The following assumptions are made for MANA modeling.

- Ship design, force structure, and capability requirements were generated based on a single tactical battle outcome.
- Campaign level scenarios were not developed.
- A single missile hit, regardless where it hits a ship, constitutes a "mission kill." In modern missile combat, the lethality of modern warhead would cause considerable reduction in mission effectiveness, even if the ship did not sink.
- The various missile probabilities of hit are summarized in Table 8 for U.S. capabilities and Table 9 for the PLAN. The probabilities of hit p_{hit} are rationalized with historical data from post-1982 missile combat (Schulte 1994). Based on historical data, $p_{hit} = 0.981$ for defenseless targets while $p_{hit} = 0.630$ for defendable targets. The value $p_{hit} = 0.75$ was selected in taking into consideration that historical victims are smaller ships.

Deviations from baseline are due to assumptions that advanced guidance and tracking systems in the missile would contribute to higher p_{hit}.

USN	WEAPON TYPE	P_{hit}
LCS	Anti-Sub	0.75
DDG	Missile	0.85
	Anti-Sub	0.75
	Anti-Air Missile	0.8
FFG	Missile	0.85
	Anti-Sub	0.75
SCS	Missile	0.85
SUB	Torpedoes	0.85
UAS	N/A	N/A
P-8	Torpedoes	0.85

Table 8. Assumed USN capabilities for modeling.

PLAN	WEAPON TYPE	P_{hit}
DDG	Missile	0.75
FFG	Missile	0.75
	Anti-Sub	0.75
PTG	Missile	0.75
SUB	Torpedoes	0.85
UAS	N/A	N/A

Table 9. Assumed PLAN capabilities for modeling.

- For ships that are hit, forward maintenance as well as port maintenance is irrelevant in the tactical battle outcome as these activities take a longer time than compared to the battle duration.

- Direct fire weapons such as naval guns and small arms fires are not modeled.
- Soft kill, hard kill and other missile countermeasures are not individually modeled, which keeps the model simple enough to gain insights on the impact of a missile battle. All of these capabilities are combined into the probability of hit metric.

5. Initial Results

After running the scenario using varying capabilities, a result summary was compiled in Table 10.

Run	# Ships	Network (Off:0) (On:1)	Missile Range (nm)	Salvo Size (Number of missiles)	Sensor Detection Range (nm)	Sensor Classification Range (nm)	BLUE Casualties (# of assets lost)	RED Casualties (# of assets lost)
1	10	0	60	2	30	15	20.5	10.8
2	10	0	60	2	45	22.5	20.7	9.3
3	10	0	60	2	60	30	20.9	8.7
4	10	0	60	4	30	15	20.6	10.6
5	10	0	60	4	45	22.5	21.1	6.1
6	10	0	60	4	60	30	8.7	3.2
7	10	0	90	2	30	15	5.9	1.3
8	10	0	90	2	45	22.5	6.5	1.5
9	10	0	90	2	60	30	5	1.7
10	10	0	90	4	30	15	6.7	3.3
11	10	0	90	4	45	22.5	6.9	2.9
12	10	0	90	4	60	30	4.9	3
13	10	1	60	2	30	15	13.8	7.0
14	10	1	60	2	45	22.5	13.5	5.7
15	10	1	60	2	60	30	10.5	9.1
16	10	1	60	4	30	15	13.6	5.2
17	10	1	60	4	45	22.5	12.2	5.8
18	10	1	60	4	60	30	12.6	9.2
19	10	1	90	2	30	15	6.7	1.2
20	10	1	90	2	45	22.5	5.6	1.5
21	10	1	90	2	60	30	5.6	1.3
22	10	1	90	4	30	15	7.0	1.7
23	10	1	90	4	45	22.5	3.5	1.2
24	10	1	90	4	60	30	5.1	1.2

Table 10. Summary of the original MANA trial runs.

The raw data in Table 10 was broken down by individual capability characteristics and then a regression analysis was performed. Each run in the table represents a different combination of the capabilities. In this initial data series, only 10 ships were analyzed (data series used for follow-on analysis can be found in Appendix C). The run number in the left hand column of Table 10 represents the combination of capabilities in the corresponding row. Each of the run combinations were evaluated 30 times (as discussed in Chapter V Section C.3.), and the average number of BLUE and RED casualties are calculated and reported in the "BLUE Casualties" and "RED Casualties" columns.

6. Analysis of Results

A regression analysis can help to identify the most significant variables following the initial trial runs. A complete analysis for each variable is found in Appendix C, and a result summary is found in Table 11. Four univariate models were used to analyze the data. In these models, the casualty ratio was used as the dependent variable. The primary method with which the regression results will be analyzed is by comparing the R^2 and F significance values. The R^2 value, or coefficient of determination, provides an indication of how close a particular data set correlates to a given statistical model. A R^2 value of one describes a data set that is a perfect fit to a statistical model. The F significance value provides a probability that any correlation between the data and the statistical model occurs by chance. A lower number generally signifies a more relevant variable.

Variable	F Significance	R^2
Networking	0.482	0.023
Missile Range	0.002	0.370
Salvo Size	0.320	0.045
Detection Range	0.421	0.030

Table 11. A summary of regression statistics for the initial MANA model run.

From the data in Table 11, the missile range variable appears to be more statistically significant than the other variables. The assessment of missile range is based on the R^2 value of 0.370 (which is nearly an order of magnitude higher than all other variables) and a F significance of 0.002. Graphical data evaluation was conducted to produce some additional insight. This graphical representation can be seen in Figure 22.

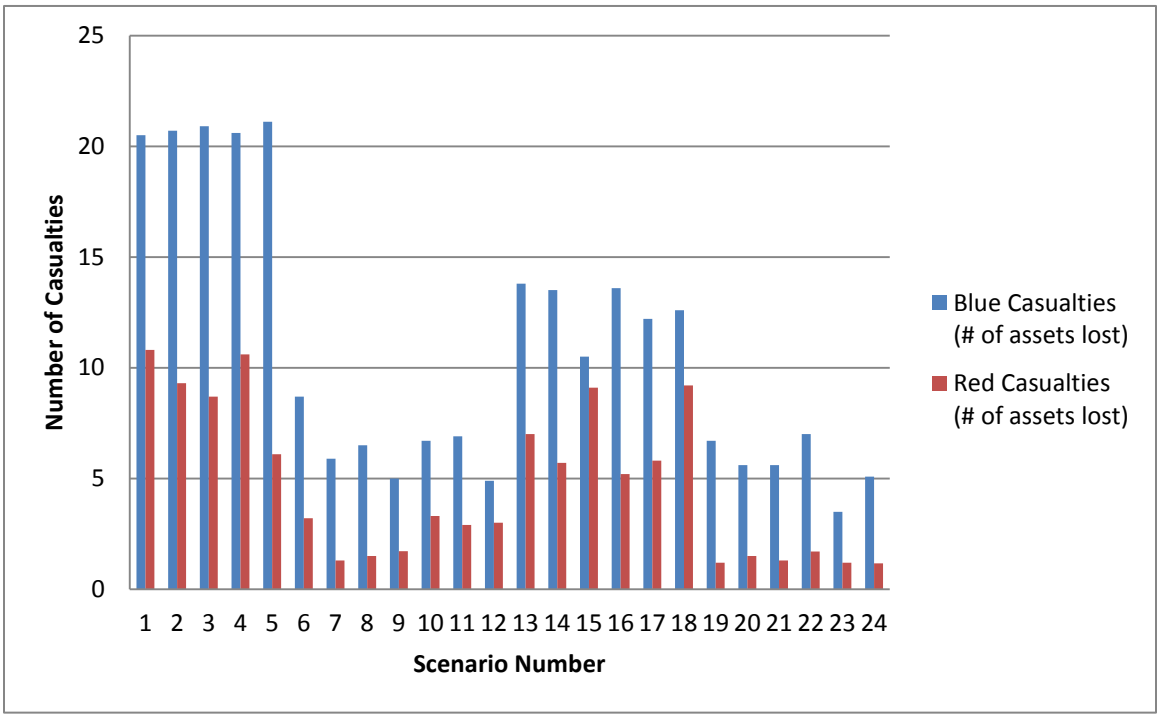

Figure 22. Plot of casualties versus MANA scenario number.

When analyzing Figure 22, some variables (or combination of variables) appear to influence the outcome of the engagement. Closer inspection provides a little more insight. In particular, runs 1–6 and 13–18 are runs in which the missile range is 60 nm, while runs 7–12 and 19–24 are runs in which the missile range is extended to 90 nm. A clear decrease in the number of U.S. casualties occurs when the missile range is extended. Similarly, runs 1–12 occur when networking is off, while runs 13–24 occur when some networking capability exists. On examination, it appears that the average number of U.S. casualties decreases when some form of networking exists within the group system. While the results of the regression analysis seen in Table 11 are inconclusive, the runs in

which a reduced number of U.S. casualties occur can be visually correlated to the extended missile range and, to a lesser extent, the presence of networking. This decrease in casualties may be explained by the increase in effective sensor range experienced by individual flotilla ships that would be provided through networking capability. More result context is provided in Figure 23.

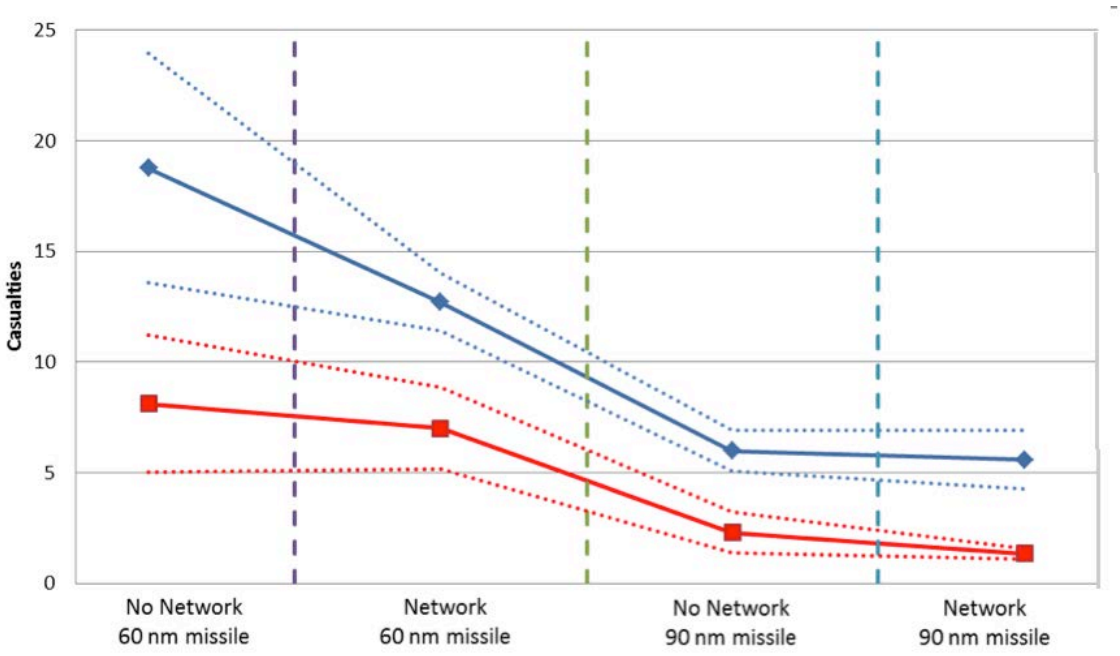

Figure 23. Graph of casualties versus networking and missile range.

To further expand on the impact of missile range and networking, the average U.S. and RED casualties for the runs in which the networking and missile ranges varied was calculated. The results can be seen from analyzing Figure 23. In addition to the average U.S. and PLAN casualties, the 95 percent confidence interval used for the data set is also displayed to provide statistical relevancy to the data. As expected, the number of U.S. casualties decreases when networking is applied and when the missile range is extended. Not so intuitively, however, is that the number of PLAN casualties also decreases. This reduction in PLAN casualties requires additional consideration and is the

result of this initial model's stopping criteria, which will be discussed in the following section.

7. Issues Encountered

Several issues become immediately apparent with the first model run results. For starters, the number of U.S. casualties decreases as the individual variables improve. This decrease in U.S. casualties is desired, as decreasing casualties can generally be categorized as an improvement in efficiency and effectiveness. A simultaneous decrease in PLAN casualties as these variables improve, however, raises questions about the effectiveness of the U.S. force capability improvements. An in-depth model and result evaluation reveal the following issues: the model run time is insufficient to gain all of the pertinent insights, e.g., overall attrition rates and time of engagement, combined with few surface on surface engagements occurrences during the duration of the battle. The reasons for these issues will be elaborated next.

a. Model Run Time

The stopping conditions for the model (the conditions that end the simulation should they occur) are:

- all U.S. ships are eliminated,
- all PLAN ships are eliminated,
- any PLAN ship reaches the Spratly Island objective, or
- any PLAN capital ship (a DDG for this model) is destroyed.

The first two of these stopping conditions make intuitive sense, as the purpose of the flotilla group in this scenario is to deny access to the Spratly Islands to the PLAN. The last condition is implemented as a deterrent threat. If the PLA understands that the flotilla force is capable of inflicting a serious blow to the PLAN fleet, the possibility alone may deter them from initiating such action. The "destruction of any PLAN DDG" stopping condition ends the conflict "early," preventing analysis of attrition rates for the overall battle. As the U.S. sensor ranges and missile ranges are extended in the model, the likelihood of a PLAN DDG being eliminated earlier in the scenario, thus ending the scenario more rapidly, increases.

b. Minimal Surface on Surface Engagements

As stated in Chapter V Section C.2, the PLA force consists of a combination of air, surface, and undersea assets. The main goal of the model was to determine the effectiveness of a small combatant ship flotilla, with the understanding that its desired single mission capability would leave it vulnerable to other domains of warfare. Minimal ASW and AAW capabilities exist in defense of the flotilla group. Another goal of the model was to determine the defensive capabilities the small surface combatant and other support ships must have to increase the survivability and mission effectiveness of the overall armada. Without this additional support, however, the majority of U.S. casualties occur from PLA submarines and air assets before any surface combat can occur. The effectiveness of the PLA air and subsurface assets provide incredible insight, but does very little for evaluating the effectiveness of a surface combatant against enemy surface combatants.

D. REVISED SPRATLY ISLAND RUNS

Several issues are identified in the original model setup. Some modifications are required to ensure the relevant data can be obtained.

1. Modification to Model

The initial model produces very minimal surface combatant versus surface combatant engagements. Instead, the majority of the U.S. ships killed are the result of engagement by PLAN air and subsurface threats, which occur well before the surface ships close within weapons range of each other. The object of the model is to determine the required capabilities of a surface combatant; thus, all submarines and enemy air forces are removed from subsequent models. While this exclusion of forces is certain to bring up some questions about the relevance of the results (as it is reasonable to assume that air and subsurface components would certainly exist in this scenario), it will provide a base capabilities requirement for a surface combatant in a surface warfare engagement by isolating the variables associated with surface combat. A method of addressing the air and undersea threats will be required as a system of systems process.

Another notable result from the original model is that the scenario typically ends prior to any relevant data being obtained. During the scenarios in which surface on surface engagements do occur (most notably when the sensor and missile ranges are at the assumed maximum), the stopping condition of one DDG being eliminated is usually satisfied early on. While this early termination does provide valuable insight, it prevents obtaining a complete picture of a full-scale assault. If the idea of the SSC is provide a credible threat, then understanding the entire sequence of events and outcomes is important. Removing the stopping condition of one PLAN DDG killed is a way forward in achieving this evaluation. A screenshot of the revised MANA model is displayed in Figure 24.

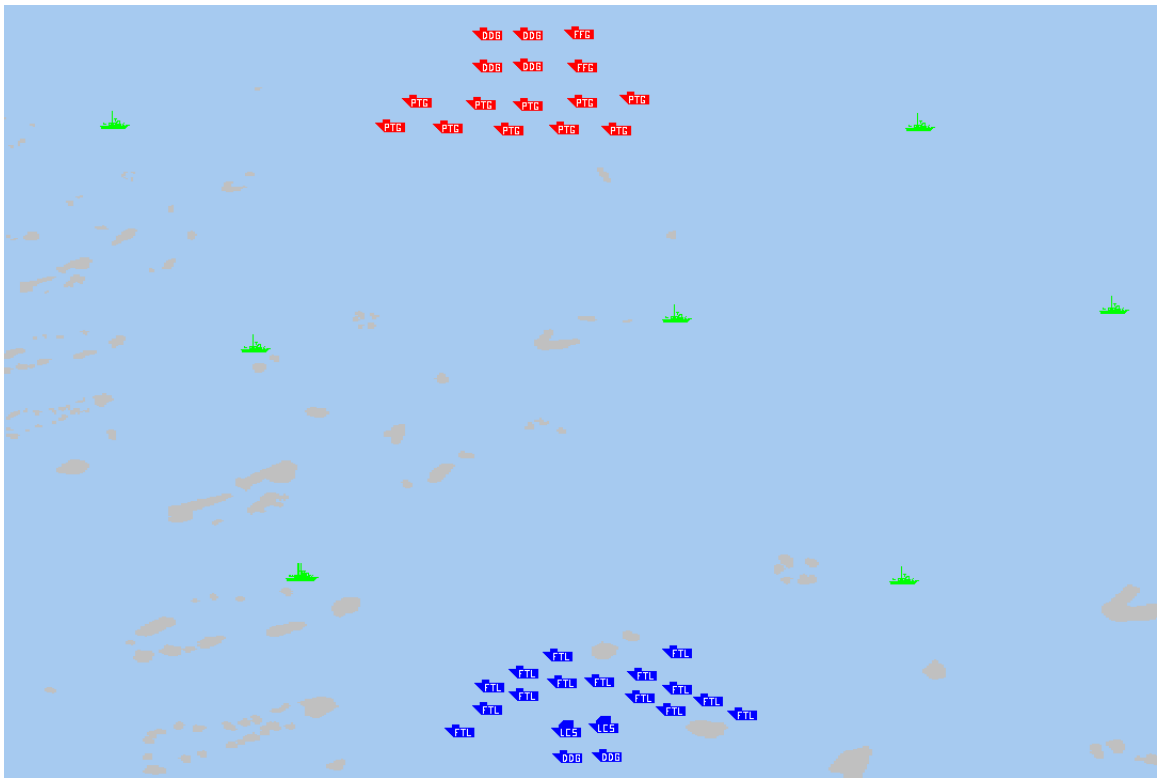

Figure 24. Revised MANA model scenario image.

Aside from less units involved in combat, all other aspects remain the same. 15 SSCs are depicted in Figure 24, but the actual number varies with the different scenarios.

2. Model Results

Runs 1–48 of the revised Spratly Island scenario allow us to evaluate the effectiveness of the SSC without any networking capability. Runs 49–96 evaluate the effectiveness of the SSC with limited networking capability applied. These results can be found in Appendix C. The raw data is broken down by individual capability characteristics and a regression analysis is performed. We accomplished four univariate regressions, each with response variable given by casualty ratio.

3. Analysis of Results

Regression analysis of the results obtain in Chapter V Section D.2 was again conducted to determine the most significant variables. The full regression analysis can be found in Appendix C. A summary of these results can be found in Table 12. Again, as explained prior to the previous regression analysis, a higher R^2 value and a lower F significance are good indicators of a variable that is significant and relevant.

Variable	F Significance	R^2
Number of Ships	0.972	0.000
Networking	0.695	0.002
Missile Range	0.899	0.000
Salvo Size	0.917	0.000
Sensor Range	0.000	0.732

Table 12. Summary of the regression analysis.

The only factor that provided any real relevance to the overall outcome of the engagement was the sensor detection/classification range. An initial evaluation of the raw data shows that a significant improvement in the casualty ratio occurs when the sensor detection range is extended beyond 45 nm. A graph of these results can be seen in Figure 25, which is sufficient to observe the correlation regarding the impact of sensor range on the armada efficiency.

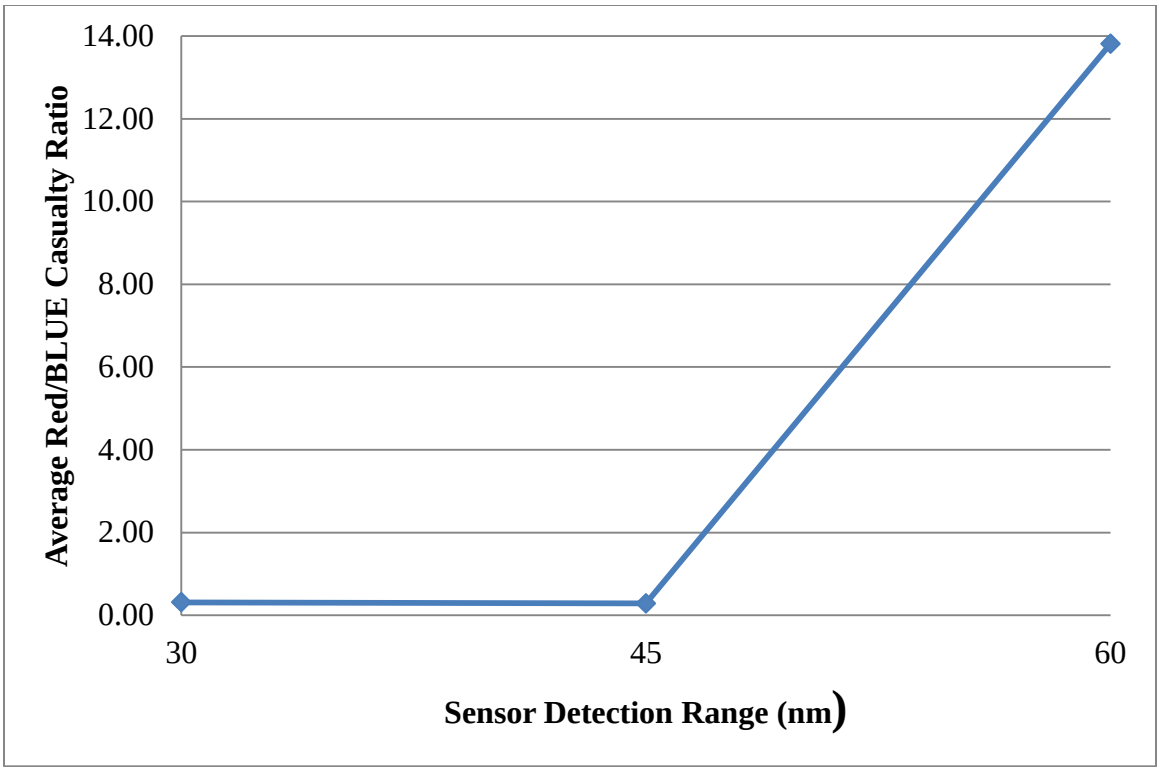

Figure 25. Graph of average casualty ratio versus sensor detection range.

As seen in Figure 25, a rapid increase in the casualty ratio occurs when the sensor range is extended beyond the 45 nm range. Increasing force efficiency with longer attack ranges is not a new concept. The magnitude of this increase, however, is made very clear when looking at these model outputs. The significance of this range is that the last data point of 60 nm is further than the range the enemy is capable of achieving. *The biggest takeaway from this analysis is that the ability to fire effectively first at an adversary is far more important than any other single factor.*

4. Optimal Force Structure and Capabilities

From the analysis, it becomes clear that the most significant factors in maximizing efficiency of the force are sensor range and missile range, with all other factors contributing very little to the outcome of the engagement. From this insight, a force structure and capabilities requirements recommendation can be made. This force structure with given capabilities is capable of achieving mission success in each modeled scenario. Each armada should have 15 SCS, with each SCS carrying eight long-range

surface-to-surface missiles. Each missile should have an effective range of at least 90 nm (this is a minimum, but the range should correlate to the maximum sensor range). The ship should be capable of firing two missiles per salvo. The ship should be capable of obtaining a minimum speed of 25 knots. The minimum detection range of the sensor system should be 60 nm, and the minimum classification range should be 30 nm. As described in Chapter V Section D.3, longer ranges may be achieved using external sensor systems, and increased detection and classification ranges only enhance the combatant ship performance. Finally, a robust networking system is not required. More specifically, the ability to share targeting information is not needed, but communicating with possible external sensor systems is required.

5. Refinement of Sensor Range evaluation

After determining the force structure and capabilities in Chapter V Section D.4, a more detailed analysis of the impact on sensor range to the casualty ratio can be conducted. This evaluation is conducted with only the optimal force structure and capabilities, as evaluation of smaller range increments for all possible variable combinations would take a substantial amount of time and manpower.

As identified in Figure 26, some significant increase in effectiveness of the flotilla group occurs somewhere between a 45 and 60 nm sensor range. To determine where this transition occurs, the force structure and capabilities were evaluated at 1.5 nm sensor range increments between 45 and 60 nm. The results of this evaluation can be seen in Figure 26.

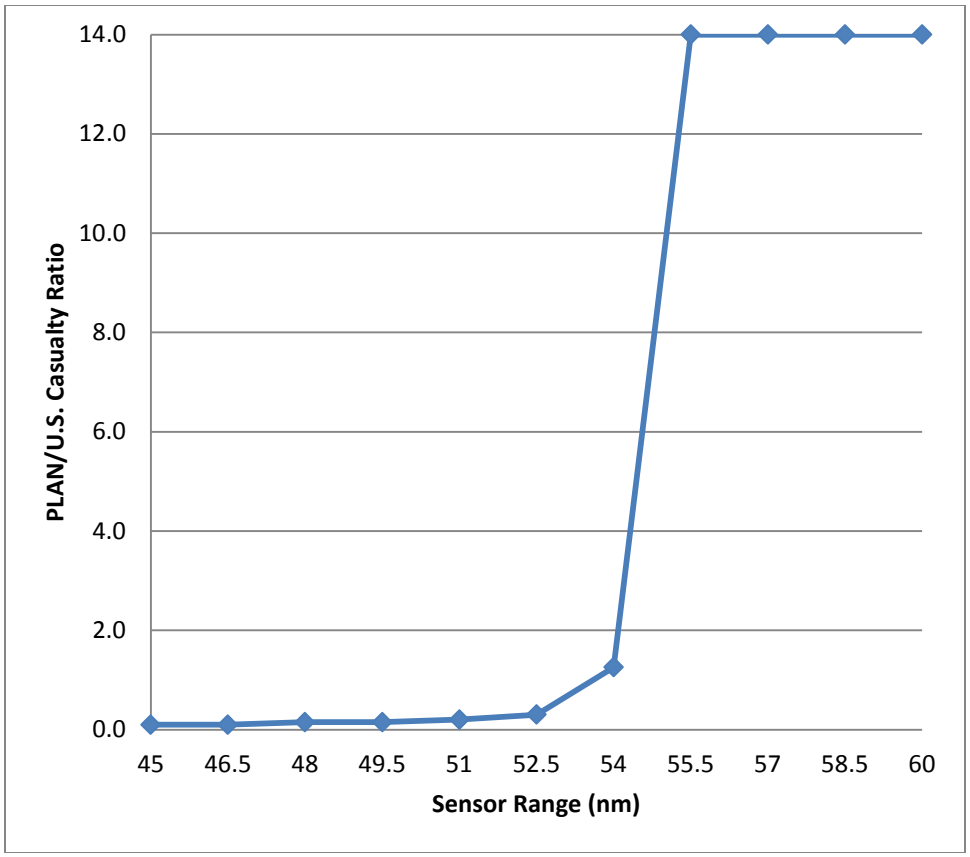

Figure 26. Refined casualty ratio versus sensor range plot.

A large U.S. force efficiency increase occurs when the U.S. sensor range is extended beyond 55 nm. A less significant increase in efficiency can be noted when the U.S. sensor range is extended beyond 50 nm. One assumption made during the modeling process was that the PLAN sensor detection range was 50 nm. As the U.S. sensor range is extended beyond that of the adversary, the effectiveness of the flotilla rapidly increases. The major takeaway from this observation is that extending the sensor range beyond that of the adversary has significant impacts on the outcome of the battle.

E. REINTRODUCTION OF UNDERSEA AND AIR DOMAINS

In all previous model runs subsequent to the initial trials, PLAN submarines and aircraft are removed to determine the SSC effectiveness in a surface-on-surface engagement. This is assumption is highly optimistic, however, and some analysis must be conducted to determine the impacts of these multi-domain threats.

1. PLAN Submarines with Minimal U.S. ASW Capabilities

The first scenario that requires analysis is one in which PLAN submarines are introduced with no effective U.S. anti-submarine warfare (ASW) capability. In such a scenario, it is assumed that no additional ASW assets are allocated to the armada, and only those ASW capabilities inherent to the original force structure are present.

To maximize the value of data gained from this modified scenario, the best force structure and capabilities (as determined from in Chapter V Section D.4) are used. PLAN submarines are introduced to the simulation one at a time to determine the impact on the recommended force structure. The results of this analysis can be found in Figure 27.

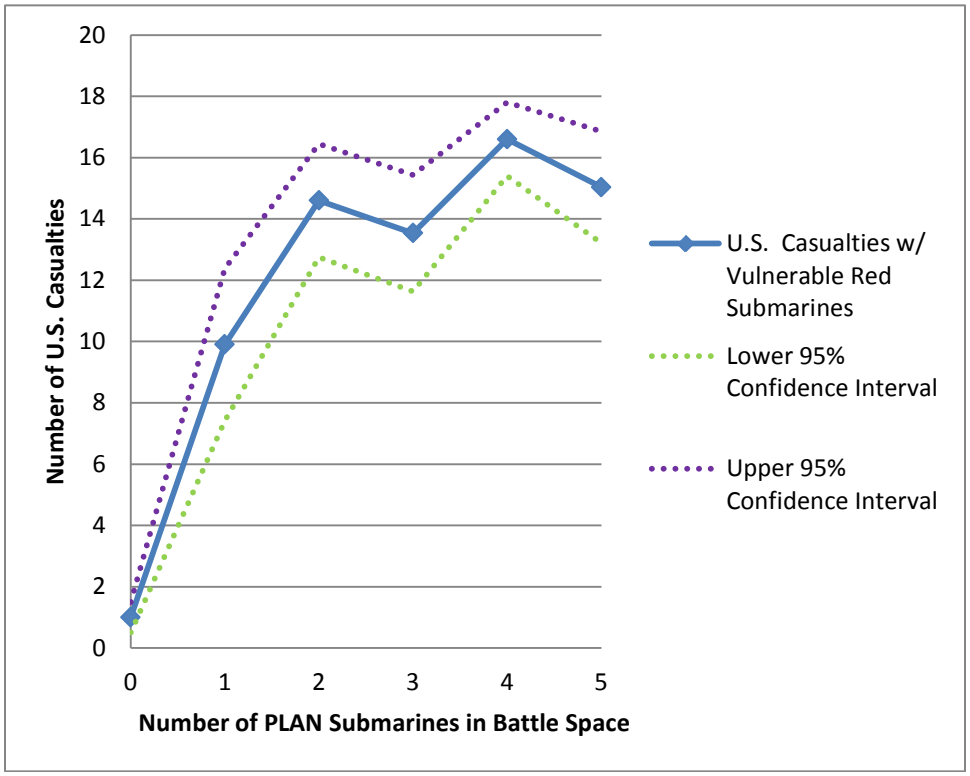

Figure 27. U.S. casualties versus added PLAN submarines (no ASW capabilities).

The first data point in Figure 27 represents the average number of U.S. units lost when no PLAN submarines were present. In this scenario, the armada is assumed to have no ASW capability. This capability gap is implemented by giving the U.S. forces a five

percent probability of detecting the PLAN submarines (regardless of the actions of the submarines). The addition of PLAN submarines results in an expected increase in U.S. forces lost. At four submarines, the number of U.S. forces lost remains constant, with nearly every unit being killed and the PLAN forces reaching their Spratly Island objective.

The results from this scenario are expected, and it is entirely feasible to expect PLAN submarine forces to be engaged in this combat scenario. *The major takeaway from these trials is that the armada cannot survive in the Spratly Island combat scenario if PLAN submarines are engaged without some additional ASW capability*. Evaluation of the scenario with some ASW capability may provide additional insight into the scenario.

2. PLAN Submarines with Additional U.S. ASW Capabilities

The second scenario that requires analysis is one in which PLAN submarines are introduced and additional effective U.S. ASW capabilities are present. This ASW capability can be obtained from inorganic ASW air assets, organic ASW sensors, or additional assets in the system (such as the ASW mission package on the LCS).

The best force structure and capabilities (as determined from Chapter V Section D.4) are used. PLAN submarines are again introduced one at a time to the simulation to determine the impact on the recommended force structure. The results of this analysis can be found in Figure 28.

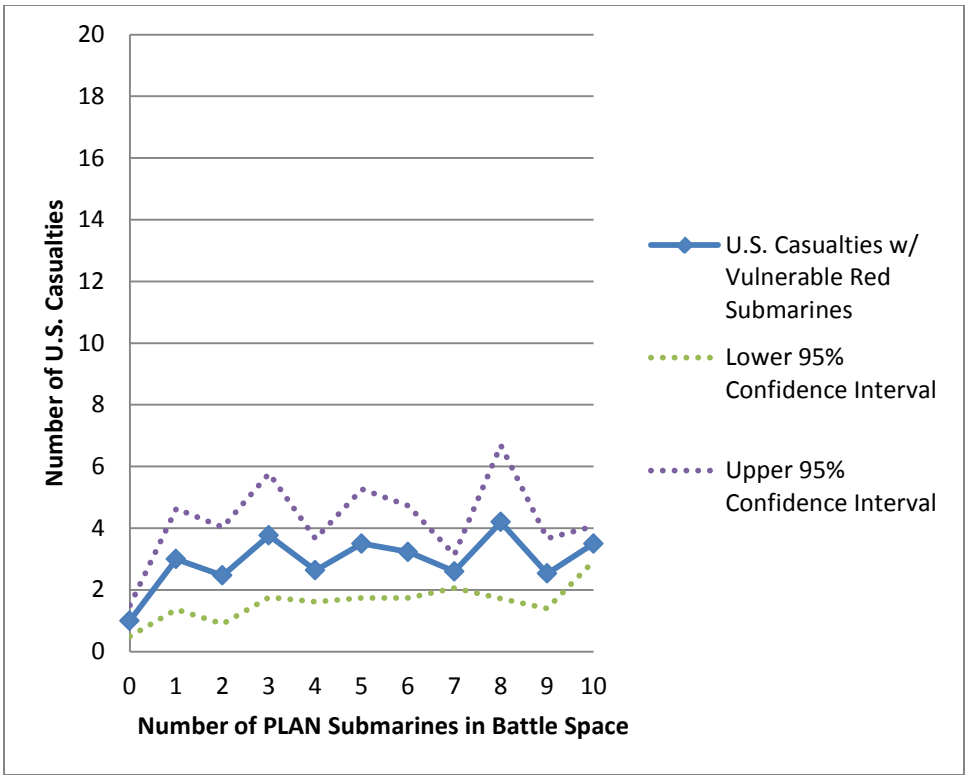

Figure 28. U.S. casualties versus added PLAN submarines (ASW capabilities).

The first data point represents the average number of U.S. casualties observed when no submarines are present. In this scenario, the armada is assumed to have some ASW capability. Initially, the PLAN submarines have the same low probability of detection (5 percent) as in the previous model. After the submarine engages, however, the probability of detection is increased to 70 percent and the submarine becomes vulnerable to attack. The addition of one submarine results in the average number of U.S. casualties increasing notably. Further increasing the number of submarines, however, does not result in significantly larger casualties. This result is not intuitive and may require further analysis.

The results observed from this scenario are insightful, as they show the necessity of additional ASW capabilities within the armada system. This capability can be inherent to the small surface combatant or contained on additional external units. Either way, it is necessary for the survivability of the armada in a submarine scenario.

3. PLAN Aircraft

The next scenario that requires analysis is one in which PLAN offensive aircraft are introduced and no additional AAW capabilities are present. The best force structure and capabilities are again used. Offensive PLAN aircraft are introduced one at a time. The results of this analysis can be found in Figure 29.

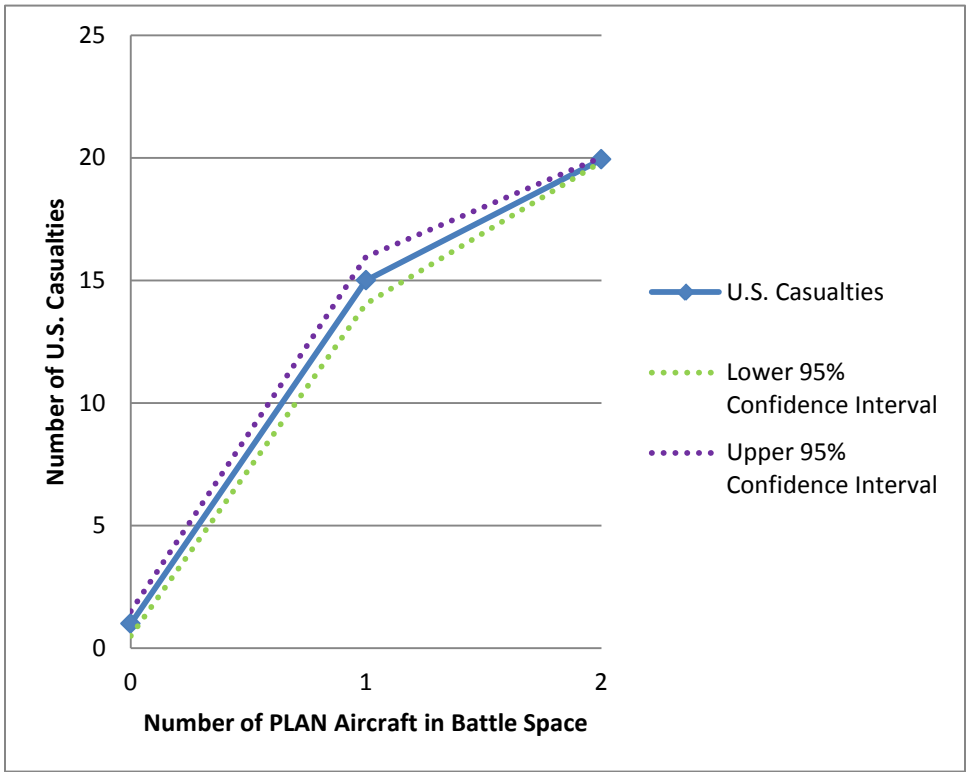

Figure 29. U.S. casualties versus number PLAN aircraft.

The first data point represents the average number of U.S. casualties observed when no PLAN aircraft are modeled. The addition of the first aircraft results in very significant increases in U.S. casualties. The addition of an additional aircraft results in complete destruction of the U.S. forces.

The major takeaway from this analysis is that the SSC is susceptible to enemy air warfare, and some support is required to ensure their continued survivability in a combat scenario.

F. ADDITIONAL SCENARIOS

The best force structure size and capabilities are proven to be effective in the Spratly Island scenario. An analysis of the same force's effectiveness can be conducted in other threat areas to determine force interoperability in other regions.

1. Strait of Malacca

This scenario aims to determine how the proposed force structure and design will operate in narrow waterway. Typically, straits are flanked on both sides by land. This proximity to land presents additional complications, such as land launched ASCMs and small arms, which are not specifically addressed in this analysis. In order to evaluate the effectiveness of the SSC and the armada as a whole in a surface-on-surface engagement, some assumptions must be made.

a. Scenario Assumptions

To focus the derived force structure and capability performance in the Strait of Malacca scenario, the model had the following overarching assumptions.

- The land masses near the SOM are assumed to be sovereign and neither the U.S. military nor the PLA forces have additional assets deployed which are able to affect the naval battle outcome.
- The littoral states in the SOM do not provide any form of military support or interference for either the U.S. military or the PLA.
- The USN and PLAN forces are engaged in a force on force engagement in the SOM. Neither side had the relative advantage of being pre-deployed in the area.
- The airspace above the SOM is available for use for both USN and PLAN.

With the assumptions listed above, the modeling effort has ensured that the application of the baseline model to the SOM scenario is fair and realistic. The model isolates the other operational complexities associated with a strait environment. The assumptions attempt to simplify and focus the effort to determine how forces operating in close proximity in a confined waterway perform.

b. Model Results

Similar to all other scenarios run, the Strait of Malacca model scenario was run 30 times with the same force structure and capabilities. The raw data can be seen in Appendix C. The results obtained during this scenario were very similar to those obtained during the Spratly Island scenario. Specifically, in nearly every scenario, all PLAN forces were destroyed while nearly no U.S. casualties occurred. In the worst run of the 30, three U.S. SSCs were lost. These results help to validate the idea that the optimal force structure is capable of operating in multiple threat environments effectively.

2. Persian Gulf Scenario

Another likely theater in which the SSC may be employed is the Persian Gulf. Operation in the region will present many of the same complications that operation in a strait presents. Several assumptions must again be made to ensure the relevant data is obtained.

a. Scenario Assumptions

The optimal force structure and capabilities for the U.S. forces were used, and the opposing forces were modified to better approximate the force structure of likely enemies in the area. These RED forces consist of small combatants, frigates and corvettes, and were modeled in large numbers, as it is likely that the enemy would attempt to swarm the allied forces during this scenario. The RED force was composed of 10 frigates and 20 corvettes. This force structure is based on one-third of the current Iranian fleet, assuming they are the most capable adversary in the region.

b. Model Results

Similar to all other scenarios run, the Persian Gulf model scenario was run 30 times with the same force structure and capabilities. The raw data can be seen in Appendix C. Based on the geography of the region (very wide and open with little natural impediments), very little restriction in maneuverability was encountered. The average number of U.S. casualties incurred was less than one (similar to previous scenario results), while the average number of enemy casualties was approximately 25.

3. Analysis of Results

It has already been identified that the flotilla must be capable of engaging the enemy forces first. The additional scenario simulations support that with longer effective targeting and engagement range, the flotilla forces are highly dominant. Even outnumbered, the armada generally sank most of the enemy forces with minimal loss. These results reinforce the concept that the best force structure and capabilities (identified in the Spratly Island scenario) are sufficient to engage a credible threat in the Strait of Malacca and the Persian Gulf.

G. COMBAT MODELING SUMMARY

Modeling is an invaluable tool in evaluating capabilities and combat effectiveness. For this analysis, modeling and simulation was used to identify significant capabilities requirements for the individual SSCs, to identify a desired number of SSCs, and to discover the support ships required to augment the flotilla within the armada system of systems concept.

First, the model helped to identify the importance of firing effectively first. To ensure this capability is achieved, the SSC must have a sensor range of at least 60 nm. This capability may be achieved by deployment of external sensor systems, such as unmanned vehicles, manned aircraft, or space systems. While achieving this relatively long sensor range does not require any organic sensor capability (the external sensor may be launched from a separate platform with the ability to communicate the data to the SSC), providing the SSC with the ability to organically deploy the sensors will increase each unit's flexibility and interoperability.

Second, the SSC must be able to deploy a missile with the capability of effectively engaging an enemy combatant at the maximum range the sensor system. The results of this model indicate that the missile should be capable of effectively engaging a target out to 90 nm. Realistically, any effective range greater than that of the sensor used to target the enemy is overkill, and would most likely result in an increase in cost with no corresponding increase in capability. However, we include the excess range to ensure we

are able to capitalize on any further sensor enhancement, either organic to the ship or off-board.

Third, the SSC should be capable of launching two missiles per salvo. No increase in effectiveness of the combatant was noted when salvo size was increased, so investing money in this larger salvo size capability will not produce any substantial increase in effectiveness of the combatant.

As far as capabilities are concerned, the last major takeaway is that networking within the individual combatants is not required. As long as all SSC are capable of receiving targeting information from their associated external sensors, relaying that targeting data to other ships in the armada does not significantly improve the system effectiveness.

To obtain the most return on investment, the flotilla should consist of 15 SSCs. Any more than 15 ships provide minimal increase in efficiency or effectiveness of the flotilla for the threat presented in the Spratly Island scenario.

Finally, the armada must consist of ships that can provide anti-submarine and anti-air warfare capabilities. Adding these capabilities to the SSC would unnecessarily increase the size and cost of the ships. The small surface combatant must operate within the armada system of systems to provide the maximum offensive capability with maximum survivability.

H. LOGISTICS MODEL

The methods used to provide logistic support to ships of today's U.S. Navy are adequate for open-ocean and unopposed environments. However, future conflicts may bring with it the need to operate deeper in regions blanketed by anti-access area denial (A2AD) systems. This need to operate in contested areas introduces substantial risk, however, as logistics ships may become attractive targets for these area denial systems. Ships such as the Lewis and Clark-class T-AKE and Supply-class T-AOE currently provide significant refueling capability. However, these logistic ships' larger size and slower speed can make them vulnerable to detection and engagement by long-range

ASCM and ballistic missiles. One method of reducing the risk is to introduce the concept of the intermediate fuel ferry.[2]

The fuel ferry concept is premised on a large traditional logistics ship, such as a T-AKE, to transport the fuel and supplies from the central supply point to an area outside A2AD effective range. Once outside A2AD range, the fuel and supplies are transferred to a small logistics ship (the intermediate fuel ferry). This much smaller logistics ship is faster, making it difficult to detect and engage by distant area denial systems. The smaller logistics ship transports the fuel and materials into the A2AD environment, introducing substantially less risk to the cargo and ultimately the mission. This concept can be visualized in Figure 30.

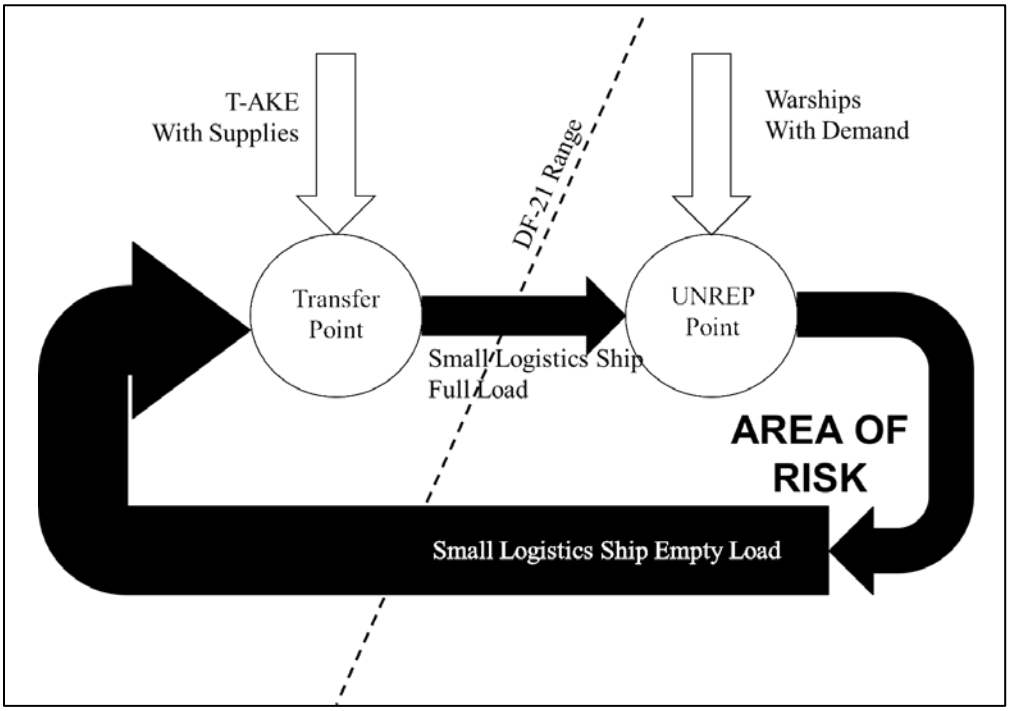

Figure 30. Fuel ferry concept.

[2]A fuel ferry is envisioned as a vessel similar to the Joint High Speed Vessel (JHSV) which has been designed to carry fuel in addition to cargo. It should have some stealth characteristics and would have a fuel capacity of 210,000 gallons of fuel.

In Figure 30, the T-AKE brings the cargo (fuel and materials) from an established supply depot significantly outside the A2AD boundary. Guam is the primary supply depot used for all problem analysis, but several other depots are available (e.g., Australia, Singapore, Philippines). Prior to entering the effective range of the A2AD system, a portion of the load is transferred from the T-AKE to the small logistics ship (up to the capacity of the smaller ship). The small logistics ship approaches the designated UNREP point inside the A2AD region, taking care to blend in with the surrounding commercial and fishing vessels. The small logistics ship then transfers the available cargo to warships operating within the A2AD range. Once the transfer is complete, the logistic ship travels back outside of the A2AD range and repeats the process.

The need for a stealthy intermediary fuel platform to transfer fuel between the T-AKE and the combatants is vital for the fuel ferry concept to succeed. The ability to blend in with the surrounding environment greatly reduces the risk of detection and engagement. This blending capability may be achieved through decisive maneuvering and navigational tactics, effective electronic warfare, and a minimally projected radar cross section. Speed of the fuel ferries will also be instrumental in minimizing any exposure of the ferry to the A2AD danger since the ability to quickly egress the area after completing the fueling operations may be an essential risk reduction tactic. The Joint High Speed Vessel (JHSV), a modified Littoral Combat Ship (LCS), or an entirely new class of ship could meet the small logistic ship requirements. An illustration of this concept is shown in Figure 31.

Figure 31. The SEA-20A logistics visual depiction of the concept (after Google 2014).

1. Background

Military logistics have been in existence as long as there have been standing armies, as early as 700 BC with the Assyrians (Antill 2001). Alexander the Great used the sea to transport supplies to fuel his conquest into India. As ships converted from sail to steam, the need for ability to fuel the ships was apparent. As coal gave way to fuel oil, the Navy began refueling at sea training. During World War II, extensive use of refueling and resupplying at sea allowed the U.S. Navy to operate away in areas away from friendly ports such as the Western Pacific and the North Atlantic. This at-sea refueling and resupply capability enabled significant reach and more importantly staying power for these ships (Antill 2001). Current naval ships and aircraft require continuous, coordinated, and strategically located logistic support as they conduct deployments worldwide. Therefore, it is prudent to explore how logistics may affect all operational levels.

2. Model Selection

Various modeling tools were used to gain insight into the armada logistics requirements. Some of the tools and techniques considered include queuing theory,

discrete event simulation, and optimization. The Simulation Modeling framework based on Intelligent Objects (SIMIO) package was selected due to the modeling team's access to professors with SIMIO experience, and ease of displaying the model and results. Also, SIMIO provides for the assignment of probabilistic or deterministic values to various aspects of the supply chain. Some of these variables include in modeling are ship speed, fuel transfer time, fuel capacity, and fuel usage (burn) rate.

The SIMIO software allows the user to not only set the distances of each transit leg, but also overlay the legs onto a map image to promote a complete understanding of the operational scenario. The software also allows for the user to conduct multiple simulations in a single experiment, and to generate output data that can be exported and displayed in Excel. SIMIO automatically creates data that is often useful in analyzing issues with current supply assets and operations (Kelton, et al. 2011). For example, the SIMIO modeling software provides idle times, quantity of goods transported with the supply chain, and the number of times the various vehicles (T-AKE, JHSV, and combatant) travel on a particular path.

An issue faced with SIMIO was the need for significant computer memory and processing time. This need was particularly evident for the model size increased. The computers that hosted the SIMIO software for this project were at times unable to run more than 30 simulation replications. Regardless, a minimum of 30 replications of each simulation experiment were performed. This number of replications permitted Central Limit Theorem use to compute simulation results confidence intervals (Ross 2009).

3. Parameter Research

Prior to utilization of SIMIO, the values that established fuel burn rates, SSC fuel capacity, and the number of logistic ships required to support the flotilla were calculated. Transit speeds for BLUE forces in the model vehicles (T-AKEs, fuel ferries, and combatants) were modeled with a triangular distribution around estimated minimum transit, cruising, and sprint speeds. Triangular distributions were also used due to for product transfer rates. This distribution function increased model simplicity and provided sufficient fidelity (Brighton Webs Ltd 2013).

Fuel burn rates in the model depended on the ship's speed, which in turn depended on whether the ship was in transit or engaged in combat. The endurance patrol speed is a constant 15 knots. Combat speeds are from a triangular probability distribution based on speeds of five, 15, and 35 knots. A probability density plot of the triangular distribution is shown in Figure 32.

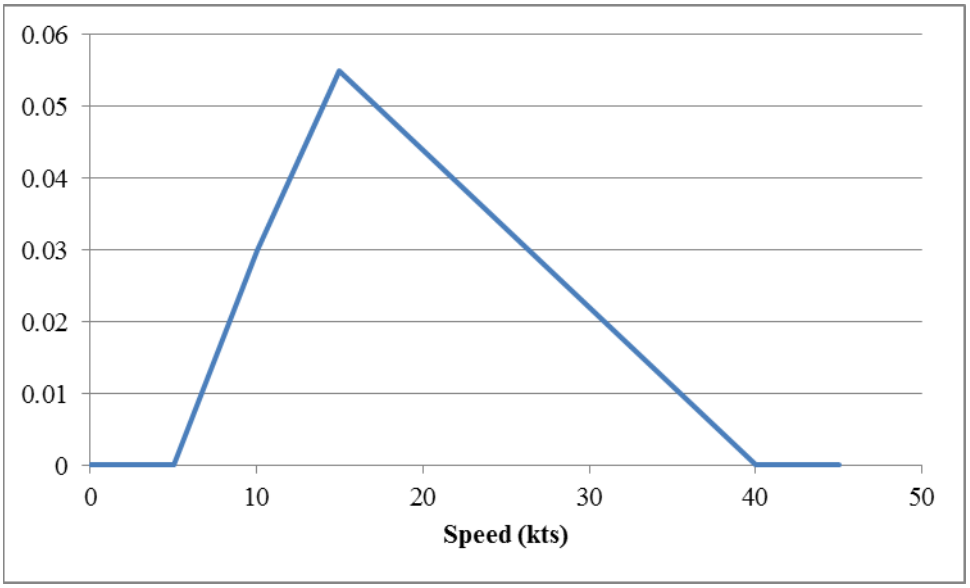

Figure 32. Triangular PDF for combat speed.

The number of T-AKEs and fuel ferries was established using fuel burn rates, a replenishment point of 50 percent total fuel capacity, and the combatant's fuel capacity. The results show that one T-AKE and one fuel ferry prevented the need for significant numbers and/or tonnages of ships. This finding led to the decision that four of each would be used to supply the flotilla.

a. Vessel Characteristics

After evaluating current and projected ship classes for the logistics train, the focus was narrowed down to the Lewis and Clark class T-AKE and the Joint High Speed Vessel (JHSV) as components for the logistic ship primary design. The following data was used as input parameters for SIMIO (F. Papoulias 2014b).

- Supply ship data (T-AKE): 7,000 metric tons of dry cargo and ammunition and 23,500 barrels of marine diesel fuel (987,000 gal) (Saunders 2013).
- Fuel ferry data (JHSV): Payload baseline: 635 metric tons (approximately 210,000 gallons of fuel) (Saunders 2013).
- Fuel (Diesel Marine): 7.2 lbs. per gal (.003 metric tons) and 42 gallons per barrel (Becker 2013).
- Missiles (LRASM/JAMM-ER): 2200 lbs. (0.997 metric tons) (Oestergaard 2014).
- Food: 0.75 lbs. per person per day.

These vessel values were used to determine the individual SSC's required logistics capacity, and were applied to SIMIO as logistic transport ship values along with burn rates, transit and transfer speeds, and transport distances.

b. Equation Definitions

This section defines the variables that will be used in the following sections to determine fuel burn rates and ship fuel capacity. C_1 is the fuel burn efficiency. The choice of a diesel engine would equate to $C_1 = 0.4\, lbs/hr \cdot hp$. If gas turbine engines were chosen, the new fuel burn efficiency would be $C_1 = 0.35\, lbs/hr \cdot hp$. A second variable C_2 is the constant of proportionality that one can get from similar ships which establishes the following (F. Papoulias 2014a):

- power is force times speed,
- force (resistance) is proportional to wetted surface and speed-squared,
- wetted surface (ft^2) is proportional to $volume^{2/3}$ (ft^3) to make the dimensions match,
- volume is proportional to weight (displacement), and
- $C_2 = Horsepower \big/ \left(Displacement^{2/3} \times Speed^3 \right)$.

The information used to generate Table 13 is from (Saunders 2013) and construct from (F. Papoulias 2014a). For the scenario, C_2 varies between $0.008 - 0.018\, hp/kts^3 \cdot lbs^{2/3}$ for 100–1000 ton ships and $0.016\, hp/kts^3 \cdot lbs^{2/3}$ for ships 1000 ton and larger. Fuel specific weight (FSW) of marine diesel fuel is $7.2\, lbs/ga$

(Becker 2013). From the visual data representations in Figure 33 and Figure 34, we can analyze the effect of speed and tonnage on various ships' endurance.

Nation	Ship Class	Installed Power	Speed (kts.)	Displacement (lbs.) (full load)	Displacement (MT) (full load)	C_2
US	WW2 U.S. MTB	3600	39	123424	56	0.00415
Germany	WW2 S-boat	3960	35	209380	95	0.00444
Germany	WW2 S-boat	6000	39.5	238032	108	0.00429
Germany	WW2 S-boat	6150	37	253460	115	0.00513
US	Island	12492	29	377000	171	0.01663
Venezuela	Constitución class	12000	31	381400	173	0.01297
Iran	Houding	24075	35	454024	206	0.01610
US	Asheville	12500	35	527000	239	0.00757
Columbia	PC145	5150	22	539980	245	0.01235
Bangladesh	Padma	6265	23	595080	270	0.01233
India	Rani Abbakka class	32526	34	615000	279	0.01938
Cape Verde	P511	5800	23	639160	290	0.01088
S. Korea	Sea Wolf	14640	25	694260	315	0.02024
Angola	Rei Ekuiki II	4732	20	709688	322	0.01259
Sri Lanka	Jayesagara Class	4360	15	738600	335	0.02678
US	Sentinel	11520	28	791400	359	0.01039
US & Philippine	Cyclone class	53600	35	848800	385	0.02362
Malta	Diciotti class	12670	23	879600	399	0.01921
Nambia	Oryx	4000	14	910252	413	0.02629
S. Africa	Warrior	15000	32	963148	437	0.00795
Iran	Hendijan	12200	21	985188	447	0.02253
Latvia	Valpas	2000	15	1221400	554	0.00878
S. Korea	Taichung	30940	30	1388520	630	0.01559
S. Korea	PC 501	19200	24	1432600	650	0.01851
Faroe Island	Tjaldrid	4800	15	1454640	660	0.01876
Spain	Rio Tajo	3800	12	1503128	682	0.02838
Taiwan	WPSO	39700	30	1567400	711	0.01846
Morocco	OPV 70	10730	22	1763200	800	0.01169
Germany	Bad Bramstedt	7000	22	1791852	813	0.00755
Taiwan	Shun Hu 2	2500	16	1877808	852	0.00679
Trinidad	Nelson	11280	17	2071760	940	0.02393
Sweden	KBV 181	7510	16	2219428	1007	0.01825
Romania	Damen OPV	13720	21	2265712	1028	0.01454

Table 13. Worldwide ship data used to calculate C_2 for 100–1000 ton displacements (after Saunders 2013).

After deriving the values of C_1 and C_2, they were applied to equations that were used to calculate the fuel burn rates from the endurance and combat patrols.

c. Fuel Burn Rate

With assistance from a SME (F. Papoulias 2014b), the following equations (Tupper 1997) were used to estimate fuel burn rates:

$$C_1 \times C_2 \times Displacement^{2/3} \times Speed^3, \tag{2}$$

$$\frac{C_1 \times C_2 \times Displacement^{\left(\frac{2}{3}\right)} \times Speed^3}{FSW}. \tag{3}$$

The results derived from Equations (2) and (3) provided baseline fuel burn rates for simulating the logistics requirements in Table 14.

Tonnage	Speed in Knots						
	5	10	15	20	25	30	35
100	2.29	18.32	61.82	146.54	286.21	494.56	785.35
200	3.63	29.08	98.13	232.61	454.32	785.07	1246.66
300	4.76	38.10	128.59	304.81	595.33	1028.73	1633.59
400	5.77	46.16	155.78	369.25	721.19	1246.22	1978.96
500	6.69	53.56	180.76	428.48	836.87	1446.11	2296.37
600	7.56	60.48	204.13	483.86	945.03	1633.01	2593.17
700	8.38	67.03	226.22	536.23	1047.31	1809.76	2873.83
800	9.16	73.27	247.28	586.15	1144.82	1978.26	3141.40
900	9.91	79.25	267.48	634.03	1238.34	2139.85	3398.01
1000	10.63	85.02	286.95	680.17	1328.45	2295.56	3645.27
1500	14.76	118.12	398.65	944.94	1845.59	3189.18	5064.31
2000	17.89	143.09	482.93	1144.72	2235.78	3863.42	6134.97
3000	23.44	187.50	632.81	1500.00	2929.70	5062.51	8039.08
4000	28.39	227.14	766.60	1817.13	3549.07	6132.80	9738.66
5000	32.95	263.57	889.56	2108.59	4118.33	7116.48	11300.71
6000	37.20	297.64	1004.53	2381.11	4650.60	8036.24	12761.25

Table 14. Calculated fuel burn rates in gallons per hour.

We used triangular distribution around five, 15, and 35 knot speeds to calculate the SIMIO input values for the combatant fuel burn rates.

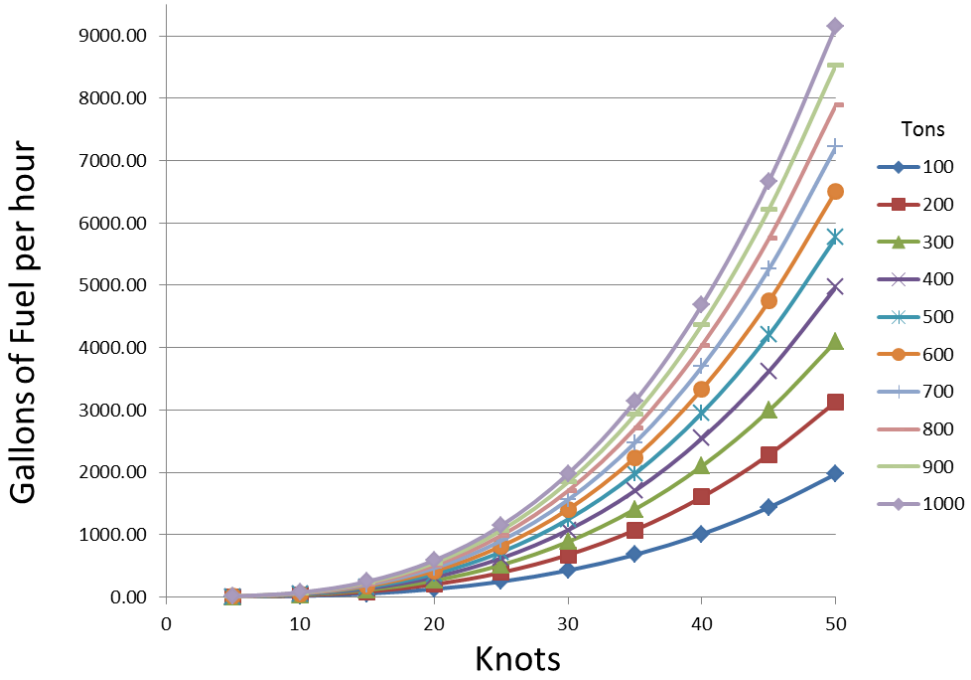

Figure 33. Graph of 100–1000 ton fuel burn rate in gallons.

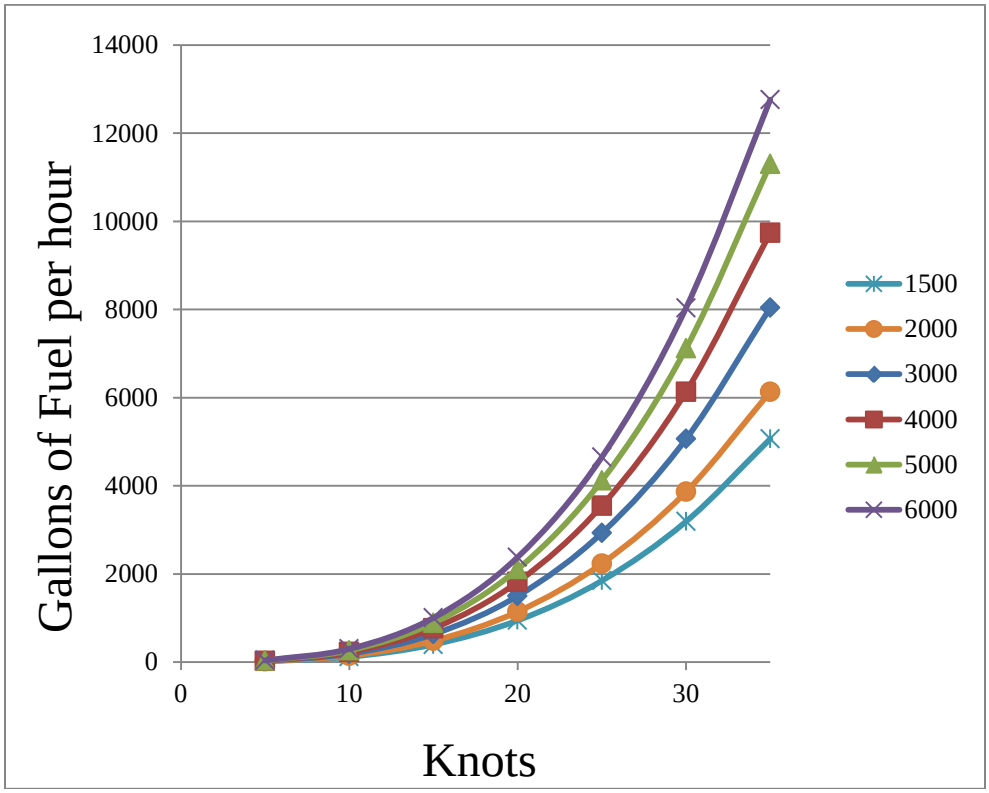

Figure 34. 1500–6000 ton ship fuel burn rate in gallons.

These burn rates are conservative first-order approximations as they do not take into account the improved efficiency gained by reduction gears and transmissions, multiple engines online to achieve specified speeds, and different propulsion systems. The derived burn rates used for this model are based upon vessels with diesel engines as the prime mover. Higher ship speeds (generally greater than 25 knots) have an increase in fuel burn rate that closely follows an exponential curve.

For logistics development, there may be a higher demand at sprint speeds than projected on Figure 33 and Figure 34. These values were used in conjunction with capacity levels to develop the patrol duration and for application to the SIMIO model.

d. Fuel Weight as a Percentage of Total Tonnage

Although the SSC type and design is not intended to be determined within the scope of this project, it was necessary to estimate the SSC fuel capacity and refueling requirements. One method to achieve this estimate was to calculate the ratio of total U.S. naval ship fuel weight to total tonnage and apply that same ratio to the SSC. The amount of fuel that would be available was calculated using analogous ship assessment from (Wasserbly 2013). Multiple platforms were assessed to ensure that a wide variety of ships were covered. These platforms included a range of ship displacements from small (500 ton) to large (10,000 ton), as seen in Table 15. The 18 percent summary result from the different ship classes was rounded to 20 percent for ease of calculation. This estimate was considered sufficient after consultation with SME (F. Papoulias 2014b).

Class/Type	Tonnage with 0 Percent Fuel Load out	Tonnage with 100 Percent Fuel Load out	Percent of Total Full Load out Tonnage Resulting from Fuel
DDG-51	6800	9800	31%
LCS	2300	3100	26%
Tarantul Corvette	488	540	10%
Sa'ar Corvette	1075	1227	12%
Grisha	950	1200	21%
Pauk	500	580	14%
Nanucka	560	660	15%
Percent of weight used for fuel			18%

Table 15. Percentage of tonnage dedicated to fuel for multiple ship classes.

The capacity calculations establish the amount of fuel that is available for the SSC to burn. This information is then used to derive the SSC duration of patrol without refueling.

e. Results of Calculating Fuel Burn Rates

The capacities of the vessels are based on 20% of the ship's total tonnage. For the 100–1000 ton ship operating at combat speeds, that requirement equates to less than a day underway before refueling is required. However, when operating at a nominal transit speed of 15 knots the time the ship can remain at sea without refueling greatly increased. The total number of days underway without required refueling was calculated using the following equation:

$$DaysUnderway = \frac{0.2 \times ShipTonnage_{Total}}{FBR \times FuelWeight \times 24}. \qquad (4)$$

There results of Equation (4) at 15 knots are displayed in Figure 35, while the results for a combat patrol as shown in Figure 36.

As can be derived from Figure 35 and Figure 36, the duration of patrols depends on when doctrine requires the ship to refuel. Additionally, speed is also a significant factor regarding duration of patrol. At slower speeds the duration of patrol is three to four times longer than for a large variation in speeds between five and thirty-five knots.

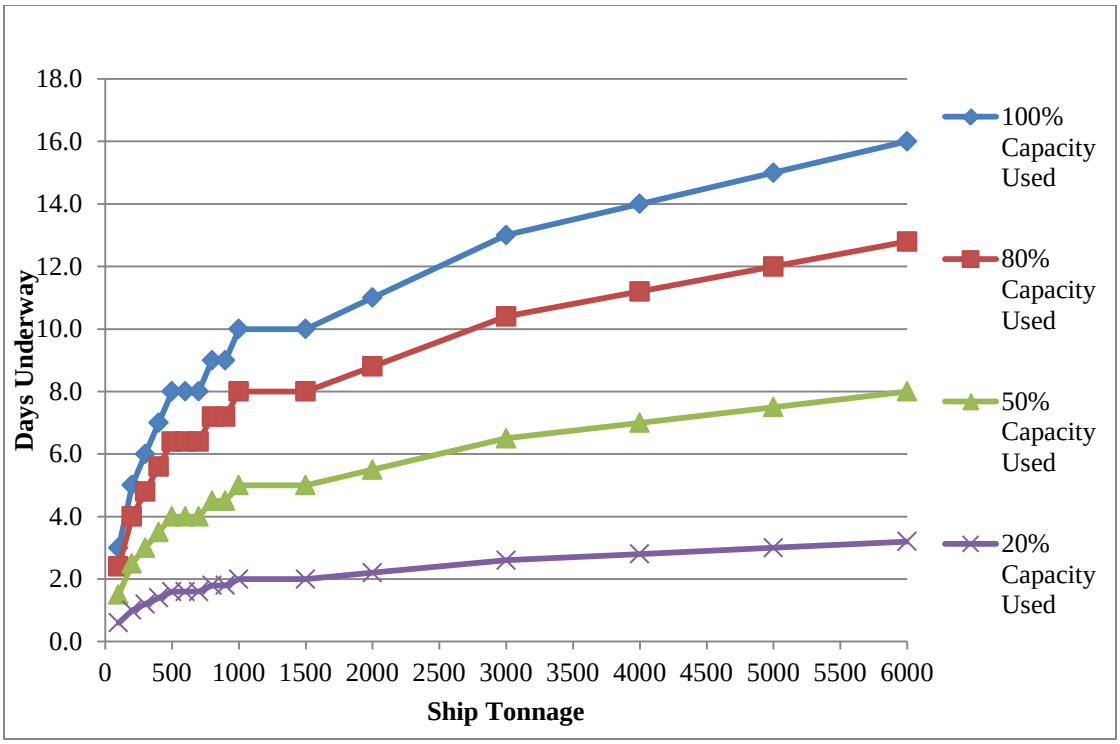

Figure 35. Fuel endurance versus ship tonnage at 15 knots.

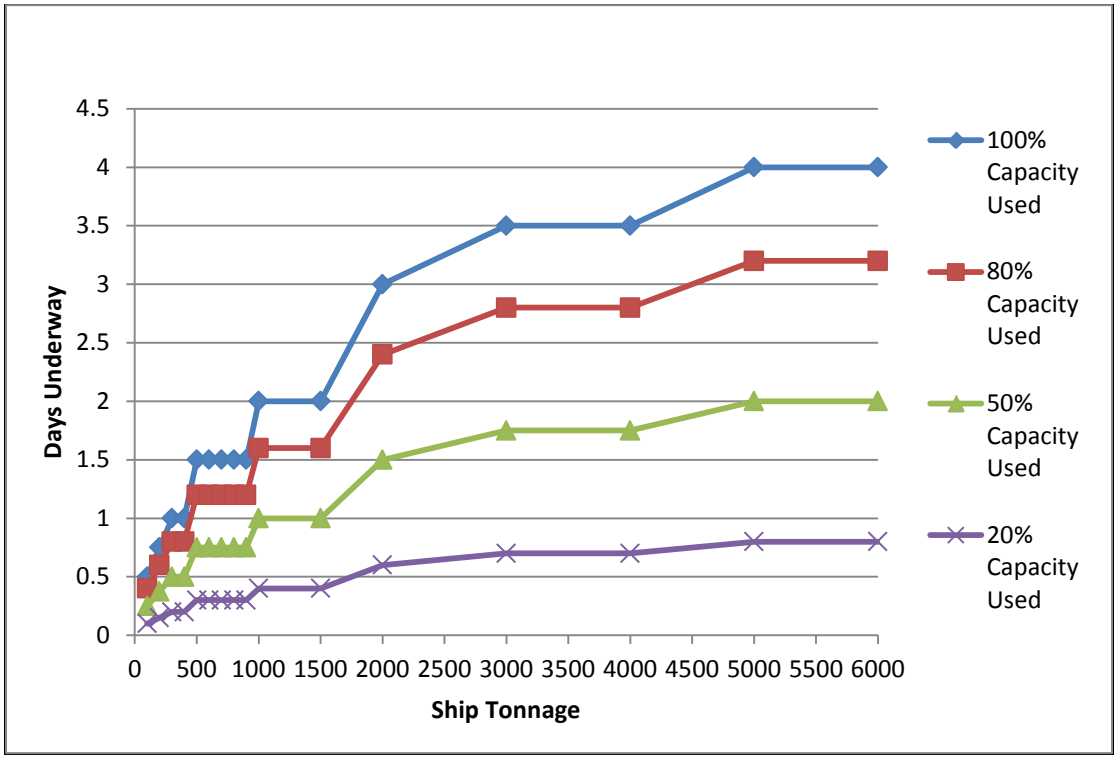

Figure 36. Fuel endurance at combat speeds.

The patrol durations are an important component for fleet commanders to understand. Figure 35 and Figure 36 not only give insight into the possibilities available to the logistics planners, but also show that setting a specific refueling doctrine at a specific fuel percentage could significantly restrict the ship patrol duration. The ability to remain at sea is important to a fleet, and the means with which to do so are described in the next section.

f. Supportability

To determine which size platforms are supportable, we assessed the most difficult logistics scenario for four fuel ferries and four T-AKEs. This scenario involved a situation with no casualties to the combatants and a constant demand for fuel from start to finish. The main supportability driver is then the combatant's fuel capacity. The scenario takes place in and environment where the DF-21 and ASCM threat is significant to the large deck combatants and larger oilers. As of the writing of this report there were no in-region locations. Should that change the possibility of refueling and resupplying through shore-based logistics would become feasible.

For Table 16 and Table 17, green represents ships that can be supported by four fuel ferries, each with a 210,000 gallons capacity. These fuel ferries would operate within ASBM range. The four fuel ferries would be supported by the four T-AKEs, which would operate outside the ASMB range. Yellow represents ships that can only be supported by four T-AKEs with a capacity of 900,000 gallons each. These T-AKEs would either be required to enter the A2AD envelope, or the fuel ferries would have to make multiple trips to support the combatants. Red represents a capacity that cannot be supported by four T-AKEs. An assumption of 50 percent of fuel burned is used as the capacity requirement for the calculations.

We can derive the number of combatants ships the T-AKEs and fuel ferries can support based on appropriate combatant ship tonnage and information in the preceding paragraph. As the size of the ship or the number of ships increase, the likelihood decreases that the ships are supportable by the four T-AKEs and four fuel ferry

configuration. The decision when to refuel is an important factor in determining how effectively the logistics ships can support the armada.

Tonnage	Single Ship	2 Ships	4 Ships	6 Ships	8 Ships	10 Ships	12 Ships	14 Ships	16 Ships
100									
200									
300									
400									
500									
600									
700									
800									
900									
1000									
1500									
2000									
3000									
4000									
5000									
6000									

Table 16. Combatant ship supportability at 15 kt speeds.

Tonnage	Single Ship	2 Ships	4 Ships	6 Ships	8 Ships	10 Ships	12 Ships	14 Ships	16 Ships
100									
200									
300									
400									
500									
600									
700									
800									
900									
1000									
1500									
2000									
3000									
4000									
5000									
6000									

Table 17. Combatant ship supportability for combat patrol speeds.

Using data from Table 16, four T-AKEs and four fuel ferries can support up to sixteen 2000-ton ships and four 6000-ton ships. This concept is only true if these ships refueled at 80 percent capacity, or conversely when the ship uses 20 percent of its total fuel. If the refuel point is set at 50 percent, four fuel ferries and four T-AKEs can only support six 2000-ton ships and two 6000-ton ships.

After completing the calculations for the requisite number of T-AKEs and fuel ferries, the information from Table 16 and Table 17 was used to populate the SIMIO model. The use of four T-AKEs and four JHSVs in SIMIO is to ensure the capacity for the required amount of fuel is available.

4. SIMIO Scenario

Upon completion of the initial calculation of fuel capacities, burn rates, and logistic ship numbers, the SIMIO model was programmed for the most difficult logistic scenario. As a result, the scenario allows for insight into the difficulties of re-supply in an A2AD environment. Additionally, there was no consideration of land-based refueling, as these small combatants may be called to operate near shore against hostile countries in areas such as regions around Iran, Taiwan, the Red Sea, the Baltic Sea, or any number of unanticipated operating environments. These hostile countries may not have the abundant amount of small islands as seen in the South China Sea (SCS) scenario. Another consideration is that the United States may not have facilities available within the area of conflict.

The scenario takes place in the SCS where the DF-21 and ASCM threats are too great to risk the large deck combatants and oilers such as a Lewis and Clark class T-AKE. The scenario begins with the onset of hostilities, and four T-AKEs depart Guam upon completion of loading. Guam was selected as the nearest regional U.S. controlled port facility outside DF-21 range (Google 2014). The T-AKEs will transit using a random triangular distribution around 12, 15, and 20 knots to a refueling box located outside of the DF-21 and ASCM ranges, which is an area where a fuel ferry will wait to refuel. The triangular distribution is used to take into account possible weather and shipping traffic. The fuel ferry will transit to a combat refueling box to transfer fuel to the combatants.

The transit speed will be a random triangular distribution around the speeds 17, 25, and 40 knots. The combatants will then move to a combat location and expend their fuel based on the fuel burn rate found through the fuel burn calculations. The time in combat patrol will be five days assuming that the combatant will require refueling at 50 percent. Upon transferring fuel, each vessel (T-AKE, fuel ferry, combatant) will return to the supply side refueling locations outside the DF-21 range.

5. SIMIO Parameters

The geographical setup in SIMIO is shown in Figure 37. All distances are taken from Google Earth (Google 2014) to develop an estimated route. The routing method seeks to keep the T-AKE out of range of the anti-ship ballistic missile (ASBM) capabilities of China, namely the DF-21 and the ASCM threat from operations in the combat area. The assessed location where combat most likely will occur is approximately a $500nm^2$ region located between Vietnam and the Philippines. The duration of the scenario is six months in order to allow for multiple "runs" by the logistic ships.

Figure 37. The layout of SIMIO logistics route (after Google 2014).

The simulation starts in Guam, which already handles the region's logistics and is the closest U.S. controlled port to the SCS. Fuel arrives in Guam every six to eight days; this estimation of fuel arrival rate is based on a random normal distribution centered on eight days with a standard deviation of two days. Fuel is delivered to Guam at a capacity of 9,870,000 gallons to ensure there is no shortage of fuel for the T-AKEs.

The T-AKEs then transfer fuel from the island. The fuel transfer duration is based on a random triangular distribution around eight, 10 and 14 hours. The T-AKE holds 980,000 gallons of fuel. For SIMIO the total fuel the T-AKE holds is 900,000 gallons, which appears in SIMIO as the value of 90 individual 10,000 gallon increments. The ship then departs Guam transiting along a 1600nm transit leg leading to UNREP box one's location outside of the expected DF-21 range. The transit speed is based on a random triangular distribution around 12, 15, and 20 knots. Upon reaching the UNREP box one, the T-AKE conducts fuel transfer onto the fuel ferry.

The fuel transfer time for the fuel ferry is a random triangular distribution around three, five, and six hours. The fuel ferry holds 210,000 gallons, which is based on the 635-ton storage capability of the JHSV. For the SIMIO software the value of the fuel ferry is 21 individual 10,000 gallon increments. The fuel ferry transits a 300 nautical mile leg to the second UNREP box two located within the DF-21 range, but outside the expected combat area by 100nm. The fuel ferry then conducts logistics transfer with the combatant.

The combatant's time to refuel is based on a random triangular distribution around two, three, and five hours. The quantity held is varied by tonnage within each simulation contained in the experiment. The combatant then transits to the combat area and discharges its fuel based on the designated fuel burn rate. The combat domain box is in the vicinity of the Spratly Islands, which is assumed to be the location with the highest conflict probability. This assumption is based on geographic location, a history of contention (British Broadcasting Company 2014), and reasons discussed in Chapter V Section A.2.a.

When each of these vehicles is idle (not in the act of refueling or transit) they return to the transfer point to await supply. The combatant remains at the combat UNREP box two, the Fuel ferry remains at UNREP box one, and the T-AKE waits at Guam if fuel is unavailable. The duration of the simulation is six months.

Fuel burn rates were calculated and entered into SIMIO as either combat patrol or endurance burn rates. The combat patrol burn rates were generated using a triangular distribution. This distribution was used due to a limited number of data points pertaining to speeds and transfer rates that are available. Multiple runs using the triangular distribution were conducted, and the results can be seen in Table 18. Due to the volume of fuel required for the larger tonnage and larger quantity experiments, the total values were then reduced by 10,000 in order to allow for SIMIO to complete its simulation as derived from the data in Table 18. The values needed to be reduced because the student version of SIMIO is limited to 20,000 entities, which consist of vessels and the fuel they transport.

Tonnage	Single Ship Fuel Burn Rate per Hr.	SIMIO Value, Combatant Fuel Burn Rate per Hr.
100	335.805	0.034
200	533.057	0.053
300	698.502	0.070
400	914.363	0.091
500	981.900	0.098
600	1108.803	0.111
700	1228.813	0.123
800	1343.220	0.134
900	1452.944	0.145
1000	1558.668	0.156
1500	1941.777	0.194
2000	2014.475	0.201
3000	2639.709	0.264
4000	3197.780	0.320
5000	3710.695	0.371
6000	4190.277	0.419

Table 18. Combat fuel burn rates based on triangular distribution sample of speed.

Next, the fuel burn rate for endurance speed was calculated. The assumption of 15 knots as the endurance speed was based off research on Jane's fighting ships and other open sources (Global Security 2014b; Saunders 2013). Endurance is often explained based on speeds of 10 and 20 knots depending on the type/class of ship. The same equations were used and results shown Table 19, which are significantly different than the combat burn rates for SIMIO.

Tonnage	Single Ship Fuel Burn Rate per Hr.	SIMIO Values, Endurance Fuel Burn Rate per Hr.
100	61.82	0.006
200	98.13	0.010
300	128.59	0.013
400	155.78	0.016
500	180.76	0.018
600	204.13	0.020
700	226.22	0.023
800	247.28	0.025
900	267.48	0.027
1000	286.95	0.029
1500	398.65	0.040
2000	482.93	0.048
3000	632.81	0.063
4000	766.60	0.077
5000	889.56	0.089
6000	1004.53	0.100

Table 19. Endurance fuel burn rates based on triangular distribution sample.

These values are what were used to build the SIMIO model. After the model was built and tested it then was set up as a SIMIO experiment. Again, the values in Table 18 and Table 19 represent 10,000 gallon increments.

6. Design of Experiments

The SIMIO software allows the user repeat the experiment a number of times and to vary different design aspects and parameters. The scenarios were based on number of ships in the action group (two, four, six, 10, 12, 14, and 16), and each will account for variations in the supply chain. These variations are:

- four T-AKEs and four fuel ferries with 50 percent specified number of combatants,
- four T-AKEs and eight fuel ferries 50 percent of specified number of combatants, and
- eight T-AKEs and eight fuel ferries with specified number of combatants.

These variations will be sorted by tonnage of the ships. Values held constant for each scenario are:

- fuel capacity of the T-AKE, fuel ferry, and combatant.
- fuel burn rates listed in Table 20 for combat speeds and Table 21, and
- distance the T-AKE, fuel ferry, and combatant must travel to reach UNREP locations.

The adjusted scenario experiment controls for combat and endurance speeds are displayed in Table 20 and Table 21.

Combatant Tonnage	Combatant Fuel Capacity in 10000 Gal Increments	Fuel Ferry Fuel Capacity in 10000 Gal Increments	T-AKE Fuel Capacity in 10000 Gal Increments	Combatant Fuel Burn Rate
100	0.4451	21	90	0.03358
200	1.1776	21	90	0.05331
300	1.8517	21	90	0.049696
400	2.6171	21	90	0.060203
500	3.4707	21	90	0.069859
600	3.9192	21	90	0.078889
700	4.3434	21	90	0.122881
800	5.3413	21	90	0.134322
900	5.7776	21	90	0.145294
1000	6.8867	21	90	0.155867
1500	9.5676	21	90	0.194178
2000	12.7493	21	90	0.201448
3000	19.7438	21	90	0.263971
4000	25.7578	21	90	0.319778
5000	32.0242	21	90	0.371069
6000	38.5739	21	90	0.419028

Table 20. Adjusted SIMIO experiment controls for combat speeds.

Combatant Tonnage	Combatant Fuel Capacity in 10000 Gal Increments	Fuel Ferry Fuel Cap in 10000 Gal Increments	T-AKE Fuel Cap in 10000 Gal Increments	Combatant Fuel Burn Rate
100	0.4451	21	90	0.00618
200	1.1776	21	90	0.00981
300	1.8517	21	90	0.01286
400	2.6171	21	90	0.01558
500	3.4707	21	90	0.01808
600	3.9192	21	90	0.02041
700	4.3434	21	90	0.02262
800	5.3413	21	90	0.02473
900	5.7776	21	90	0.02675
1000	6.8867	21	90	0.02869
1500	9.5676	21	90	0.03986
2000	12.7493	21	90	0.04829
3000	19.7438	21	90	0.06328
4000	25.7578	21	90	0.07666
5000	32.0242	21	90	0.08896
6000	38.5739	21	90	0.10045

Table 21. Adjusted SIMIO experiment controls for endurance speeds.

An experiment consisted of each scenario executed 30 times to normalize the data (Ross 2009). After all scenarios were conducted, the SIMIO software provided an Excel spreadsheet with all data captured during the experiments. The value that was specifically targeted was idle time of the combatants for each experiment. Idle time begins after the combatant takes fuel for the first time, burns the fuel, and returns to the replenishment location where it would receive fuel from the fuel ferry. While no specific idle time was set to establish an acceptable standard, the highest number of the largest (tonnage) ships was selected as “the best.”

Design | Response Results | Pivot Grid | Reports

Scenario			Replications		Controls						
	Name	Status	Required	Completed	fuel_capacity_combatant	fuel_capacity_JHSV	fuel_capacity_T_AKE	Fuel_burn_rate	T_AKE_numbers	JHSV_numbers	Combatant_numbers
	Combatant_fuel_Cap_1000	Idle	30	0 of 30	3.444	21	90	0.01808	4	4	8
	Combatant_fuel_Cap_1500	Idle	30	0 of 30	4.784	21	90	0.02041	4	4	8
	Combatant_fuel_Cap_2000	Idle	30	0 of 30	6.375	21	90	0.02262	4	4	8
	Combatant_fuel_Cap_3000	Idle	30	0 of 30	9.872	21	90	0.02473	4	4	8
	Combatant_fuel_Cap_4000	Idle	30	0 of 30	12.789	21	90	0.02675	4	4	8
	Combatant_fuel_Cap_500	Idle	30	0 of 30	1.736	21	90	0.02041	4	4	8
	Combatant_fuel_Cap_600	Idle	30	0 of 30	1.96	21	90	0.02262	4	4	8
	Combatant_fuel_Cap_700	Idle	30	0 of 30	2.172	21	90	0.02473	4	4	8
	Combatant_fuel_Cap_800	Idle	30	0 of 30	2.671	21	90	0.02675	4	4	8
	Combatant_fuel_Cap_900	Idle	30	0 of 30	2.889	21	90	0.02869	4	4	8
	Double_JHSV_1000	Idle	30	0 of 30	3.444	21	90	0.01808	4	8	8
	Double_JHSV_1500	Idle	30	0 of 30	4.784	21	90	0.02041	4	8	8
	Double_JHSV_2000	Idle	30	0 of 30	6.375	21	90	0.02262	4	8	8
	Double_JHSV_3000	Idle	30	0 of 30	9.872	21	90	0.02473	4	8	8

Figure 38. Sample SIMIO experiment list.

After successful completion of the various experiments, SIMIO provides results of all the data collected. With these results, the most ideal vessel tonnage can be selected.

7. SIMIO Results

The SIMIO software performed calculations for varying model inputs. SIMIO is capable of tracking the following parameters: fuel entering, transferring through, and exiting, vehicles transferring fuel, interactions at the servers (UNREP locations), and interactions between vehicles. The software model supplied average combatant idle time at the server. In addition, the SIMIO software will also output minimum, maximum, and average times. Combatant idle time at UNREP box two, which is located inside the DF-21 range and outside the combat area, was used to track how well the logistics train functioned. The average and median idle times used for each combatant were recorded and placed into tables located in Appendix C. In order to discover the most likely tonnage range, stakeholder analysis was conducted. This involved establishment of the current JHSV and logistic ship capacity, and current USN patrol vessel tonnages focused the modeling on 500 to 4000 ton size vessels using flotilla sizes from one to sixteen. Initial analysis also included the amount of fuel burned during combat and endurance patrols along with assuming ship deployment for ten days with a single refueling.

The SIMIO output data in Appendix C show the simulated idle days for SSC tonnage variations, and multiple fuel ferry and T-AKE configurations. In general, the logistic force compositions with the least idle time were:

- four fuel ferries and four T-AKEs,
- eight fuel ferries and four T-AKEs, and
- eight fuel ferries and eight T-AKEs.

The lowest idle time tonnage is shown in Table 22 and Table 23.

a. Combat Patrol

More than eight ships on combat patrol will have significant idle time, which in the scenario is 90 or more out of 182 days. This idle time accounts for approximately 50 percent of the total simulation time. It appears there is not a specific tonnage that results in better performance in the combat patrol situation. There is no noticeable correlation to tonnage and endurance based on the calculations for C_1, C_2, or fuel burn rate. The lack of a clear dominant factor may be due to the variability in fuel ferry, T-AKE, and combatant speeds within SIMIO. The tonnage that appears the most often is the 800-ton combatant; however this ship would only be capable of operating for a few days at the combat speeds (as seen in Figure 36) dependent upon the acceptable replenishment level. The ship tonnage with the least idle time during combat patrol is provided in Table 22.

Least Amount of Idle Days: Combat Patrol			
Ship Numbers	4 Fuel Ferry, 4 T-AKE	8 Fuel Ferry, 4 T-AKE	8 Fuel Ferry, 8 T-AKE
1 Ship	4000 ton, 3% of time idle	4000 ton, 3% of time idle	4000 ton, 2% of time idle
2 Ship	3000 ton, 1% of time idle	3000 ton, 1% of time idle	3000 ton, 1% of time idle
3 Ship	500 ton, <1% of time idle	600 ton, <1% of time idle	900 ton, <1% of time idle
4 Ship	500/600 ton, <1% of time idle	700-900 ton, 1% of time idle	900 ton, <1% of time idle
5 Ship	500/600 ton, <1% of time idle	800/900 ton, <1% of time idle	800 ton, <1% of time idle
6 Ship	600/1500 ton, 25% of time idle	700 ton, 25% of time idle	900/4000 ton, 18% of time
7 Ship	4000 ton, 42% of time idle	4000 ton, 42% of time idle	4000 ton, 31% of time idle
8 Ship	4000 ton, 42% of time idle	4000 ton, 42% of time idle	4000 ton, 31% of time idle
9 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
10 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
11 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
12 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
13 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
14 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
15 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
16 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time

Table 22. Ship tonnage with least amount of idle days during combat patrol.

It was observed that for combat patrol the smaller 500–900 ton ships have the lowest idle time in groups of three to six ships. For one to three ship groups as well as seven to eight ship groups, 1000–3000 ton ships are the better choice for less idle time. These ships have endurance time exceeding eight days, as observed from the data in Figure 36. The graph representing the percentage of time the flotilla is idle for combat patrols is provided in Appendix C.

After completing the experiment for the combat patrol, new burn rates were used to conduct endurance patrol simulations. The endurance speeds were based on 15 knots. The same number of runs and controls that were applied in the combat speed experiments were used.

b. Endurance Patrol

An indication of which ship tonnage would have the smallest amount of idle time on an endurance patrol can be derived using Table 23.

Least Amount of Idle Days: Endurance Patrol			
Number of Ships	4 Fuel Ferry, 4 T-AKE	8 Fuel Ferry, 4 T-AKE	8 Fuel Ferry, 8 T-AKE
1 Ship	900 ton, 2% of time idle	900 ton, 2% of time idle	900 ton, 2% of time idle
2 Ship	3000 ton, 1% of time idle	3000 ton, 1% of time idle	3000 ton, 1% of time idle
3 Ship	500 ton, <1% of time idle	600 ton, <1% of time idle	600 ton, <1% of time idle
4 Ship	500/600 ton, <1% of time idle	500-900 ton, <1% of time idle	700-900 ton, <1% of time idle
5 Ship	500/600 ton, 25% of time idle	600-900 ton, 25% of time idle	700-900 ton, <1% of time idle
6 Ship	500/600 ton, 23% of time idle	1500 ton, 23% of time idle	1500 ton, 23% of time idle
7 Ship	700 ton, 23% of time	700 ton, 23% of time	700 ton, 23% of time
8 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
9 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
10 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
11 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
12 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
13 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
14 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
15 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
16 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time

Table 23. The tonnage with least amount of idle days during endurance patrol.

Additionally, as the numbers of ships increase the ship tonnage decreases. This result is expected as the ships would require less fuel per visit and the slower and more consistent combatants' speed would allow time for the T-AKE and the fuel ferry to transit between stations. Again, any quantity over seven ships creates extensive idle days. However, the ships in the range of 500 to 600 tons result in the fewest idle days and the largest group sizes. These ships would provide six to eight days of endurance and 0.5 to 1.5 days of combat patrol depending on which replenishment levels were acceptable based on data from Figure 35. The graph representing percentage of time the flotilla is idle for endurance patrol is provided in Appendix C.

Finally, the data was compared between combat and endurance patrols from Table 22, Table 23, and Appendix C. The ship tonnage that had the lowest idle time and closest matching idle time are listed in Table 25.

In order to determine ideal tonnage, the idle time for cruising and combat speeds were compared. This comparison takes into account that ships will not only conduct combat operations, but also patrol and transit operations. An example of this comparison is seen in Table 24.

Cruising Speed		Difference	Combat Speeds	
Scenario	Average		Average	Scenario
Double_JHSV_500	5.3365	1.1851	4.1514	Double_JHSV_500
Double_JHSV_600	5.3312	1.1839	4.1473	Double_JHSV_600
Double_JHSV_700	5.5926	2.9348	2.6578	Double_JHSV_700
Double_JHSV_800	5.5497	1.0673	4.4824	Double_JHSV_800
Double_JHSV_900	5.2749	3.1434	2.1315	Double_JHSV_900
Double_JHSV_1000	2.8996	2.3556	5.2552	Double_JHSV_1000
Double_JHSV_1500	2.1676	4.0198	6.1874	Double_JHSV_1500
Double_JHSV_2000	2.6841	**0.5523**	3.2364	Double_JHSV_2000
Double_JHSV_3000	2.5006	0.5882	3.0888	Double_JHSV_3000
Double_JHSV_4000	3.1981	1.2336	1.9645	Double_JHSV_4000

Table 24. Sample table for estimating ideal tonnage.

As highlighted by the data, the fewest number of idle days for cruising speed was for the 1500 ton vessel. The lowest idle time for the combat speed was the 4000 ton vessel. However, by comparing the median of the average idle times, the 2000 ton has the smallest difference. A small difference in idle time provides insight into which ship is best-suited for both combat and patrol operations. Next, the comparison is made for the endurance patrol, and then the same process is used to find the "best overall."

The ideal tonnage for both the combat and endurance fuel burn rates appears to be approximately 2000 tons (1000-3000). A 2000 ton ship would provide a five to nine day patrol window at endurance speeds, and a 1.5 to 2.5 day patrol window at combat speeds; both which are replenishment-level dependent. However, any quantity over seven ships creates idle time with a median of 90 days, which is approximately 50 percent of the total experiment days.

Tonnage With Closest Idle Days Comparing Combat and Cruise Speeds			
Number of Ships	4 Fuel Ferry, 4 T-AKE	8 Fuel Ferry, 4 T-AKE	8 Fuel Ferry, 8 T-AKE
1 Ship	3000 ton, 7% of time idle	2000 ton, 7% of time idle	1500 ton, 9% of time idle
2 Ship	3000 ton, <1% of time idle	2000 ton, <1% of time idle	300 ton, <1% of time idle
3 Ship	500 ton, <1% of time idle	500 ton, <1% of time idle	600 ton, <1% of time idle
4 Ship	600 ton, <1% of time idle	600 ton, <1% of time idle	800 ton, <1% of time idle
5 Ship	600 ton, <1% of time idle	700 ton, <1% of time idle	700 ton, <1% of time idle
6 Ship	1500 ton, 24% of time idle	1500 ton, 24% of time idle	3000 ton,25% of time idle
7 Ship	1000 ton, 47% of time idle	2000 ton, 46% of time idle	900 ton, 47% of time idle
8 Ship	1000 ton, 49% of time idle	2000 ton, 49% of time idle	2000 ton,48% of time idle
9 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
10 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
11 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
12 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
13 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
14 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
15 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time
16 Ship	Idle ~50% of time	Idle ~50% of time	Idle ~50% of time

Table 25. Combat and endurance patrol tonnage with closest matching days.

It appears the ideal tonnage for both the combat and endurance fuel burn rates is near 2000 tons. However, any quantity over seven ships creates an idle time that is 50 percent of the total simulations time. Due to significant idle time for a 15-ship flotilla, a single run simulation was conducted. For this simulation, a single variable was adjusted, while all other remained fixed values. The results from these simulations are located in Appendix C. The results signify that another method or a reduced distance to the T-AKE may be required. Another means to address the deficiency is to have a larger number of ships rotate into the combat area. Based on a simple SIMIO model, an improved fuel ferry is the most efficient means to reduce idle time. Simulation improvements tested were increased cruising speed and capacity, both of which reduced overall idle time. Another means to reduce idle time could be forward positioning of logistic assets within the region of conflict, which was not tested.

8. Logistics Takeaways

There are potential threats from ASCMs and ASBM in various locations throughout the world. Operating in these A2AD threat areas requires a new concept for the logistics train and equipment. Understanding the drivers for logistics in a specific area has been the focus of this section. The use of fuel was found to be the most significant resource to resupply, since combat evolutions and "peace time" steaming both demand fuel usage. While food and weaponry logistics were also considered, the impact on the total weight was comparably less significant than fuel.

Calculations for fuel capacity and burn rates were necessary to further understand and apply the logistics concept. The rates and capacities were determined using basic formulas and calculations. The results provided could be improved with modifications to the propulsion systems, including gearing and hybrid drives, as well as changes in fuel source. Additionally, while some consideration was paid to hull design through the use of the C_2, future hull designs could improve efficiency as well. The analysis has shown that patrol times are not only affected by fuel burn rate, but by doctrine as well. The determination of when to refuel could add days to an endurance patrol and hours to a combat patrol. These days could determine the outcome of a battle.

The SSC concept has been narrowed from a 500 ton to 4000 ton to a 1000 ton to 2000 ton ship concept. These ships could operate in groups up to five or six ships depending on which platforms are available, and more importantly developed for vessels such as the fuel ferry. However, changing the logistic platform types to vessels such as T-AOs and T-AOEs allow for more available capacity (which comes at the expense of the ability to move food, parts, and weapons). These larger ships could provide a fuel resource to support a larger force size or larger ships.

Future analysis is required to provide investigate the potential for land based replenishment in various regions throughout the world. Additionally, the effects on potential future propulsion systems such as diesel electric propulsion, turbine propulsion (as the analysis conducted pertains to diesel engines), improved transmission systems, and developing propellers or water jet designs could provide further avenues toward a successful ship design.

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VI. COST ANALYSIS

The cost estimation results play an important role in the major program acquisition decision making. Cost estimation provides the basis and quantitative benchmark for the program planning and budgeting of the new platform which includes the cost of new construction, maintenance and the operational cost of deploying the vessel. In this study, a cost estimate has been developed in order to establish a sound cost estimating relationship based on the displacement of the proposed small surface combatant (SSC). This evolution has been determined by analyzing the statistical data of the current fleet's smaller surface combatant and their respective program acquisition costs. The finalized cost estimating model will be useful in predicting the total life cycle cost of building, owning and operating the proposed SSC for the U.S. fleet in the 2025–2030 timeframe. All monetary values are in FY2014$ unless otherwise specified

A. BACKGROUND

The cost estimating effort objective is to provide a reliable life cycle cost estimate (LCCE) for the proposed SSC. These estimates are based on historical lead ship "theoretical first unit cost" (T_1) from several surface combatant platforms with similar characteristics. The purpose is to provide a detailed LCCE, which is an estimate of the total expected cost of a system or program. LCCE includes research, development, testing, and evaluation (RDT&E), procurement, operations and support (O&S), and disposal costs. The results from these methodical analysis tools, in conjunction with the results of the modeling and simulation (M&S) and logistic analysis, will provide the decision maker with appropriate data to establish trade-offs and evaluate the SSC cost effectiveness. The LCCE will serve as one set of decision factors to aid in trade space evaluation and feasibility analysis for a small surface missile delivery platform to augment U.S. Naval fleet in the 2025–2030 timeframe.

Cost estimation is traditionally accomplished by utilizing one of three approved methods: build-up, analogy or parametric (Nussbaum 2014b). Care should be taken to

analyze the model's strengths and weaknesses with relation to a given application to ensure the model delivers optimal results.

B. COST ESTIMATION METHOD SELECTION

The engineering build-up method requires a more robust design consideration baseline. Information on every item such as maintenance, logistics, industrial facilities are critical in developing an accurate estimate. The SSC is still in the conceptual phase; no prototype currently exists to provide an initial assessment of operations and maintenance. Therefore, it is difficult to collect the needed detailed information that is required to use the engineering build-up method, and thus that method is not used in this study.

Analogy is a second method that is available for cost estimators. It allows the estimator to use the robust cost and technical data compared to the most analogous existing systems. Using this method, one relationship of the two systems is leveraged to determine an estimate for the new system. For example, if a new platform is assessed as 20% more technologically advanced than an existing system, the estimator can apply a 20% increase in cost for the new system T_1 estimate. So if the "old" system is $100 million, the new system can be expected to cost approximately $120 million. For this study, the analogy method is used to calculate the SSC O&S cost. The Littoral Combat Ship's (LCS) annual O&S cost data is used as a model for the SSC O&S cost. The SSC will operate in similar environments to the LCS and will, therefore, presumably have similar O&S requirements.

Finally, the parametric method looks at several similar systems through regression analysis and seeks costing relationships within the group. As with the analogy method, the various systems' cost data used in the model must be sufficient to provide a credible new system estimate. The cost analysis team determined the SSC cost by using regression analysis utilizing similar surface combatants and displacement comparisons. With the benefits in mind, the parametric method was used in this study, and by varying the displacement of the SSC we were able to explore trade-space. Through stakeholder input and the efforts realized in other sections of this study, we have determined an optimal

SSC minimum displacement of 600 long tons and a maximum displacement of 1500 long tons.

Using the LCCE process, a cost estimate and annual O&S cost per ship was determined taking into account the desired total number of ships and the anticipated years of service. In addition, the cost analysis priced possible SSC alternatives, to include the expected cost of modifying and integrating the LCS or national security cutter based "patrol frigate" with an equivalent surface-to-surface strike missile system.

Costs are summed using a work breakdown structure (WBS). The WBS definition is "a product-oriented family tree composed of hardware, software, services, data, and facilities which results from systems engineering efforts during the development and production of a defense material item" (Nussbaum 2014d). A well-developed WBS provides a comprehensive system or program cost breakdown, and ultimately results in an accurate cost estimate. The build-up is the most valuable method when there is known cost data for every WBS item because the program manager (PM) is enabled to track and compare actual cost versus budgeted cost. An example of a WBS hierarchy is in Appendix B.

C. ASSUMPTIONS

The following assumptions were made for the duration of the cost estimating process in this study:

- The SSC is envisioned to augment and interoperate with the expected fleet in 2025. To this end, for a cost effective design, the SSC has minimal self-defense and sensor capabilities. The protective measures for the platform are provided by other force platforms (both surface and air assets) in the operational area.
- The LCS and SSC will operate together and will require similar O&S budgets to perform their respective missions.
- A correlated assumption is the LCS will be fitted with an ASW capability.
- AAW will be provided by CRUDES ships and/or coalition air assets in the operational area.
- The expected service life of the SSC is 20 years.

- The historical T_1 ship data, regardless of commissioning date, is expected to be accurate and provide the best information for conducting a LCCE on the SSC.
- The shipbuilding learning curve for the SSC is 85 percent, based on the ship construction historical average (Mislick 2014).

D. METHODOLOGY

The parametric method was used to estimate the life cycle cost of the platform. This technique is iterative and comprised of six steps: definition and planning, data collection, estimate formation, review and presentation, risk and uncertainty analysis and final document generation. A visual example of this process is in Figure 39.

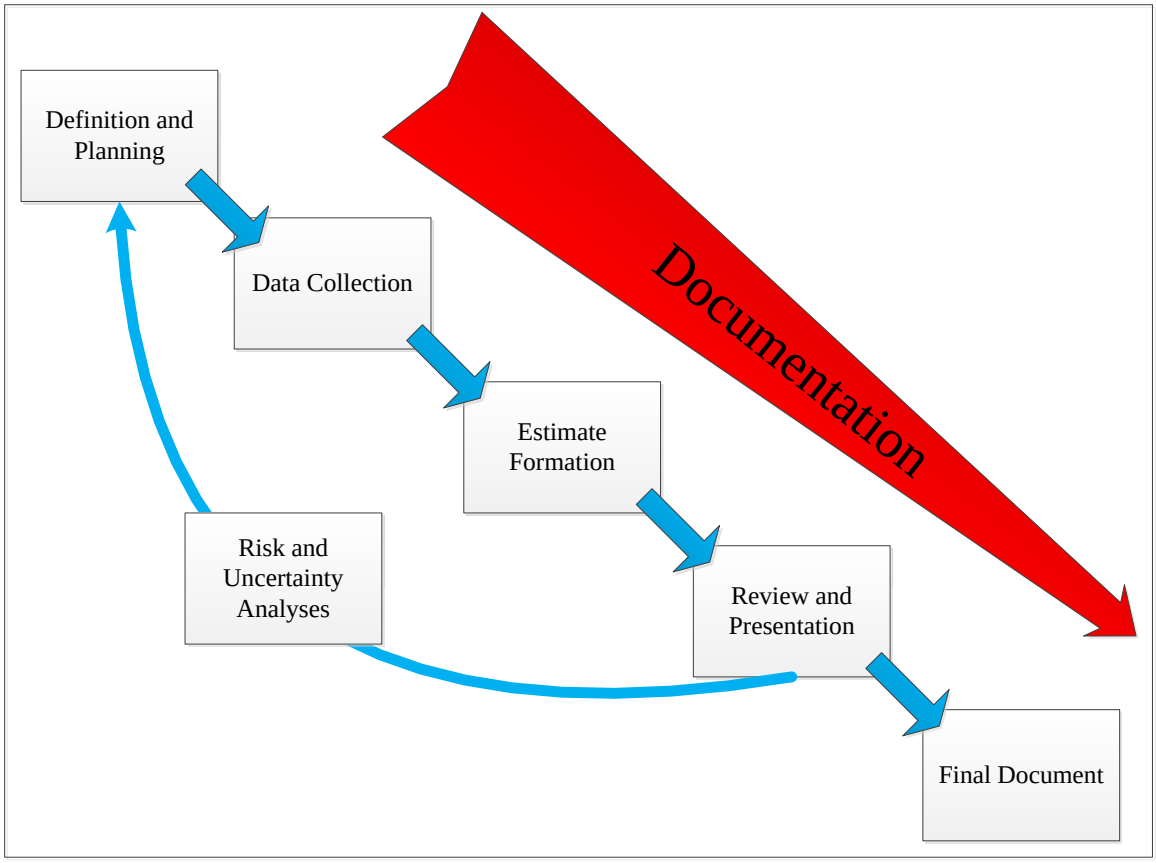

Figure 39. Cost estimating process (from Nussbaum 2014b).

We will now define each key step of the process, and illustrate the application of each step into the overall cost estimation of the proposed SSC.

1. Definition and Planning

The definition and planning phase is appropriate when utilizing any problem-solving algorithm. Before any attempt to address this phase, the problem must be fully defined. To reiterate, this study analyzes the U.S. Navy's lack of a modern, cost-effective surface-to-surface missile delivery platform. The delineation of capital shipping is important. For this study, capital shipping is a term referring to destroyer (or larger) ship classes. Therefore, platforms such as frigates, LCSs, and other small surface combatants are possible solutions for missile delivery. This distinction is important because retrofitting any capital shipping does not truly provide a cost effective solution since modern day surface combatants are multi-mission capable, and, therefore, this method is an uneconomical solution to address the capability gap.

Through this iterative process, the model is designed to answer the following questions:

- How many ships are necessary?
- How big does the ship need to be?

The definition and planning effort within the phase allows the freedom to consider all possible variables as equal contributors in providing a sufficient problem solution.

As a result, the problem can be summarized into a single statement: The U.S. Navy requires a surface combatant that is small, fast, distributed, cost effective, and capable of augmenting the envisioned fleet of 2025 by delivering a surface-to-surface missile to the enemy in an environment that is navigationally constraining for capital shipping.

2. Data Collection

The data collection phase involves taking results developed in the definition and planning phase and establishing cost estimate similarities with existing systems or platforms in order to develop a cost estimating relationship (CER). The CER binds

applicable O&S categories to T_1 cost for use in the cost estimating process. As described in the assumptions, several historical surface combatant platforms have similar characteristics to those desired in the SSC, and, therefore, can provide accurate cost data for the analysis of this new platform. Initial platforms considered included:

- Oliver Hazard Perry class frigates (FFG-7),
- Flight I (DDG-51), Flight II (DDG-72) and Flight IIA (DDG-79) Arleigh Burke class destroyers,
- Freedom (LCS-1) and Independence (LCS-2) class Littoral Combat Ships and
- Egyptian Ambassador MK III corvette (manufactured in the United States) (American Maritime International 2010).

A breakdown of each ship class and its respective characteristics is in Table 26.

Class	Displacement (LT)	Max Speed (kts.)	Range (nm)	Cruising Speed (kts.)	Length (ft.)	Draft (ft.)	Crew Size	Average Unit Cost (FY2014 M$)
FFG	4100	29	5000	18	453	22	205	367
DDG FLT I/II	6794	30	4400	20	505	31	281	2422
DDG FLT IIA	9203	30	4400	20	509.5	31	350	2074
LCS Freedom Class	2617	46	3500	18	378	12.9	70	700
LCS Independence Class	2771	45.5	4300	19	418	14	75	773
Ambassador MK III	490	41	2000	15	199	6.6	36	326

Table 26. Surface combatant characteristics.[3]

During the initial stakeholder interviews and in using an initial needs analysis, it was determined that the SSC should have a displacement around 600 long tons, a

[3] (After Destroyer History Foundation 2013; Global Security 2014a; United States Navy Fact File 2013b; Labs 2008; United States Navy Fact File 2013c; Naval Sea Systems Command 2012; American Maritime International 2010).

nominal range of 2500nm, and must be capable of exceeding 40 knots. While researching several surface combatants within these respective ranges, additional data was determined to be useful. This data included ship's length, cruising speed, navigational draft, crew size and displacement. We determined, through regression analysis, that the "best fit" relationship was displacement to cost. Using this information, the SSC cost is modeled as a function of its tonnage. The upper bound to maintain cost effectiveness in FY2014$ is $700 million (the T_1 cost of the LCS).

3. Estimate Formation

The initial stakeholder discussions involved a platform with a 600 long ton displacement for missile delivery. As performance and logistics analysis matured, it was determined that the top of the displacement range should be 1500 long tons. The initial results are illustrated in Figure 40. The best-fit equation for the initial cost estimating relationship was determined to be:

$$\text{COST} = \$41{,}104{,}775.47 + \$247{,}030.16 * DISPLACEMENT \ . \quad (5)$$

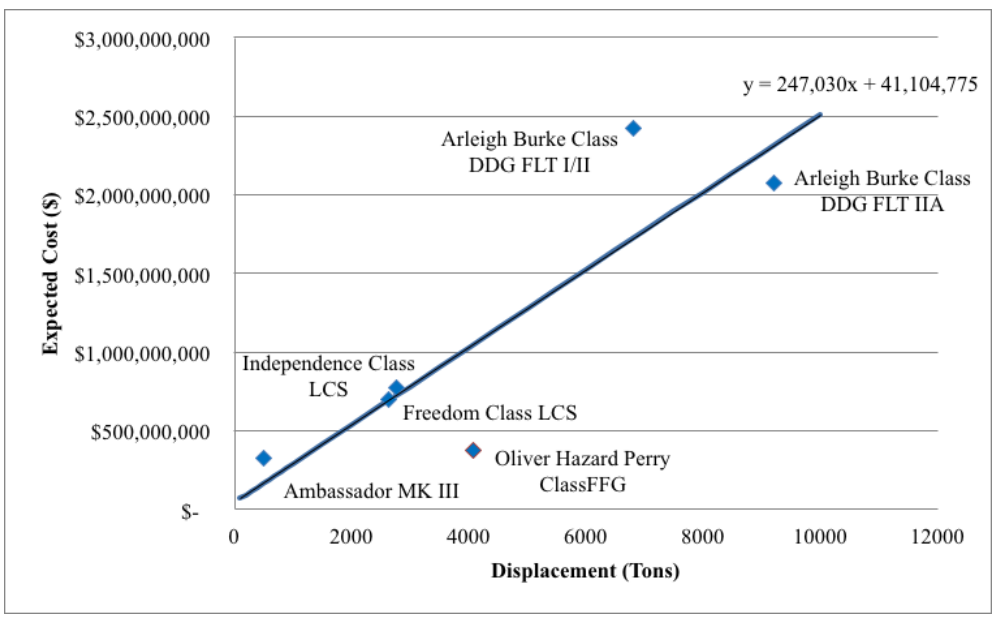

Figure 40. Expected SSC T_1 cost versus displacement in FY2014$.

The regression data is provided in Appendix B (Model #1 regression). The numbers displayed in Figure 40 are reasonable for this study since they are relatively close to the T_1 cost of the Freedom (LCS-1). The envisioned SSC 600–1500 ton displacement costs are a fraction of that of the first LCS. If these figures exceed the LCS T_1 cost, the decision maker will be unable to consider Equation (5) as a viable cost effective solution because, in this case, it would be more cost effective to redesign the LCS platform for missile delivery.

4. Review and Presentation

The review and presentation phase permits the cost estimator to conduct his or her own review of the data as well as to perform an analysis to identify and correct any deficiencies and errors prior to presentation. Once the initial work is complete, the estimator will present the product to an independent viewer for improvement recommendations.

An SME assessed the preliminary model and suggested implementing a shipbuilding learning curve (85%) (Mislick 2014), which helps illustrate how follow-on ships for each particular class will have a lower "sticker price" as the workforce becomes more efficient with the construction process. The learning curve provides a better method to determine T_1 cost, and ultimately leads to a more accurate estimate for the entire program. The O&S costs of manpower, operations, maintenance, sustainment support, system improvement, and indirect support have historical ratios that are a function of the estimated T_1 platform cost. The applicable LCS platform ratios from Chapter VI Section C determine the O&S costs. The benefits of using these ratios are twofold: first, the two platforms are similar, and second, the envisioned operations are similar.

5. Risk and Uncertainty Analysis

The risk and uncertainty analysis utilizes the T_1 data from the following ships: the Spruance class destroyer (DD-963), the Oliver Hazard Perry class frigate (FFG-7), the Ticonderoga class cruiser (CG-47), the Arleigh Burke-class destroyer (DDG-51), and the Freedom (LCS-1) and Independence (LCS-2) classes of LCS. Costs per thousand tons of

lightship displacement (the weight of the vessel without its crew, weapons, fuel, and material) (Labs 2008) are the basis for the cost figures. Using this data in conjunction with the LCS's selected acquisition report (SAR), the new regression model better reflects the expected T_1 cost of the proposed SSC. The T_1 data for the identified ships are listed in Table 27.

Platform	**Displacement (LT)**	**Cost factor per 1000 tons (in 2009$M)**	**Cost (in 2009$M)**	**Cost (in 2014$M)**
Spruance Class	7800	260	2028	2261
Oliver Hazard Perry Class	4100	250	1025	1143
Ticonderoga Class	10,700	410	4408	4914
Arleigh Burke Class	8300-9800	390	3594	4008
Freedom Class	3700	N/A	637	700
Independence Class	3400	N/A	704	773

Table 27. Summary of T_1 Data for the Revised CER Model[4]

Using the data in Table 27 and taking into account displacement as the key cost driver, a new CER function representing a better "apples-to-apples" comparison of each of the platforms was developed and, therefore, allows for a more accurate projection of the expected cost of the SSC. Figure 41 illustrates the initial results and Equation (6) represents the revised CER:

$$COST = \$-616,522,049.92 + \$466,456.53 \times DISPLACEMENT. \quad (6)$$

A summary of T_1 data for the revised CER model is provided in Figure 41.

[4] (After Labs 2008; NavSource Naval History n.d.; United States Navy Fact File 2013a; United States Navy Fact File 2013b; United States Navy Fact File 2013c) .

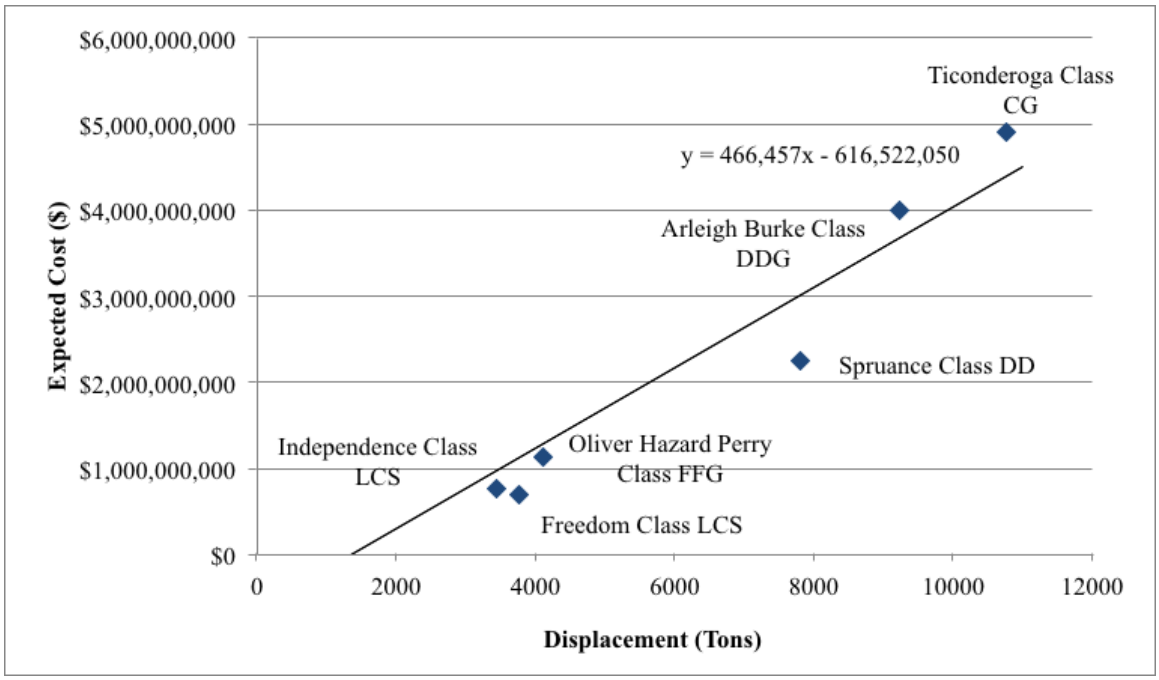

Figure 41. A summary graph of T_1 data for the revised CER model.[5]

The regression data is provided in Appendix B (Model # 2 regression). The model results present a challenge in the evaluation of a cost-effective surface combatant. The Ticonderoga class cruiser and Arleigh Burke class destroyer are not similar to the proposed SSC; they are highly-capable, multi-platform ships and categorized as capital shipping. In order to conduct a credible cost estimate, the analysis was revised to look at more analogous ships having a similar design and capability to the SSC. As the graph in Figure 41 demonstrates, this model is not useful in determining small displacement ships.

6. Final Document

The final document must provide "a means for other analysts to reproduce our work" (Nussbaum 2014c) and must be understandable by non-engineers. The final document needs to make sense first and foremost, but like all estimates, it must be credible and reliable. The first two models discussed above failed to meet the reliability criteria. The first model used average cost (instead of T_1) and the second leveraged data

[5] (After Labs 2008; NavSource Naval History n.d.; United States Navy Fact File 2013a; United States Navy Fact File 2013b; United States Navy Fact File 2013c).

from platforms which did not have similar characteristics as the envisioned SSC (it used capital shipping data). In order to ensure the decision maker has credible and reliable data, model three utilizes combatant platforms that most closely resemble the concept of the SSC. The analogous ships for this revised study includes: the Oliver Hazard Perry class frigate, the Freedom and Independence class LCS, and the Egyptian Ambassador Mk III. The United States builds the MK III and is very close in specifications to the proposed SSC. As a result, the MK III will also serve as a benchmark in the evaluation of the final cost analysis. The revised characteristics are outlined in Table 28.

Class	**Displacement**	**T_1 Cost (in FY2014$)**
Oliver Hazard Perry Class Frigate	4100	$ 1,142,600,000
Freedom Class LCS	2617	$ 699,800,000
Independence Class LCS	2771	$ 773,400,000
Egyptian Ambassador MK III	490	$ 322,500,000

Table 28. Further revised small surface combatant ship displacement versus cost in FY2014$.[6]

With this new data outlined in Table 28 and Figure 42, we determine the best-fit cost using an estimating relationship with the following equation:

$$\text{COST} = \$179,667,412.14 + \$222,452.43 * \textit{DISPLACEMENT}. \quad (7)$$

Initial results are shown in Figure 42.

[6](After Global Security 2014a; Naval Sea Systems Command 2012; American Maritime International 2010; Labs 2008).

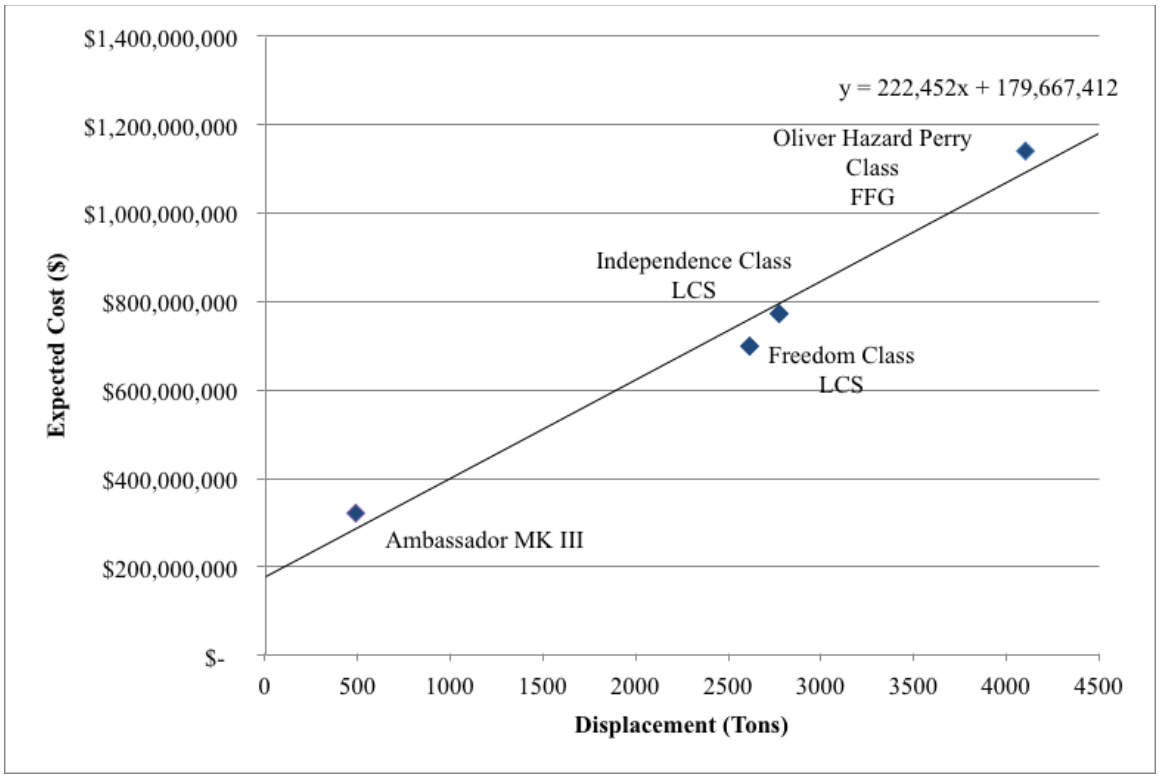

Figure 42. Final SCC T_1 cost versus displacement FY2014$.

The expected cost for a SSC with a displacement within the range of 600 to 1500 long tons is shown in Figure 42. The possible displacement trade space is a narrowed down to this range because of information gathered in the initial stakeholder interviews and logistics analysis. The stakeholder analysis revealed a desired displacement of 600 long tons (lower bound). The logistics analysis discovered a significant improvement in on-station time for 1500 long ton SSC versus a 600 long ton SSC and thus resulted in the 1500 long ton as the upper bound. The determined upper and lower bounds are shown in Figure 43.

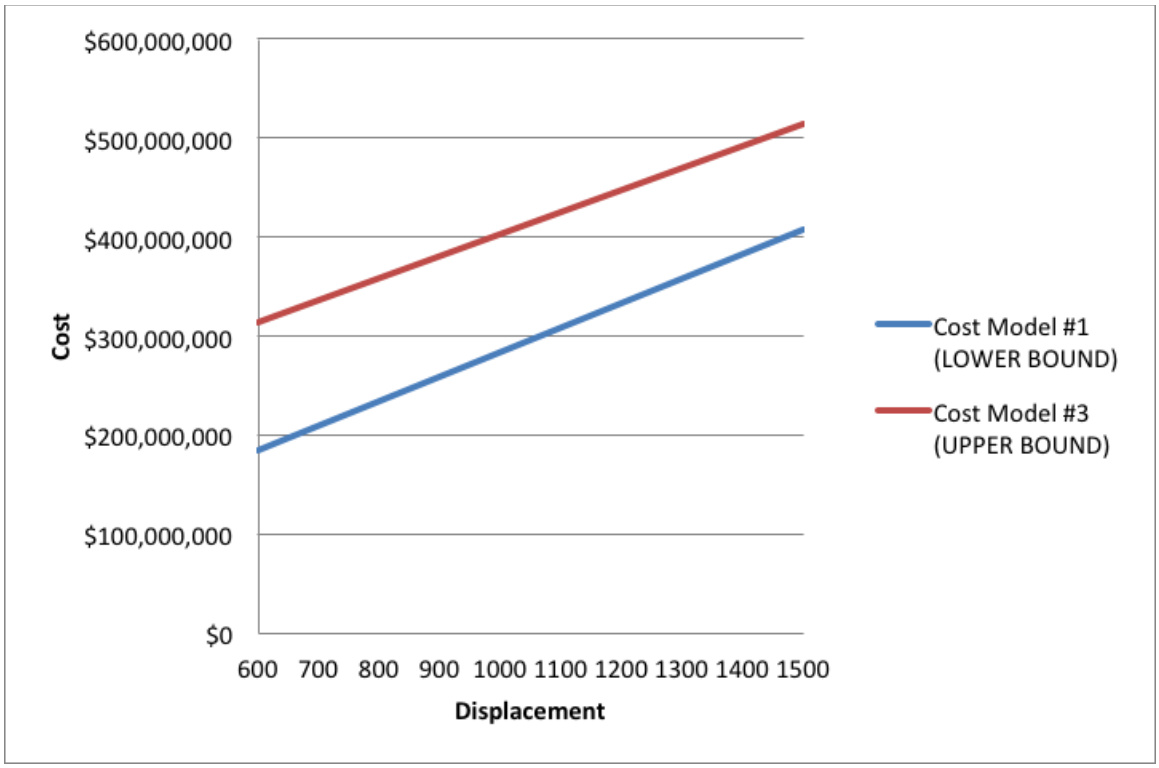

Figure 43. T_1 cost versus displacement in FY2014$.

The estimated trade space is between $183 million (600 LT vessel on the lower bound line) and $513 million (1500 LT vessel on the higher bound line). Figure 43 only includes models #1 and #3 because model #2 did not provide relevant cost data.

Additionally, results from M&S help to determine that 15 is the desired number of small combatant ships needed to win the proposed scenario in the South China Sea (SCS). In addition to the 15 required, risk, presence and deterrence are significant in the AOR and must be considered as well. In accounting for externalities and other combatant commander requirements, we determined 30 to be a safe estimate of the requirement for these ships in the SCS.

Also applicable in this final analysis is the 2014 Quadrennial Defense Review (QDR) guidance, which states the following:

> If deterrence fails at any given time, U.S. forces will be capable of defeating a regional adversary in a large-scale multi-phased campaign, and denying the objectives of – or imposing unacceptable costs on – a second aggressor in another region (Hagel 2014).

As stated in the QDR, the proposed fleet must be able to win a conflict in the South China Sea while also maintaining a significant advantage with a second aggressor in another region. This number (45) is determined by assuming the required fleet size in the SCS is 30 (the number required to defeat a regional adversary in a large scale fight as discussed above in the QDR quote) and an additional 15 additional SSCs are required to deny a second aggressor elsewhere. The SSC construction learning curve is in Figure 44.

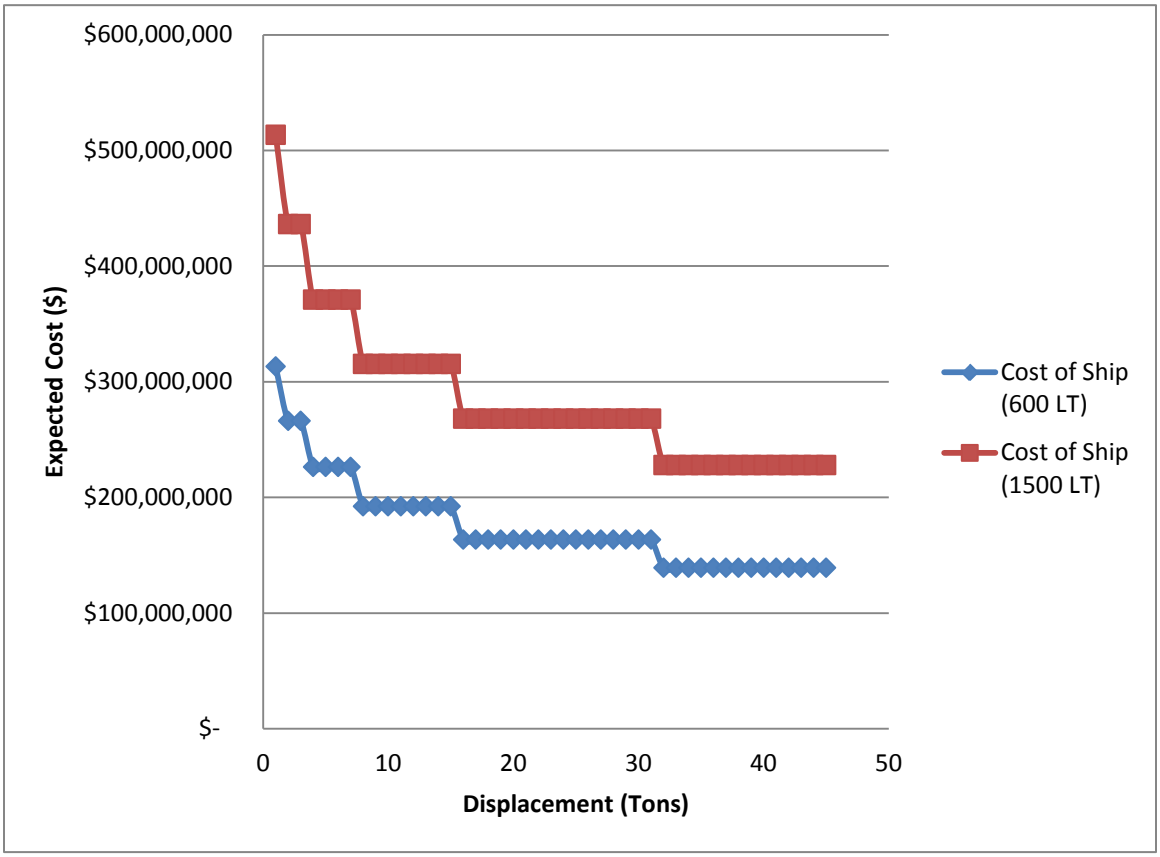

Figure 44. Expected learning curve for the construction of the SSC in FY2014$.

Next, the model can estimate the total cost of a program by estimating the lot cost in Equations (8) and (9) (Nussbaum 2014a) as follows:

$$CT_N = A(1)^b + A(2)^b + \ldots A(N)^b = A\sum_{x=1}^{N} x^b, \qquad (8)$$

where CT_N is the total cost of a lot size of N units, A is the cost of the initial unit constructed, and b is a learning curve. This function is estimated by:

$$CT_N \cong \frac{AN^{b_2+1}}{b_2+1}, \tag{9}$$

with values $A = \$513$ million and $b_2 = \ln(b)/\ln(2) = 0.23446$. Using Equation (9) the proposed 45-ship program total acquisition cost is $18,821,844,898 or approximately $18.8 billion.

The next step is to estimate the annual per ship O&S costs by category. Utilizing the same ratios of the T_1 cost for the LCS, we determine using the model the expected cost of the SSC for each of the O&S categories. Figure 45 contains the associated percentage of each cost category as a function of total O&S cost. This information is outlined to create a further trade space for follow-on study.

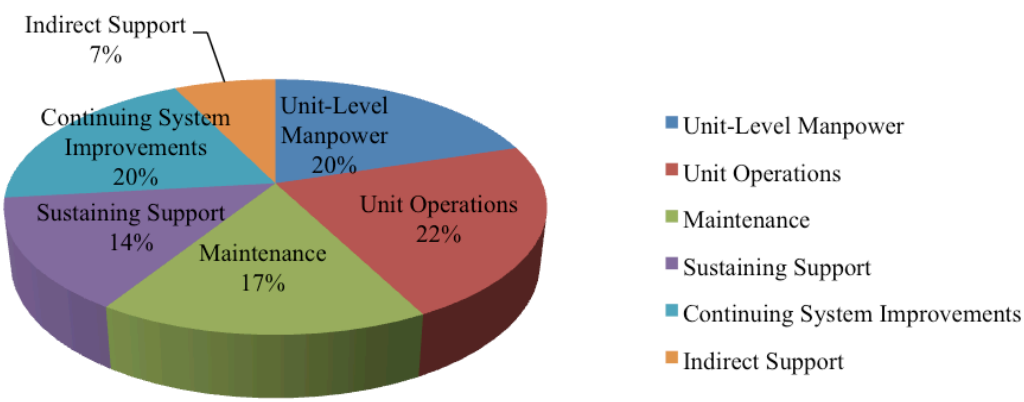

Figure 45. Operating and support costs by category for the proposed SSC FY2014$.

This study assumes a 20-year service life as outlined in Chapter VI Section C starting in 2014 and also an expedited shipbuilding plan of five craft per year (based on an average of four and one half per year to meet the 2025 deadline), the expected 10-year O&S cost for the program is estimated to be roughly $167 million per ship. The annual O&S breakdown for the SSC is contained in Table 29.

Small Surface Combatant O&S Cost by Category per year (in FY2014$)		Operational Cost for a 10 year period (in FY2014$)
Unit-Level Manpower	$ 5,501,708	$ 55,017,082.51
Unit Operations	$ 6,088,557	$ 60,885,571.31
Maintenance	$ 4,548,079	$ 45,480,788.21
Sustaining Support	$ 3,887,874	$ 38,878,738.31
Continuing System Improvements	$ 5,354,996	$ 53,549,960.31
Indirect Support	$ 1,980,615	$ 19,806,149.70
Other	$ -	$ -
Total Unitized Cost	$ 27,361,829	$ 273,618,290

Table 29. Ten-year per ship O&S calculations (after Naval Sea Systems Command 2012).

Finally, we aggregated these figures across the proposed 45-ship program the total cost of acquisition is $18,821,844,898 (approximately $18.8 billion for 45 ships) and the total O&S cost of a 45-ship program for 10 years of operation is $ $12,312,823,066. Additional considerations include an estimated disposal cost of $1,974,279 ($21.2 million) per ship or $ $88,707,543.22 ($88 billion) for the 45-ship program.

This total estimated cost for the entire 45-craft SSC program at $31,223,375,507 (roughly $31 billion) in FY 2014$.

E. WEAPON SYSTEM CONCEPT EXPLORATION

The small surface combatant is just one (albeit major) puzzle piece to the solution of a needed surface-to-surface missile capability; the other being the missile system itself. Although several possibilities exist for the missile system used on the proposed SSC, the Navy has invested significantly in the RDT&E of LRASM. For this reason, the following cost estimating exercise provides a detailed assessment of the total expected LCCE for a possible SSC LRASM system integration and cost.

1. Definitions

- **R&D:** Research and Development. In this context R&D describes the funding of Navy Research and Development efforts.
- **LRASM:** Long Range Anti-Ship Missile. Developed by the Lockheed Martin Corporation, the LRASM is a possible surface-to-surface missile system for the next generation fleet composition.

2. Option Exploration and Analysis

Several options exist to address this surface-to-surface missile capability gap. The current decision space must consider either an entirely new platform or retrofitting an existing platform such as a DDG or LCS. Extensive consideration to modifying the LCS with a surface-to-surface missile (SSM) has occurred. The LCS appears more fitting because the DDG is capital shipping and too valuable to risk in the SSM exchange.

Performing a formal cost estimate designed to determine the LCCE for the next surface-to-surface missile is challenging because the specifics (missile system and associated ship load outs) have not been determined. Looking into the missile Navy R&D funding does not provide much additional insight due to several systems still in consideration. However, the U.S. Navy currently has a five-year funding stream for the long range anti-ship missile (LRASM) development which (currently) far exceeds other funding streams in this sector. The LRASM funding stream is displayed in Figure 46.

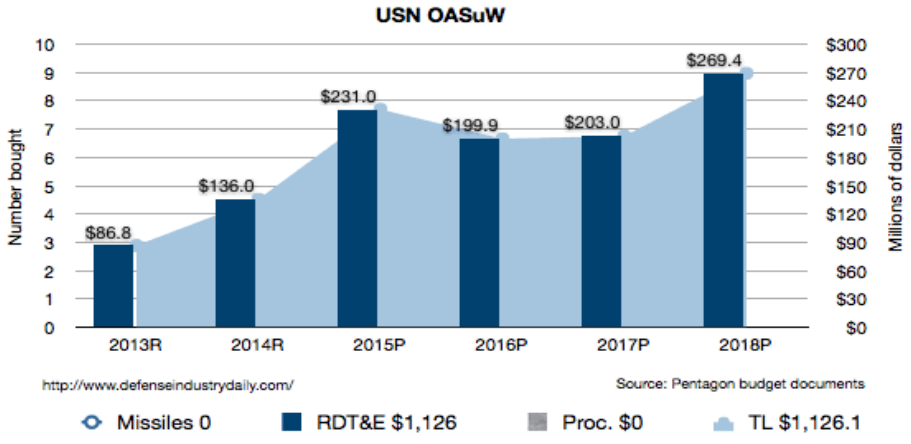

Figure 46. USN OASuW funding stream (from Defense Industry Daily 2014a).

We can analyze Figure 46 and assume the classic weapon system life cycle cost percentages of RDT&E (11 percent), production and acquisition (77 percent), and O&S (12 percent) (Galorath 2009). Next we extrapolate a system LCCE, with the cost of the LRASM program for this study is $10.2 billion as demonstrates can be demonstrated from the data in Table 30.

LRASM Life Cycle Cost Estimate		
LCCE Category	**Cost**	**Percentage of Total Program**
RDT&E	$ 1,126,000,000	11%
Procurement and Acquisition	$ 7,882,000,000	77%
O&S	$ 1,228,363,636	12%
Total	$ 10,236,363,636	
Total missiles needed	**3708**	60% of current TLAM inventory
Cost per missile (on average)	**$ 2,760,616**	

Table 30. LRASM life cycle cost estimate.

To determine the estimated total missiles in the LRASM program the analysis assumption of the current 4180 Tomahawk missiles in inventory (Federation of American Scientists 2014b) 60 percent (2508) will be retired to make room for the ship based LRASM. The air study (SEA-20B) estimates a LRASM need of approximately 840 additional missiles. Additionally, the modeling and simulation efforts determined a need for 360 additional missiles (45 ships with 8 missiles each). The total LRASM program inventory requirement is then at 3708 missiles as shown in Figure 46. By dividing the $10.2 billion program cost across 3708 missiles, we get an average per missile cost of $2.7 million each. Subject Matter Experts (SMEs) estimate the additional cost of integrating a weapon system at “50 percent the cost of the actual weapon system” (Solitario 2014). Assuming eight missiles per ship plus a 50 percent markup for ship integration costs puts the LRASM price tag at $33,127,392 per ship. To demonstrate this

idea, assuming the original T_1 cost of the Freedom (LCS-1) is $700 million (Naval Sea Systems Command 2012) and a LRASM system costs approximately $22.1 million (which includes the cost of the necessary canisters and eight missiles). Integration costs, again T_1, are estimated at approximately $11 million, bringing the final cost of the Freedom with LRASM to $733 million.

Another competing ship design option for the SSC is a new frigate design. With two variants for the Navy to ultimately choose between, the "patrol frigate" design utilizes the Coast Guard national security cutter as a baseline and modified for the Navy's specific needs. Several advantages exist for the Navy to adopt this approach. First, it's easier to meet a short deadline because the needed infrastructure is already in place since Ingalls has made six of the eight ships slated for U.S. Coast Guard use.

Some issues do exist with using this platform to fill the surface-to-surface missile gap. The proposed designs, which are multi-mission platforms, include the patrol frigate 4501 and the patrol frigate 4921. Therefore, investment in these designs will inevitably involve longer service lives and ultimately a much higher annual O&S cost per ship; both of which make the investment much higher. Even if the Navy chooses to invest in a new patrol frigate, the Navy will still have a surface-to-surface missile capability-gap. The patrol frigate seems to address the larger issue of cost effective presence around the world and self-defense, but lacks that missile punch the Navy needs in the very near future. In the end, the U.S. Navy and key military decision makers need to define their interpretation of the term "cost-effective."

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VII. RECOMMENDATIONS

While the South China Sea (SCS) was a focus in this project, there are many other areas in the region, which may demand attention. Future research on the impact of the SSC in these regions will provide continued and refined insights into the capabilities and possible operations of these ships. Worldwide there are many regions to investigate such as the Baltic Sea, Black Sea, Mediterranean Sea, and the Red Sea. The investigation into the SSC's capabilities against the dominant nations of these regions and the non-state entities that operate as well would yields new CONOPS and possibly new requirements for the future SSC.

Combat operations future research could be focused on the proposed modified LCS or new frigate detailed design. The ability for the SSC to operate in conjunction with these vessels would improve the performance of each in a symbiotic way. With the potential improvement in air defense for the armada, the SSC would be capable of plunging deeper into A2AD environments.

In addition to the new platforms, analysis on current platforms outfitted with newer weaponry and such as the NSM, LRASM, or a new unknown design. Understanding the capabilities these missiles bring to the ASUW arena, how they best integrate on new and future platforms could be applied to an upgraded SSC concept. Additionally, future research into improvements in sensor capabilities either on existing platforms, or building a new platform (manned or unmanned), could provide insight to future integration into the SSC, LCS, or existing platforms.

Ship self-defense was not considered in the combat modeling, although there was some influence for the probability of hit by RED forces. Future analysis on the effects of various defense weapons such as the ESSM, Sea Sparrow, RAM, and CIWS on not only incoming missiles but possible adversary aircraft may provide insight into the need for larger ships such as LCS, DDGs, or a new frigate designs.

The advent of new missiles would also require a change in the CONOPS for both current and future platforms. Analysis on the "old" CONOPS and generating and

modeling new CONOPS could provide insight into optimizing current operations and future operations on developing platforms such as LCS.

Areas relating to this concept and how to integrate a surface fleet with current and future logistics platforms are well suited for additional study. SEA-20A made no attempt to optimize performance of the combatants themselves, as hull design, propulsion system, and other performance factors were not considered. Focus was specific to the SCS scenario, with other geographical areas representing various challenges and ease restrictions relative to the SCS. It may be valuable to adjust the type of logistic ships or the effect of submarine based logistics, and the effect it would have of idle time for the combatants.

Another area that merits additional study is the political spectrum in allied and friendly locations for possible SSC support. The logistics portion of this study provides a general understanding of the challenges that are inherent to maritime security, focusing on the most difficult track and the most severe circumstances that allow for a baseline to be developed. This baseline is the worst-case scenario for force structure and size that would be capable of operating in this environment.

In regions such as the SCS, small islands may provide the necessary acreage to build small logistics locations to refuel and refit combatants using shore based logistics in the form of an expeditionary basing concept (EBC). The EBC is a small base, which can be set up and removed within a short time frame. These EBCs would have parts, supplies, fuel, and ammunition for the small combatants and would be established on islands and in atolls where the water is deep enough to support the SSC.

The HYDRA system is another concept that could be explored in regards to fix locations for resupply. For HYDRA, “Each payload module would plug into a standardized enclosure that would securely transport, house and launch various payloads, while sustaining payload functionality for weeks to month” (Defense Advanced Research Projects Agency 2013). Along the same lines as HYDRA submarine logistics may be a concept that deserves future investigation. Submarines could provide a protected, low detection platform to transport fuel and stores into an A2AD environment in the form of

submarine freight transportation system (SFTS) (Global Intelligent Transportation System 2011).

Cost analysis was primarily focused on the ships, while accounting for the technology inherent on the comparison platforms. The cost to retrofit current platforms to utilize newer and possible more capable missiles and weaponry was not taken into account. Platforms that could be considered are LCS, CGs, and DDGs in the current U.S. fleet inventory.

The cost of implementing unmanned systems as “organic” assets was not considered. Unmanned systems may provide a capability for ISR and targeting, which may affect the overall cost per platform. Unmanned vessels would negate the manning costs at sea, and the overall as the cost of building the ships themselves

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VIII. CONCLUSION

Designing the small surface combatant (SSC) to the demands of sea combat in the South China Sea, the Persian Gulf and the Strait of Malacca, where possible adversaries employ effective anti-access area denial (A2AD) weapon systems, is a challenging task. Tackling this task is made easier by utilizing the broad expertise of the integrated project team, which includes United States Naval officers with expertise in surface warfare, air warfare and undersea warfare combined with civilian and military officers from the country of Singapore. The team's professional and cultural diversity allows for approaching the problem from an unbiased, open-minded perspective. The integrated project team exercised the systems engineering approach to problem solving to arrive at a potential solution. Using the systems engineering process we arrived at a solution for the small surface combatant with a displacement between 600 and 2000 tons, possessing eight effective ASUW missiles, employing manned and unmanned sensor platforms to increase detection and classification range and working as a system of systems in an armada of ships.

The systems engineering process model utilized by the SEA-20A project team provided a methodical approach to solving the problem presented in the tasking statement. As the understanding of the problem continued to improve, the model was used to revisit previous work and through an iterative process, arrive at a possible solution. The first iteration of the modeling and analysis phase of the process model clearly revealed the single mission ASUW design is not capable of surviving in a multi-threat environment operating independently or with other SSCs. With the multi-threat environment capability gap identified, the focus changed to component selection including external systems with the SSC and ultimately led to the system of systems solution of the armada. Using the system of systems approach allows for other systems to make up for undersea and air domain deficiencies inherently included in the single mission SSC.

A2AD weapon systems threaten to hold at risk the U.S. Navy aircraft carrier which traditionally fills the role of power projection in the Navy surface force structure.

To augment a carrier's ability to project power into littoral or coastal regions, a concept of operations (CONOPS) was successfully tested through modeling and simulation. With a focus on Phase II (*Seize the initiative or combat*) operations in a multi-threat A2AD environment, the armada advanced from theory to validated concept. The armada concept is easily able to be tailored to the specific threats in the area and can be scaled to meet combat demands. The CONOPS for the armada utilizes Arleigh Burke destroyers to provide air defense of the group. For anti-submarine warfare (ASW) operations, Littoral Combat Ships (LCSs) equipped with ASW modules combined with air platforms such as MH-60R's and P-8 Poseidon's. SSCs will provide control the surface domain. Additionally, organic sensors in the form of manned and unmanned platforms provide intelligence, surveillance and reconnaissance (ISR) to all platforms within the armada. Utilizing manned and unmanned sensor platforms greatly expands the engagement range by allowing for long range detection and classification.

To advantageously employ the benefits of the armada system of systems approach, a significant amount of time was devoted to determine the capabilities the SSC must possess to be a successful ASUW platform. Analysis indicates the SSC should be capable of sprint speeds greater than 25 knots. Although speeds in excess of 25 knots were not significant in the analysis and did not contribute to increases in effective combat power, a sprint speed of more than 25 knots allows the SSC to move to an advantageous missile launching location. Additionally, this speed characteristic allows the SSC to maneuver to safety after completion of all salvos. Each SSC should be capable of using organic assets to attain a detection and classification range of at least 60 nautical miles. The SSC missile magazine should be at least eight missiles fired in salvos of two missiles per engagement. Each missile should be capable of engaging an adversarial ship at least equal to maximum sensor range, but the analysis also demonstrates a 90 nautical mile range is advantageous if the ships are networked. However, networking was found to be marginally effective, mainly since the ships are constrained close together in a littoral or coastal region. Composition of the armada is scalable based on enemy threat levels, but as an example, fifteen SSCs, two LCSs, and two DDGs are a sufficient armada force to

defeat large multi-threat forces with marginal losses (assuming an enemy force composed of ten missiles boats, four destroyers, two frigates, five submarines and one aircraft).

Another major component of the research is analyzing the logistical needs of sustaining the SSC at sea. Assuming A2AD threats have the ability to hold large, minimally armed replenishment ships at risk the study explored an alternative method of replenishing the SSC at sea. Initial exploration of the problem led to a discovery of the logistical item with the largest demand is fuel and not missiles or crew rations. To increase the time on station, the SSC must conduct at sea replenishment. A logistical simulation which uses a JHSV configured to ferry fuel within the A2AD zone to the SSC from a large replenishment ship (T-AKE) operating outside the A2AD zone. Analysis led to the discovery of a network of two T-AKEs operating with two fuel ferries (tanker variants of JHSV) can support up to sixteen 1500 ton SSCs operating in an A2AD environment. Although not as efficient as using traditional replenishment ships, this fuel ferry method does merit consideration if T-AKEs are unable to enter the region due to a high risk of detection and destruction by ASCMs and ASBMs. Additionally, an alternative method of artificially extending the patrol length of a small combatant by changing doctrinal triggers for requiring refueling can change add days to on station time of the SSC. For example, using an analysis of average fuel burn and capacity of a 1500 ton surface combatant indicates an average five day patrol length before the vessel was at 50 percent fuel capacity and required refueling. If the doctrine is shifted to allow for refueling at 20 percent fuel remaining, patrol length increases three days to a total of eight days. Changes in doctrine and new methods of sustaining small ships at sea combined with an efficient hull form and propulsion system are essential to the success of the SSC.

A major component of the tasking statement is to design a cost effective SSC capable of delivering additional capability to augment existing force structure. Using the 600 ton SSC as the lower bound and the 1500 ton SSC as the upper bound, analogous ships were selected and used to develop a linear regression based cost estimation model. Assuming the Navy would acquire 45 ships of the final desired tonnage, the model calculates the first unit cost (T_1) and implements an 85 percent learning curve into the

ship production calculation to determine approximate final unit cost. For example, the 600 ton SSC was calculated to have a T_1 cost of $313 million and the cost of SSC unit number 45 was determined to be approximately $138 million. For the 1500 ton SSC, the T_1 cost was estimated at $513 million and unit number 45 was estimated at $227 million. Both the 600 ton and 1500 ton SSC variants fall below current LCS acquisition cost and will effectively augment the ASUW capability of the fleet.

After using a modified systems engineering process model to provide a structured approach throughout the duration of the project, the research determined an effective conclusion that meets all of the major requirements of the tasking statement. The seaworthiness and endurance of the 600 ton variant of the SSC leads to the final recommendation of further exploring the 1500 ton variant with the capabilities listed above. A single mission SSC can be a viable platform for the Navy to grow its force structure as long as CONOPS, capabilities, sustainment and cost remain balanced necessities of the detailed design effort. This ship has the potential to be a cost-effective force multiplier that can meet the needs of the U.S. Navy in 2025 through distribution and offensive ASUW power.

APPENDIX A. JOINT C4I COURSE CAPSTONE BRIEF

CAPSTONE CC 4913

COMMAND AND CONTROL: POLICIES AND PROBLEMS

LT DUSTY BARTLETT, USN
LCDR MARC BUMATAY, USN
LT RAY CASTILLO, USN
LT RICHARD DENTLER, USN
LT ISAAC DONALDSON, USN
LT GRANT GRAEBER, USN
LCDR KEVIN JOHNSTON, USN
CAPT KEVIN MCMULLEN, USMC
CAPT JOHN MOONEY, USMC
LT VAN STEWART, USN
LT CARLTON SUMMERVILLE, USN
LT WISSEM TEBAI, TUNISIAN AF

OPERATION: MUTE MONKEY

AGENDA

- Background
- Scenario
- Assumptions
- Mission, Commander's Intent, and Org. Chart
- Naval and Air forces
- Concept of Employment (COE)
  - Over-the-horizon (OTH) Communications
  - Intra-squadron (IS) Communications
- Implementation Case

2

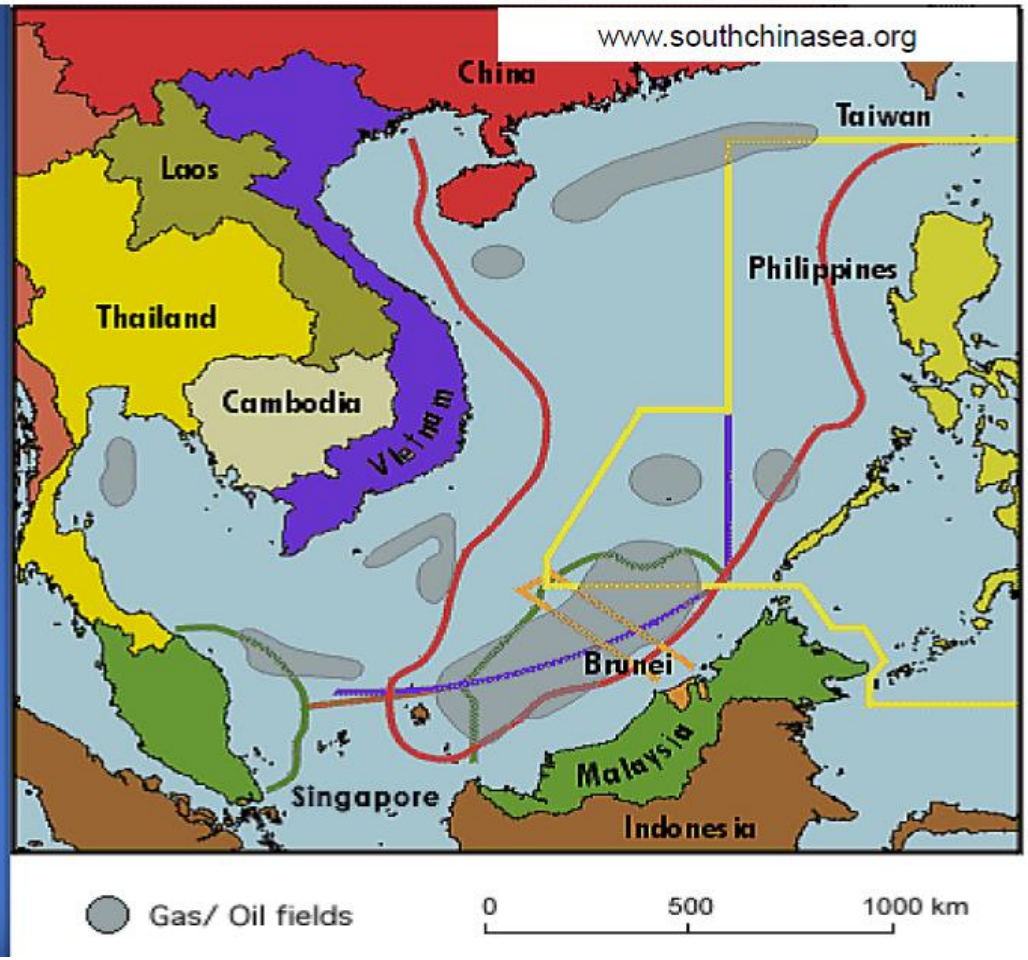
BACKGROUND

- Under direction from the new President, the Philippines altered its Taiwan policy, officially recognizing it as sovereign nation.
- In response, China has violated international law by conducting intimidating acts in the South China Sea.
- China has seized control of Flat Island and Commodore Reef, areas claimed by the Philippines and contested by US coalition partners.
- Hostile action has been non-lethal thus far, with Filipino forces giving way to PRC combatant forces.
- The international community is alarmed and the US has responded with naval and air forces.

3

AREA OF INTEREST

DISPUTED AREAS



Countries Claiming Ownership

- China
- Vietnam
- Malaysia
- Taiwan
- Philippines

5

SCENARIO ASSUMPTIONS

- China would not escalate conflict beyond maritime warfare.
- Operations will frequently involve coalition partners.
- Singapore will serve as the TOC.
- US will be TACON over all forces.
- 80% Availability of U.S. Assets.
- Assets are already forward deployed.
- Conflict where secondary communications are necessary would last no longer than 60 days.
- Reachback capability provided for by asset(s) outside SATCOM denied environment.

SCENARIO PHASES

- PHASE 0 (past):
  - US and PI lodged official complaint with the UN.
  - Security council attempted to censure PRC, which was vetoed by the PRC.
  - Diplomatic rhetoric increased.
- PHASE 1 (current):
  - US launches naval and air forces to disputed areas to deter PRC combatants.
  - PRC has begun to conduct electronic warfare, including jamming.
  - PRC and US combat forces have not directly engaged, though UAVs from both sides have been downed.
- PHASE 2 (pending): Direct naval action.
- PHASE 3 (unlikely): Land-warfare on islands to forcefully remove PRC forces.

7

MISSION

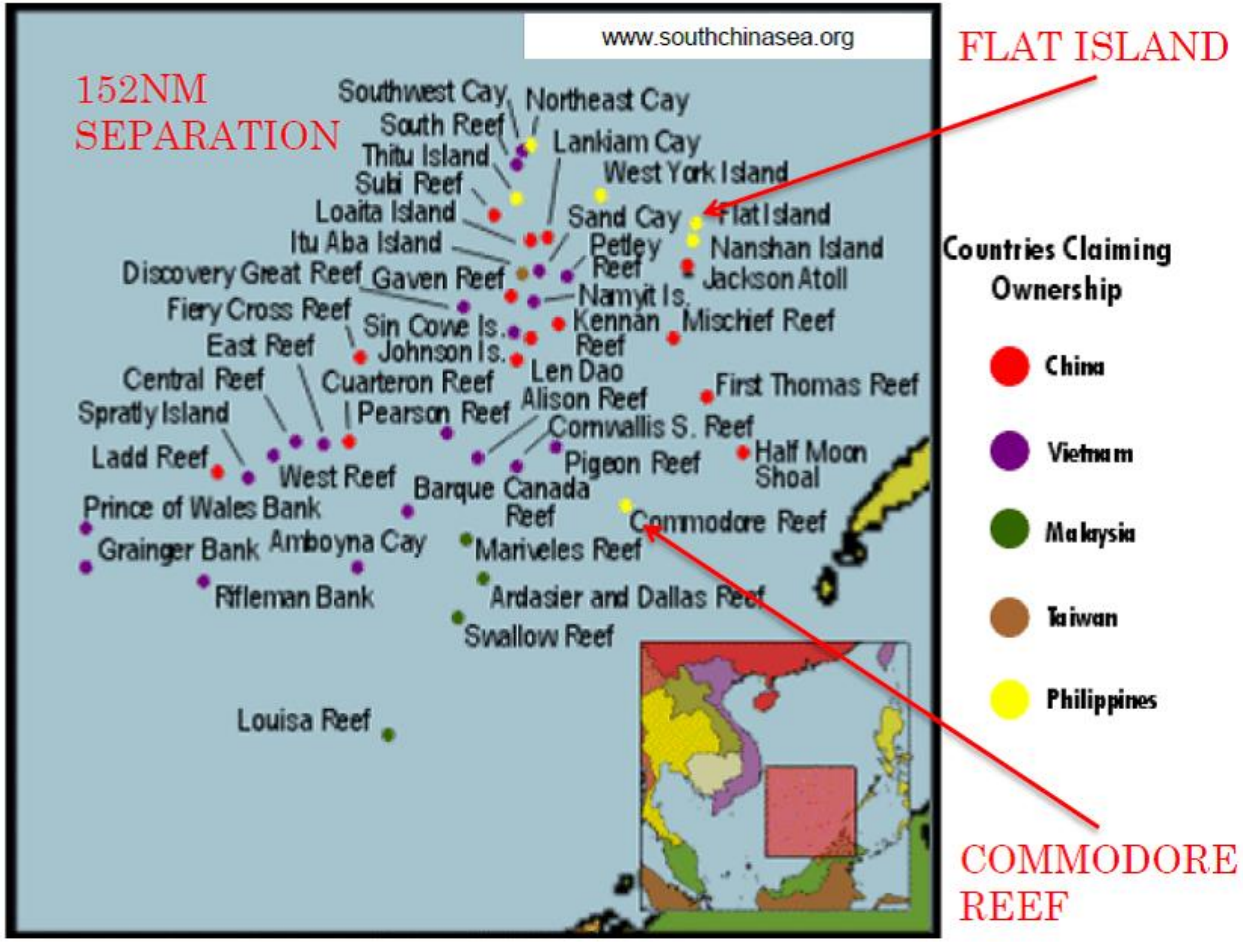
- US forces provide support to Coalition partners during the execution of Operation Mute Monkey in the South China Sea.

- End-state: Deter Chinese aggression, restore occupied islands to Philippine control, retain US influence in East Asia

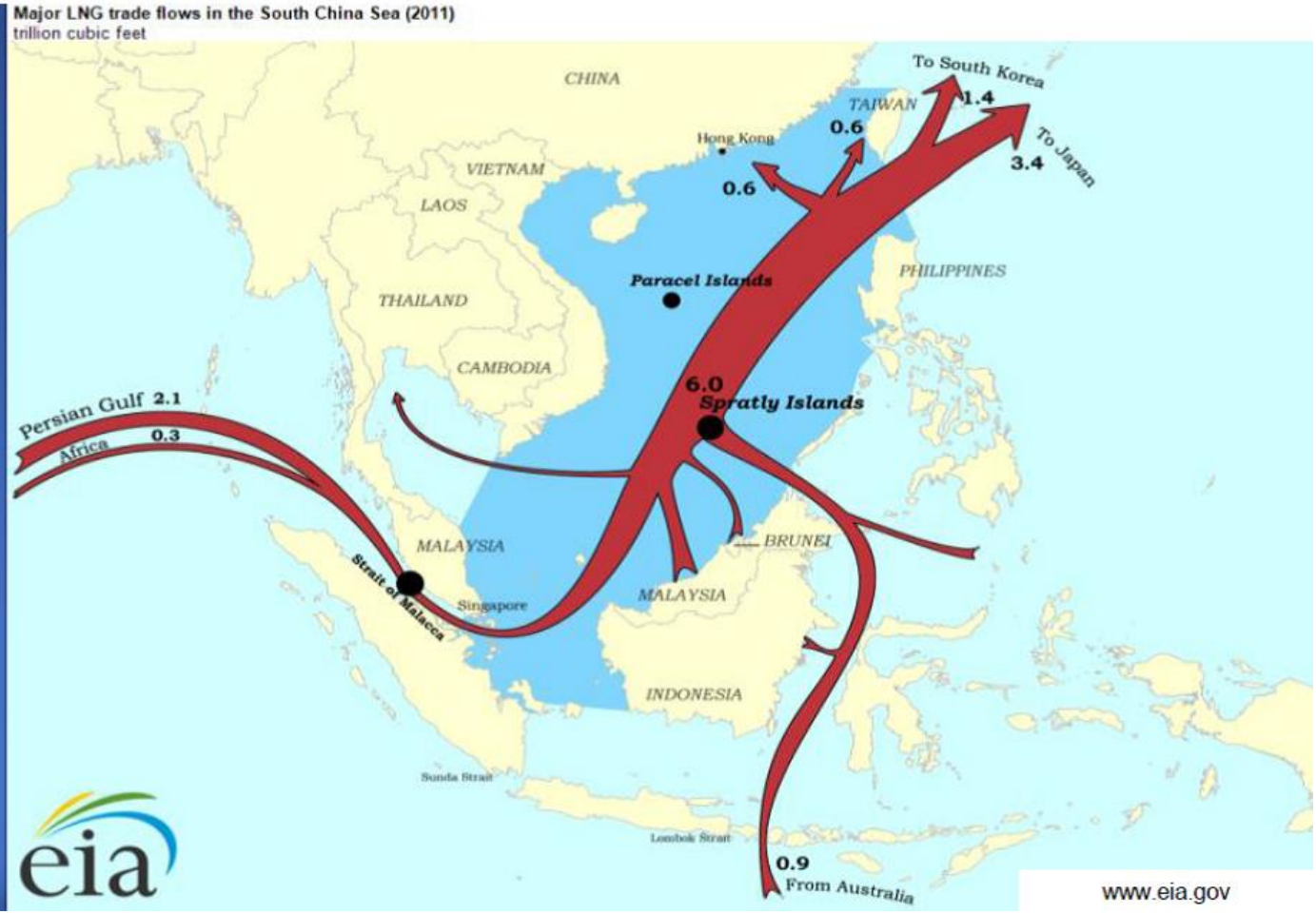
- Missions
  - Maintain freedom of the seas.
  - Deter aggression.
  - Provide leadership in coalition operations.

8

MILITARY OCCUPATION



SHIPPING LANES

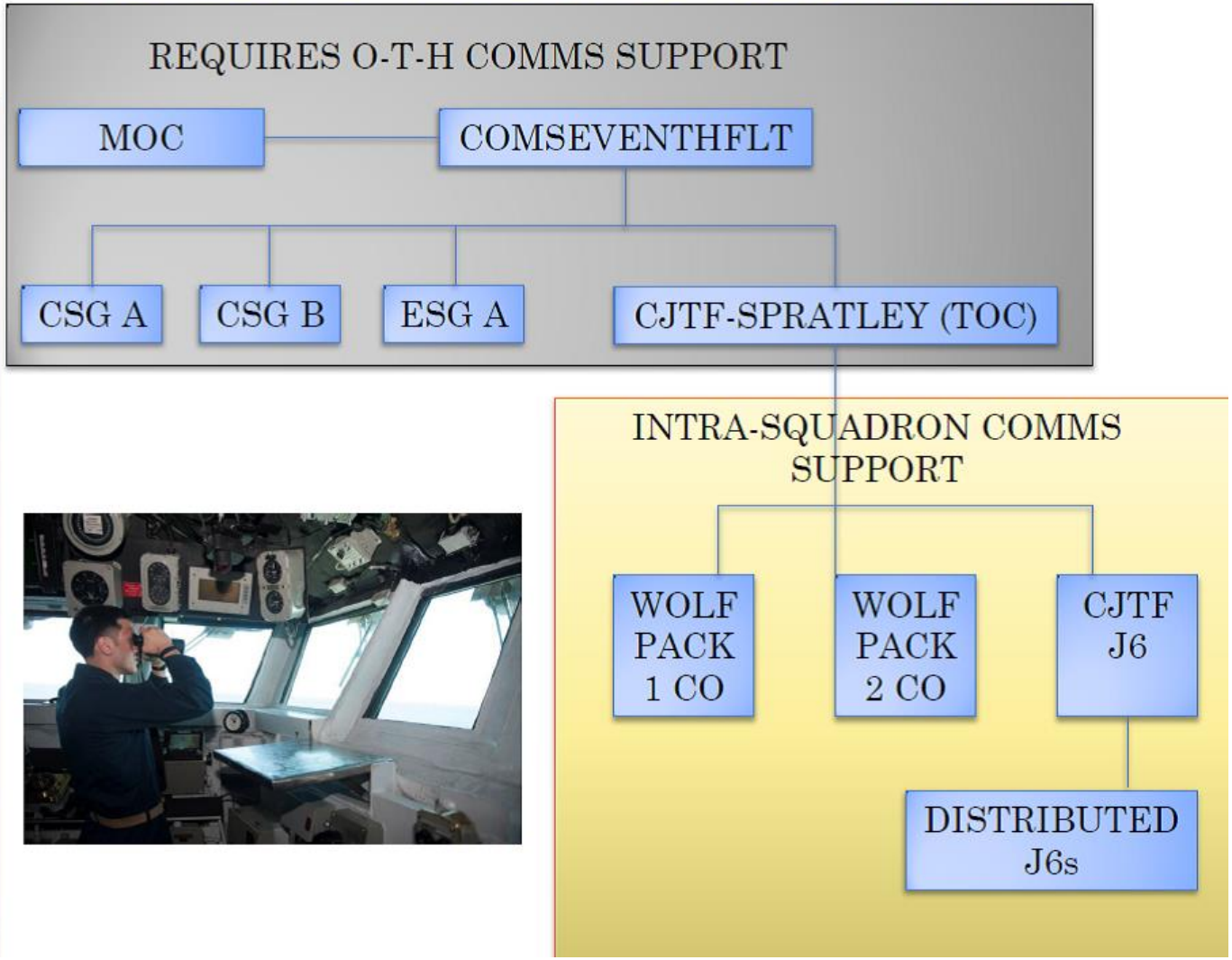


COMMANDER'S INTENT

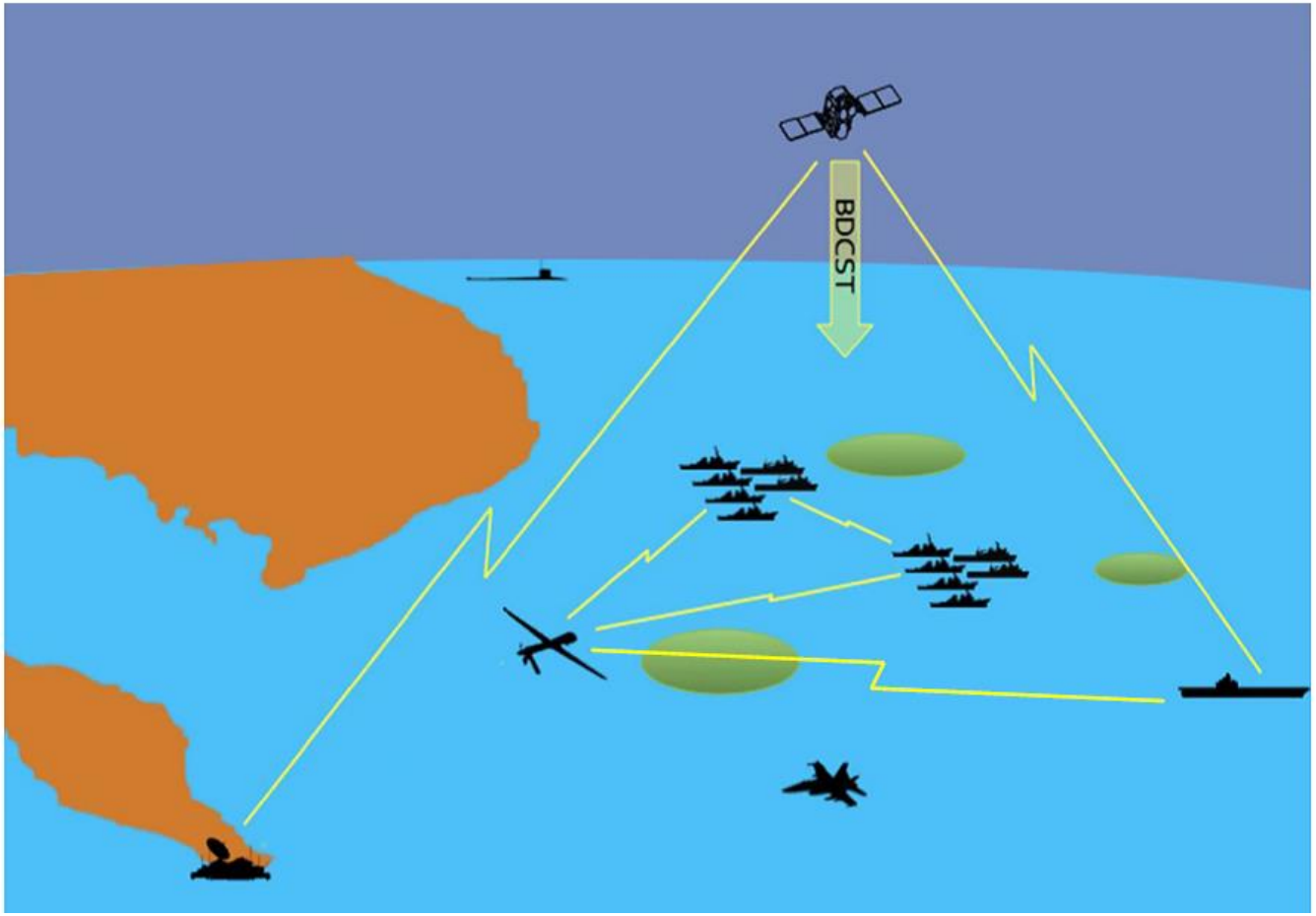
End State: Deter PRC land and maritime aggression and deny China the use of the seas in the vicinity of the Spratly Islands while hostilities are ongoing.

11

OVERVIEW OF REPORTING REQUIREMENTS



COMMUNICATIONS OVERVIEW



13

NAVAL FORCES

- 2 full CSGs: 1 each supporting the northern and southern contested areas with naval airpower. Each CSG has:
  - 1 CVN with embarked CVW
  - 1 CG, 2 DDG
  - 1 FFG, 1 SSN

- 2 Wolfpack groups located close to the contested areas (requiring comms support). Each has a combination of:
  - 1 LCS
  - 1 CVEX – with embarked rotary UAV "wing"
  - 4 Missile Boat
  - 2 PC

U.S. Surface Combatants - Large

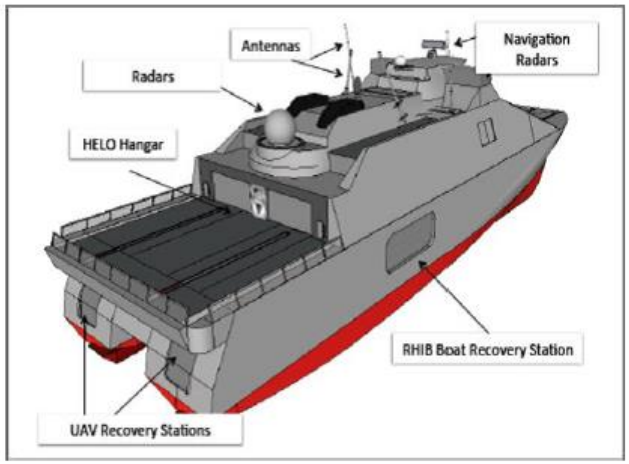
LCS

- Displacement: 3500 Metric Tons
- Crew size: Accomodations for 75 Sailors
- Speed: >40 Knots
- Length: 388 ft
- Beam: 58 ft
- Range: 3,500 nm at 14 knots, approx. 1,000 nm at full load Sprint Speed
- Configured for MIO ops

CVEX

GOAL: Ensure a robust platform that enables the use of new UAS's while facing budget constraints

- Modified JHSV hull form
- Max speed – 50 kts
- Dispace 4000 LT
- Travel up to 3200 nm
- Carries 60 BQM-74E and 15 BQM-34S target drones
- Launched via EMALS and JATO
- Flight deck – 4 flight lanes and 3 helos
- 2 diesel engines and 2 gas turbines



U.S. Surface Combatants - Small

Missle Boat

- Displacement: 586 LT
- Crew size: 49+8 officers
- Range: 4,000 nm
- Speed: 37 kts (18 cruising)
- Length: 203 feet
- Beam: 28 feet
- Propulsion: 4 diesels/4 shafts
- Armament: 8 Harpoon anti-ship, 2 VLS anti-air missiles launchers, 2x3-tube torpedo, 1x76mm Oto Melara

Coastal Patrol

- Displacement: 331 tons
- Crew size: 24+4 officers
- Range: 2,000-2,500 nm
- Speed: 35+ kts
- Length: 179 feet
- Beam: 25 feet
- Propulsion: 4 diesels/4 shafts
- Armament: 5x.50cal machine guns, 2xMG240 machine guns, 2xMK 38 25mm Bushmaster, 2xMK 19 40mm automatic grenade launchers, 6 Stingers

U.S. Naval Air Forces

- 2 CVWs:
  - 4 VFA (F-18E/F)
  - 1 VAQ (EA-18G)
  - 1 VAW (E-2C)
  - 1 HS (SH-60S)
- 2 UAVWs:
- 6 E-6B (Mercury) TACAMO
- 8 MQ-4C (Triton) BAMS UAV
  - 4 comms relay assets
  - 4 ISR assets
  - Specifically fragged on the ATO
- E-6B aerial refueling provided by USAF from Andersen AFB

CONCEPT OF EMPLOYMENT (OTH)

- Satellite resources primary means of communications.
- When SATCOM denied environment affects individual units, alternative reachback links will be provided.

- Surface Platforms
  - CVN or other large throughput surface platform is outside SATCOM denied area.
  - Store & Forward Capability.
  - Reachback provided by SATCOM through connection to IS platform.

- Aerial Platforms
  - BAMS or TACAMO inside SATCOM denied area.
  - Reachback provided through either satellite link or large throughput surface platform.
  - Multi-circuit on-station communication relay capability.

CONCEPT OF EMPLOYMENT (IS)

- Satellite resources primary means of communications.
- In SATCOM denied environment, alternative communication infrastructures required.

- Voice
  - Current voice communications infrastructure sufficient to support continued voice comms during SATCOM denied operations (LOS).
  - Some voice comms capability lost, including: UHF SATCOM.
- Data (and voice)
  - In a SATCOM denied environment, alternative IP data exchange methods are insufficient
  - Current alternatives include: BFEM (HF).
  - Future alternatives could include: Aerial MANET and QR Codes.

OTH COMMUNICATIONS OVERVIEW

OTH Communications Assumptions

- Jamming will be land based (worst case is Hainan Island)
- Positioning assets outside the landmass will avoid the jamming window.
- Multiple UAVs will need to be used to support communication and network requirements (OTH versus IS)
- Manned and unmanned aircraft can be de-conflicted and operate autonomously or in coordination with other manned platforms

MOBILE JAMMING

- Jamming footprint may be mobile depending on the capabilities of the Chinese.
  - This would be possible through ship-mounted SATCOM jamming equipment.
- Friendly forces would need to adjust position of air and surface assets to maintain level of assured communications.

OTH Communications Requirements

- SATCOM denial will impact long range communications between tactical forces, on-scene commanders, and theater leadership (fleet and COCOM level)
- Alternative methods will be required which:
  - Permit voice and data communication on non-impacted circuits
  - Traverse a distance of approximately 300nm radius (600nm diameter)
  - Be encrypted
  - Have 24-hour coverage

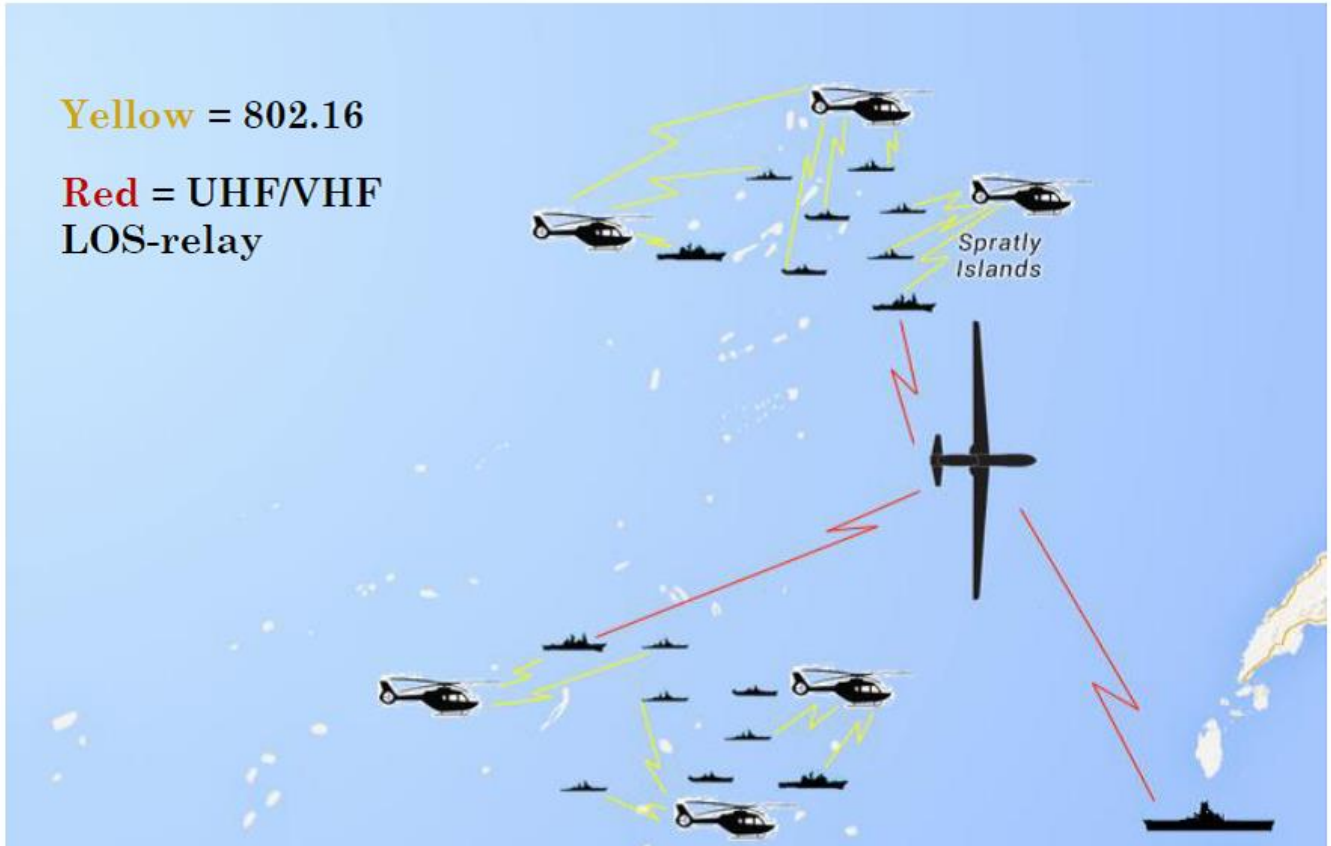
PERSISTENT-PRESENCE ALTERNATIVES

- E-6B Mercury (TACAMO):
  - Range = 6,600 nautical miles (7,590 statute miles, 12,144 km)
  - Airborne time of approximately 32 hours.
  - E-6s based out of Andersen AB, Guam, would be on station IVO Jolo Island (transit of about 1400 miles) in approximately 3 hours
  - Round trip transit time would be 6 hours, permitting 26 hours of continuous on station time.

- MQ-4C Triton (BAMS):
  - 30-hour endurance
  - Roughly 5-hour transit from Andersen to on station point. 10-hour round trip transit yields 20 hours on-station.
  - Operates at 60k plus, expanding the RF horizon and look-down footprint above what TACAMO is capable of at 40k.
  - Sensor suite offers ISR capability far in excess of TACAMO, permitting dynamic re-tasking to support emergent collection requirements.

STAGGERING ASSETS WILL PERMIT 24-HR COVERAGE

I-S COMMUNICATIONS OVERVIEW



Note: Each Wolfpack unit is a "node" in the 802.16 wireless mesh network.

IS COMMUNICATIONS ASSUMPTIONS

- SATCOM denied environment: general UNCLASS web browsing will be given the lowest priority or disabled to ensure optimal bandwidth for mission critical applications.
- A large throughput asset will be available outside EMCON environment.
- Bandwidth above conventional VHF data rates will be required.

IS COMMUNICATIONS REQUIREMENTS

- Primary Communications – Data
  - Aerial MANET
  - Option 1: 802.11
  - Option 2: 802.16
  - Both Options:
    - Sufficient for SVTC, ISR, and Command and Control
    - Coverage: Roughly 50,000 sq km surrounding the Spratly Islands
    - SIPR/NIPR and compartmentalized networks
- Secondary Communications – Voice
  - Redundant Communications Link
    - Encrypted Frequency Hopping, VHF with RTX if required
    - Encrypted HF single frequency, comms of last resort
- Tertiary Communications Link – Optical
  - 60 Hz optical scanner for signal flag or QR derivatives

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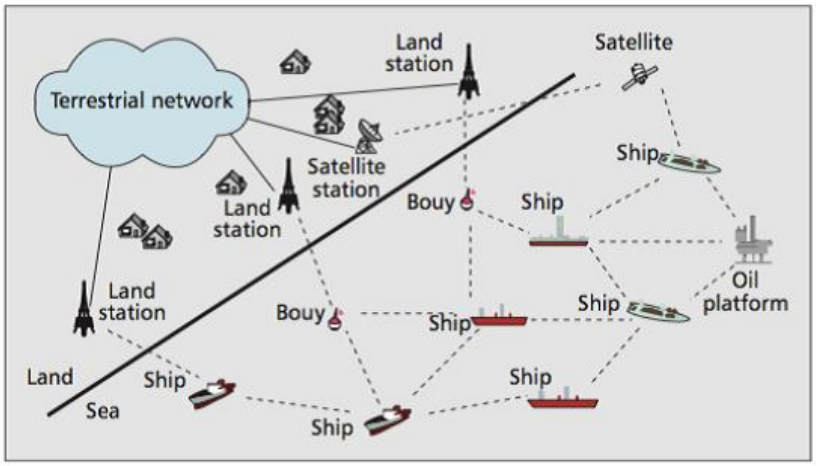
OPTION 1: 802.11

- Non-Directional UAV 802.11 is infeasible (300 ft).
- Hazra & Seah: Topo Broadcast in Maritime Mesh Networks with Dir Antennas (2010)
  - School of Eng & CompSci, University of Wellington
  - Bouys vs. Aerial
  - Phase I: Network Discovery
  - Phase 2: Network Operations
- Ioannis et al.: ROTA: an Archipelago-Wide Area Network for High Speed Communication to Ships
  - Martime Mesh network designed for Greek Isles
  - Land based nodes
    - 30 m above sea-level, up to 20 Km LoS and 10 Km Tx/Rx (802.16)

OPTION 2: 802.16

- Designed as a directional protocol.
- Zhou et al. (2013) TRITON: TRI-media Telematic Oceanographic Network
  - Designed for shipping lanes, close to shore
  - Both land and sea-based nodes
  - Dis: 14Km @ 5.8 GHz w/ 6 Mbps (Ideal weather)
  - Tx Power: 5W, Ant 4.5m diameter



VHF/UHF DATA vs 802.16

HF/BFEM	VHF/UHF	802.16
• Tx Power: N/A • Freq: <30 kHz • Antenna: Omni/Directional • Distance: Unlimited • Bandwidth: 9.6 kbps	• Tx Power: 3W • Freq: 30 kHz • Antenna: Omni • Distance: 13 nautical miles • Bandwidth: 48.6 kbps	• Tx Power: 5W • Freq: 5.8 GHz • Antenna: Directional • Distance: 7.5 nautical miles • Bandwidth: 6144 kbps

- **802.16 provides a greater level of *assured* comms function than UHF/VHF does.**
- **802.16 necessary to sup**
- **port bandwidth requirements for timely image transfer**

UAV REQUIREMENTS

- Capabilities
  - Maintain an aerial mesh network based on directional 802.16 protocol
  - Shift coverage focus as fleet conducts surface operations
  - Other capabilities as required (ISR, radar, weapons)
- Maintenance & Logistics
  - 4-Hour minimum on-station time
  - Launch and recover from ANY surface platform
  - Recovery beacons and key zero-izing protocol

Rotary UAV Approximated Physical Specifications

Specifications

Length ..... 12 ft
Width ..... 3 ft
Height ..... 5 ft (3.3 m)
Gross Takeoff Weight ..... 1,500 lbs

Performance

Speed ..... Undetermined
Operational Ceiling ..... 10,000 ft
Maximum Endurance ..... 4 hrs
Maximum Payload (Internal) ..... 250 lbs
Typical Payload ..... 175 lbs (5 hrs)

Boat Footprint

Per Unit ..... 24 ft^2 (12 ft x 3 ft)
Missile Boat, Max Carry ..... 3 units (150 ft^2)
PC, Max Carry..... 2 units (100 ft^2)
CVEX, Max Carry..... 30 units (1500 ft^2)
LCS, Max Carry..... 15 units (750 ft^2)
Fleet Max Carry (2 LCS, 2 CVEX, 8 MB, 4 PC) ..... **122 units**
WP Min Carry (LCS, CVEX, 4 MB, 2 PC) ..... 20 units (s/o 30 km)

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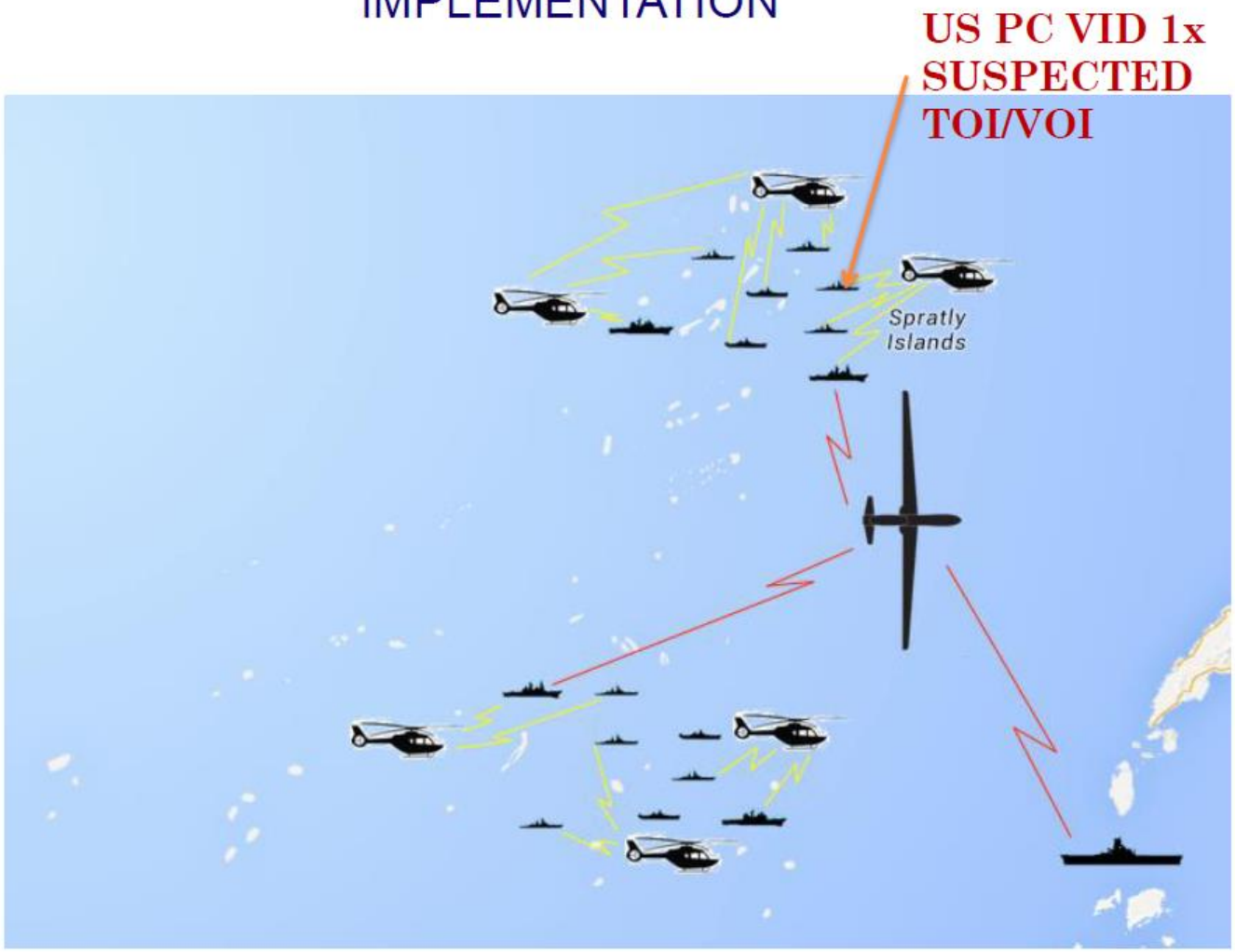
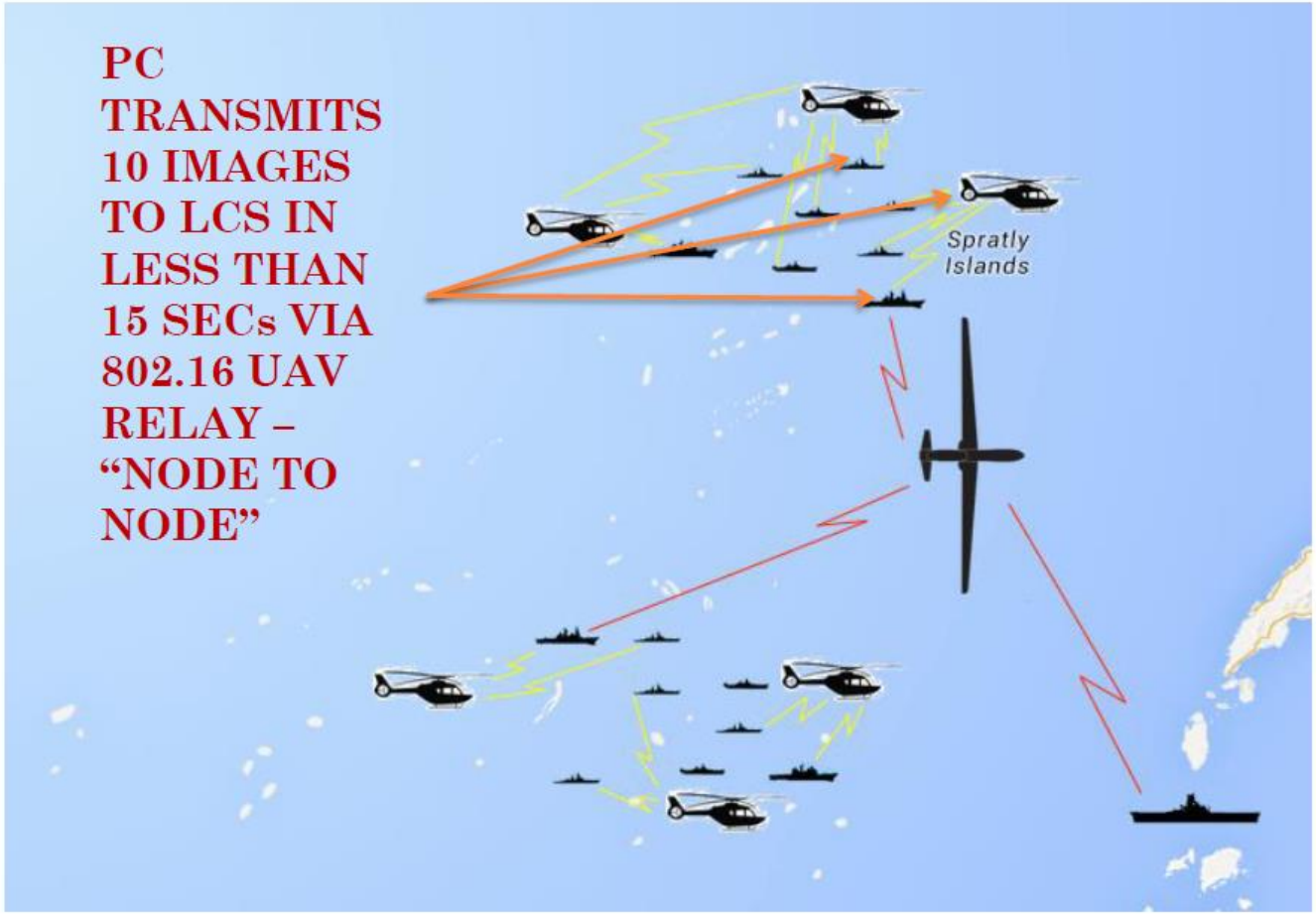
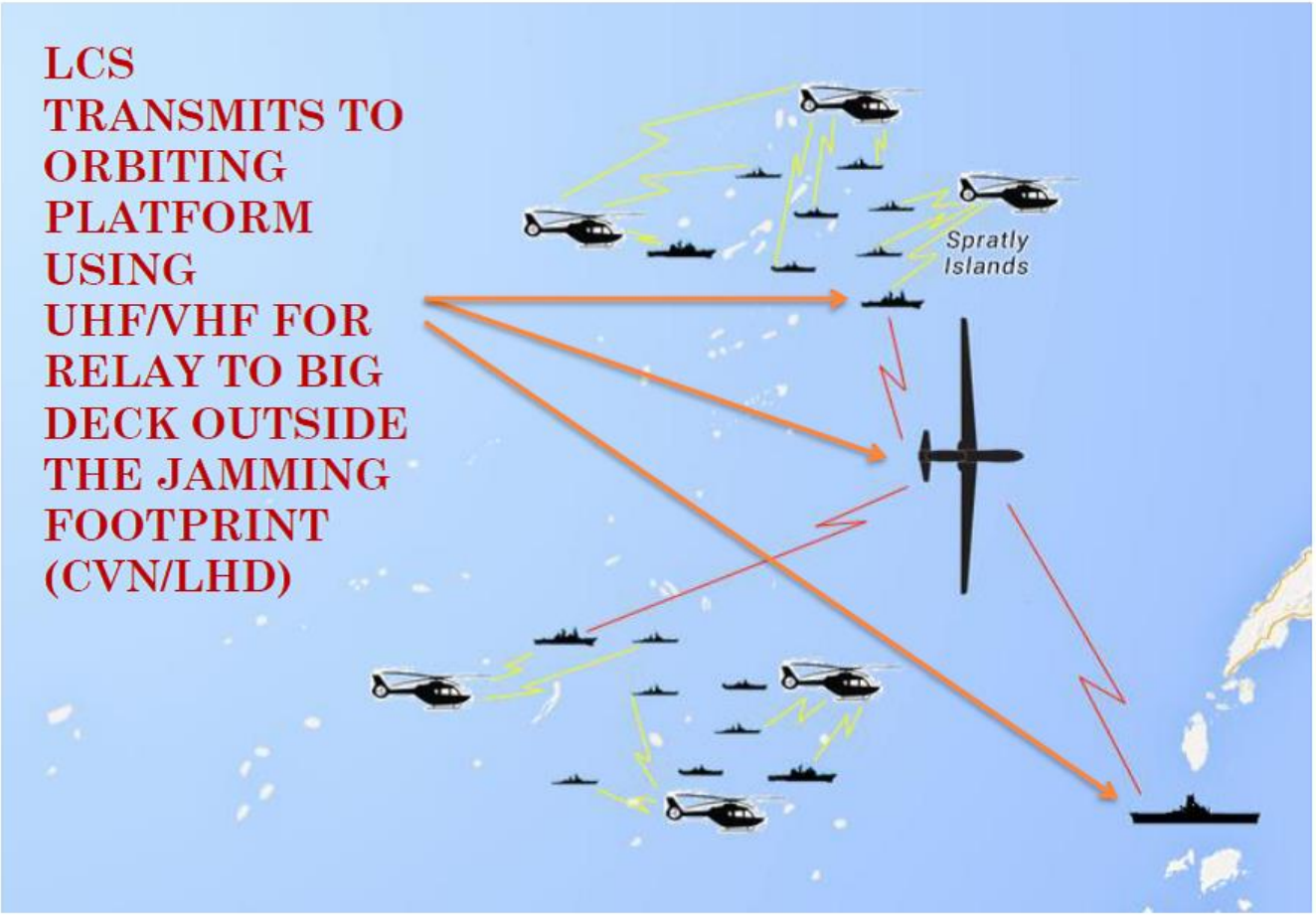
IMPLEMENTATION



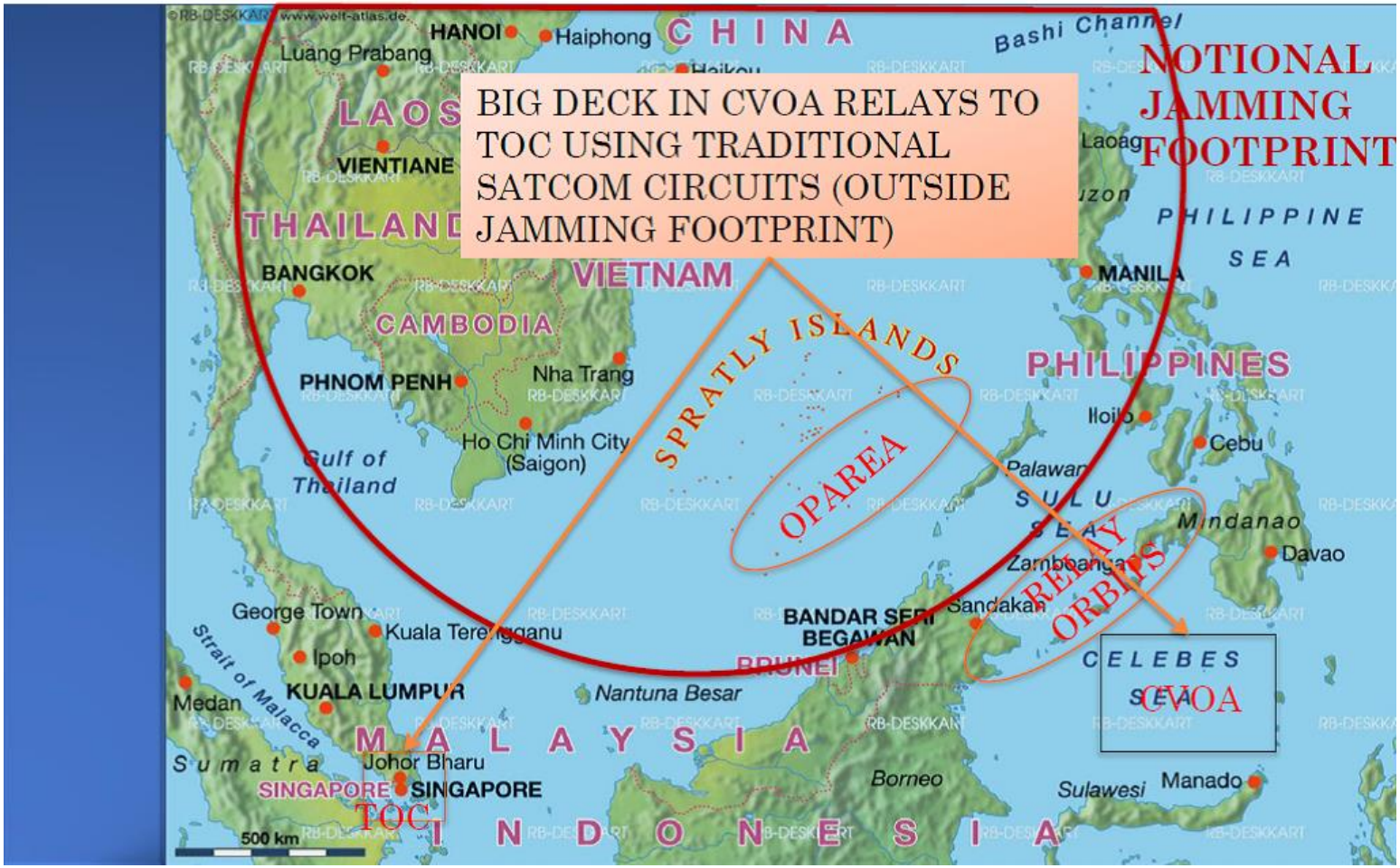
IMPLEMENTATION



IMPLEMENTATION



IMPLEMENTATION



Additional Operational Concepts:

COP, ISR, & Mobile Jamming

Common Operational Picture (COP)

- GCCS-M for COP using:
- If SATCOM available, S-TADIL J (LINK16)
- In SATCOM-denied environment LINK11
  - UHF for local tactical COP (intra-squadron level)
  - Track manager replicates on HF link for OTH push to TOC

ISR

- Intra-squadron UAVs capable of still-picture capture only, with airborne transmit capability
- BAMS ISR assets capable of:
  - Large area mapping (surface plot)
  - SSC using ISAR
  - VOI / target ID
  - Real-time streaming video

APPENDIX B. COST SECTION WORK BREAKDOWN STRUCTURE

A. WORK BREAKDOWN STRUCTURE

Work Breakdown Structure by Level							
WBS#	Level 1	Level 2	Level 3				
1.0	**Sea System**						
1.1		**Ship**					
1.1.1			Hull Structure				
1.1.2			Propulsion Plant				
1.1.3			Electric Plant				
1.1.4			Command, Communications and Surveillance				
1.1.5			Auxiliary Systems				
1.1.6			Outfit and Furnishings				
1.1.7			Armament				
1.1.8			Total Ship Integration/Engineering				
1.1.9			Ship Assembly and Support Systems				
1.2		**System Engineering**					
1.3		**Program Management**					
1.4		**System Test and Evaluation**					
1.4.1			Development Test and Evaluation				
1.4.2			Operational Test and Evaluation				
1.4.3			Mock-ups/System Integration Labs (SILs)				
1.4.4			Test and Evaluation Support				
1.4.5			Test Facilities				
1.5		**Training**					
1.5.1			Equipment				
1.5.2			Services				
1.5.3			Facilities				
1.6		**Data**					
1.6.1			Technical Publications				
1.6.2			Engineering Data				
1.6.3			Management Data				
1.6.4			Support Data				
1.6.5			Data Depository				
1.7		**Peculiar Support Equipment**					
1.7.1			Test and Measurement Equipment				
1.7.2			Support and Handling Equipment				
1.8		**Common Support Equipment**					
1.8.1			Test and Measurement Equipment				
1.8.2			Support and Handling Equipment				

1.9		**Operational/Site Activation**	
1.9.1			System Assembly, Installation and Checkout on Site
1.9.2			Contractor Technical Support
1.9.3			Site Construction
1.9.4			Site/Ship/Vehicle Conversion
1.9.5			Sustainment/Interim Contractor Support
1.10		**Industrial Facilities**	
1.10.1			Construction/Conversion/Expansion
1.10.2			Equipment Acquisition or Modernization
1.10.3			Maintenance (industrial Facilities)
1.11		**Initial Spares and Repair Parts**	

B. REGRESSION MODELS

1. Model #1

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.862173776							
R Square	0.74334362							
Adjusted R Square	0.679179525							
Standard Error	513100782.3							
Observations	6							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	3.05002E+18	3.05E+18	11.58504	0.027185024			
Residual	4	1.05309E+18	2.633E+17					
Total	5	4.10311E+18						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	$ 41,104,775.47	377624243.8	0.108851	0.9185626	-1007348208	1.09E+09	-1.007E+09	1089557759
X Variable 1	$ 247,030.16	72577.36589	3.4036804	0.027185	45523.0847	448537.23	45523.085	448537.2292

2. Model #2

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.987988968							
R Square	0.976122202							
Adjusted R Square	0.964183303							
Standard Error	63618936.05							
Observations	4							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	3.30912E+17	3.30912E+17	81.75981667	0.012011032			
Residual	2	8.09474E+15	4.04737E+15					
Total	3	3.39007E+17						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	$ 179,667,412.14	69123261.27	2.599232282	0.121600649	-117745976.7	477080801	-117745976.7	477080801
X Variable 1	$ 222,452.43	24601.81796	9.042113507	0.012011032	116599.3513	328305.5097	116599.3513	328305.5097

3. Model #3

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.987988968							
R Square	0.976122202							
Adjusted R Square	0.964183303							
Standard Error	63618936.05							
Observations	4							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	3.30912E+17	3.309E+17	81.759817	0.012011032			
Residual	2	8.09474E+15	4.047E+15					
Total	3	3.39007E+17						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	$ 179,667,412.14	69123261.27	2.5992323	0.1216006	-117745976.7	477080801	-117745976.7	477080801
X Variable 1	$ 222,452.43	24601.81796	9.0421135	0.012011	116599.3513	328305.51	116599.3513	328305.5097

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APPENDIX C. DETAILED MODEL PARAMETER BREAKDOWN

A. MANA

1. Regression Analysis for Initial MANA Trial Runs

SUMMARY OUTPUT — Networking vs. Exchange Ratio

Regression Statistics	
Multiple R	0.150866
R Square	0.022760
Adjusted R Square	0.021659
Standard Error	1.174605
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.706953	0.706953	0.512396	0.481633
Residual	22	30.353377	1.379699		
Total	23	31.060330			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.706569	0.339080	7.982106	0.000000	2.003361	3.409777
X Variable 1	0.343257	0.479531	0.715819	0.481633	-0.651229	1.337743

Missile Range vs. Exchange Ratio

Regression Statistics	
Multiple R	0.60864299
R Square	0.37044628
Adjusted R Square	0.34183021
Standard Error	0.94277505
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	11.5061839	11.5061839	12.9453900	0.00159928
Residual	22	19.5541458	0.88882481		
Total	23	31.0603297			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.58382647	0.98127139	0.59496942	0.5579345	2.61885879	1.45120583
X Variable 1	0.04616031	0.01282954	3.5979702	0.0015992	0.01955347	0.07276716

SUMMARY OUTPUT Salvo Size vs. Exchange Ratio

Regression Statistics	
Multiple R	0.21202170
R Square	0.04495320
Adjusted R Square	0.00154198
Standard Error	1.16119195
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1.39626132	1.39626132	1.0355204	0.31992665
Residual	22	29.6640684	1.34836674		
Total	23	31.0603297			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.60179795	0.74954618	4.80530492	8.4505E-05	2.04733431	5.1562615
X Variable 1	0.2412002	0.23702731	1.01760524	0.3199266	0.73276480	0.2503643

SUMMARY OUTPUT Detection Range vs. Exchange Ratio

Regression Statistics	
Multiple R	0.1722000
R Square	0.0296528
Adjusted R Square	0.0144538
Standard Error	1.1704564
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.92102751	0.92102751	0.6722984	0.42104649
Residual	22	30.1393022	1.36996828		
Total	23	31.0603297			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.5979735	0.90977424	3.95479824	0.0006733	1.71121727	5.48472987
X Variable 1	0.0159950	0.01950760	0.8199380	0.4210464	0.05645131	0.02446127

2. Data Series for Revised MANA Runs

	PARAMTERS					Rounded Data	
Run	**No. of Ships**	**Network**	**Missile Range**	**Salvo Size**	**Detection Range**	**BLUE Casualties**	**Red Casualties**
1	10	No	60	2	30	15.00	6.00
2	10	No	60	2	45	15.00	5.00
3	10	No	60	2	60	1.00	13.00
4	10	No	60	4	30	15.00	6.00

5	10	No	60	4	45	15.00	6.00
6	10	No	60	4	60	1.00	13.00
7	10	No	90	2	30	15.00	6.00
8	10	No	90	2	45	15.00	6.00
9	10	No	90	2	60	1.00	13.00
10	10	No	90	4	30	15.00	5.00
11	10	No	90	4	45	15.00	4.00
12	10	No	90	4	60	1.00	13.00
13	15	No	60	2	30	20.00	7.00
14	15	No	60	2	45	20.00	6.00
15	15	No	60	2	60	1.00	16.00
16	15	No	60	4	30	20.00	6.00
17	15	No	60	4	45	20.00	6.00
18	15	No	60	4	60	1.00	16.00
19	15	No	90	2	30	20.00	6.00
20	15	No	90	2	45	20.00	6.00
21	15	No	90	2	60	1.00	16.00
22	15	No	90	4	30	20.00	6.00
23	15	No	90	4	45	20.00	6.00
24	15	No	90	4	60	1.00	16.00
25	20	No	60	2	30	24.00	10.00
26	20	No	60	2	45	24.00	10.00
27	20	No	60	2	60	1.00	13.00
28	20	No	60	4	30	25.00	9.00
29	20	No	60	4	45	25.00	9.00
30	20	No	60	4	60	1.00	13.00
31	20	No	90	2	30	24.00	9.00
32	20	No	90	2	45	25.00	9.00
33	20	No	90	2	60	1.00	13.00

34	20	No	90	4	30	24.00	10.00
35	20	No	90	4	45	25.00	10.00
36	20	No	90	4	60	1.00	13.00
37	25	No	60	2	30	29.00	9.00
38	25	No	60	2	45	30.00	4.00
39	25	No	60	2	60	1.00	13.00
40	25	No	60	4	30	30.00	4.00
41	25	No	60	4	45	30.00	4.00
42	25	No	60	4	60	1.00	13.00
43	25	No	90	2	30	30.00	4.00
44	25	No	90	2	45	30.00	4.00
45	25	No	90	2	60	1.00	13.00
46	25	No	90	4	30	30.00	3.00
47	25	No	90	4	45	30.00	5.00
48	25	No	90	4	60	1.00	14.00
49	10	Yes	60	2	30	15.00	5.00
50	10	Yes	60	2	45	15.00	6.00
51	10	Yes	60	2	60	1.00	16.00
52	10	Yes	60	4	30	15.00	5.00
53	10	Yes	60	4	45	15.00	6.00
54	10	Yes	60	4	60	2.00	16.00
55	10	Yes	90	2	30	15.00	5.00
56	10	Yes	90	2	45	15.00	5.00
57	10	Yes	90	2	60	1.00	16.00
58	10	Yes	90	4	30	15.00	6.00
59	10	Yes	90	4	45	15.00	6.00
60	10	Yes	90	4	60	1.00	16.00
61	15	Yes	60	2	30	20.00	6.00
62	15	Yes	60	2	45	20.00	6.00

63	15	Yes	60	2	60	1.00	16.00
64	15	Yes	60	4	30	18.00	6.00
65	15	Yes	60	4	45	18.00	6.00
66	15	Yes	60	4	60	1.00	16.00
67	15	Yes	90	2	30	18.00	6.00
68	15	Yes	90	2	45	18.00	6.00
69	15	Yes	90	2	60	1.00	16.00
70	15	Yes	90	4	30	19.00	6.00
71	15	Yes	90	4	45	18.00	6.00
72	15	Yes	90	4	60	1.00	16.00
73	20	Yes	60	2	30	25.00	9.00
74	20	Yes	60	2	45	25.00	8.00
75	20	Yes	60	2	60	1.00	16.00
76	20	Yes	60	4	30	25.00	9.00
77	20	Yes	60	4	45	25.00	10.00
78	20	Yes	60	4	60	1.00	16.00
79	20	Yes	90	2	30	25.00	9.00
80	20	Yes	90	2	45	25.00	9.00
81	20	Yes	90	2	60	1.00	16.00
82	20	Yes	90	4	30	25.00	7.00
83	20	Yes	90	4	45	25.00	9.00
84	20	Yes	90	4	60	1.00	16.00
85	25	Yes	60	2	30	30.00	4.00
86	25	Yes	60	2	45	30.00	3.00
87	25	Yes	60	2	60	1.00	16.00
88	25	Yes	60	4	30	30.00	4.00
89	25	Yes	60	4	45	30.00	5.00
90	25	Yes	60	4	60	1.00	16.00
91	25	Yes	90	2	30	30.00	4.00

92	25	Yes	90	2	45	30.00	4.00
93	25	Yes	90	2	60	1.00	16.00
94	25	Yes	90	4	30	30.00	5.00
95	25	Yes	90	4	45	30.00	4.00
96	25	Yes	90	4	60	1.00	16.00

3. Regression Analysis for MANA Revised Runs

SUMMARY OUTPUT Number of Ships

Regression Statistics	
Multiple R	0.003606
R Square	1.3E-05
Adjusted R Square	-0.01063
Standard Error	6.924451
Observations	96

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.0586	0.0586	0.001222	0.972186306
Residual	94	4507.114	47.94802		
Total	95	4507.173			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	5.007529	2.322531	2.156065	0.033631	0.396088463	9.618969689
X Variable 1	0.00442	0.126423	0.034959	0.972186	0.246595384	0.255434682

SUMMARY OUTPUT Networking

Regression Statistics	
Multiple R	0.040566
R Square	0.001646
Adjusted R Square	-0.00898
Standard Error	6.918796
Observations	96

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7.416917	7.416917	0.15494	0.694750356
Residual	94	4499.756	47.86974		
Total	95	4507.173			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	4.806917	0.998642	4.813453	5.6E-06	2.824089396	6.789744416
X Variable 1	0.555912	1.412293	0.393624	0.69475	2.248229515	3.360053598

SUMMARY OUTPUT Missile Range

Regression Statistics	
Multiple R	0.013136
R Square	0.000173
Adjusted R Square	-0.01046
Standard Error	6.923899
Observations	96

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.77768	0.77768	0.016222	0.898923657
Residual	94	4506.395	47.94037		
Total	95	4507.173			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	4.63485	3.603311	1.286275	0.201506	2.519608737	11.78930827
X Variable 1	0.006	0.047111	0.127365	0.898924	0.087540008	0.099540626

SUMMARY OUTPUT Salvo Size

Regression Statistics	
Multiple R	0.010808
R Square	0.000117
Adjusted R Square	-0.01052
Standard Error	6.924091
Observations	96

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.526519	0.526519	0.010982	0.916761102
Residual	94	4506.646	47.94304		
Total	95	4507.173			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	5.307047	2.234741	2.374793	0.01959	0.869916077	9.744176986
X Variable 1	-0.07406	0.706687	-0.1048	0.916761	1.477201719	1.329085983

SUMMARY OUTPUT Sensor Range

Regression Statistics	
Multiple R	0.85529
R Square	0.73152
Adjusted R Square	0.728664
Standard Error	3.58793
Observations	96

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3297.088	3297.088	256.1195	1.37818E-28
Residual	94	1210.085	12.87324		
Total	95	4507.173			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-16.4477	1.394416	-11.7954	3.04E-20	19.21637553	13.67908478
X Variable 1	0.478502	0.029899	16.00373	1.38E-28	0.419136302	0.537868279

4. Results of MANA Alternative Scenarios

a. Strait of Malacca

RUN	US Cas	PLAN Cas	Blue Reach Goal	Red Reach Goal	US SSC Cas	US DDG Cas	US DDG Cas	US LCS Cas	US LCS Cas	PLAN DDG Cas	PLAN FFG Cas	PLAN PGG Cas
1	3	16	No	No	2	0	1	0	0	4	2	10
2	0	16	No	No	0	0	0	0	0	4	2	10
3	1	16	No	No	1	0	0	0	0	4	2	10
4	0	15	No	No	0	0	0	0	0	4	1	10
5	2	16	No	No	2	0	0	0	0	4	2	10
6	1	16	No	No	0	0	0	1	0	4	2	10
7	1	16	No	No	1	0	0	0	0	4	2	10
8	0	16	No	No	0	0	0	0	0	4	2	10
9	1	16	No	No	1	0	0	0	0	4	2	10
10	0	16	No	No	0	0	0	0	0	4	2	10
11	0	16	No	No	0	0	0	0	0	4	2	10
12	0	16	No	No	0	0	0	0	0	4	2	10
13	0	16	No	No	0	0	0	0	0	4	2	10
14	0	16	No	No	0	0	0	0	0	4	2	10
15	0	16	No	No	0	0	0	0	0	4	2	10
16	1	16	No	No	1	0	0	0	0	4	2	10
17	3	15	No	No	1	0	1	0	1	4	1	10
18	0	16	No	No	0	0	0	0	0	4	2	10
19	0	16	No	No	0	0	0	0	0	4	2	10
20	0	16	No	No	0	0	0	0	0	4	2	10
21	3	16	No	No	2	0	1	0	0	4	2	10
22	1	16	No	No	1	0	0	0	0	4	2	10

23	0	16	No	No	0	0	0	0	0	4	2	10
24	0	16	No	No	0	0	0	0	0	4	2	10
25	1	16	No	No	1	0	0	0	0	4	2	10
26	0	16	No	No	0	0	0	0	0	4	2	10
27	0	16	No	No	0	0	0	0	0	4	2	10
28	3	16	No	No	2	0	0	1	0	4	2	10
29	0	16	No	No	0	0	0	0	0	4	2	10
30	1	16	No	No	1	0	0	0	0	4	2	10
	BLUE Cas	Red Cas	BLUE Goal	Red Goal	Real Time							
Mean	0.733	15.9	0	0								
StDev	0.048	0.031	0	0	0							

b. Persian Gulf

Run	US Cas	PLAN Cas	Blue Reach Goal	Red Reach Goal	US SSC Cas	US DDG Cas	US LCS Cas	IRAN Cas	IRAN Cas
1	0	27	No	No	0	0	0	9	18
2	0	25	No	No	0	0	0	10	15
3	0	25	No	No	0	0	0	10	15
4	0	25	No	No	0	0	0	10	15
5	0	26	No	No	0	0	0	10	16
6	0	26	No	No	0	0	0	10	16
7	0	27	No	No	0	0	0	10	17
8	0	25	No	No	0	0	0	9	16

9	0	25	No	No	0	0	0	10	15
10	0	26	No	No	0	0	0	10	16
11	0	25	No	No	0	0	0	10	15
12	0	25	No	No	0	0	0	10	15
13	0	25	No	No	0	0	0	10	15
14	0	26	No	No	0	0	0	10	16
15	0	25	No	No	0	0	0	10	15
16	0	26	No	No	0	0	0	10	16
17	0	25	No	No	0	0	0	9	16
18	0	25	No	No	0	0	0	8	17
19	0	25	No	No	0	0	0	10	15
20	0	25	No	No	0	0	0	10	15
21	0	25	No	No	0	0	0	9	16
22	0	26	No	No	0	0	0	10	16
23	0	25	No	No	0	0	0	10	15
24	0	25	No	No	0	0	0	9	16
25	0	25	No	No	0	0	0	10	15
26	0	25	No	No	0	0	0	10	15

B. SIMIO

1. Endurance Patrol Simulation Results

1 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	13.894	7.999	17.606	1.027	2.751
Combatant_fuel_Cap_600	14.753	6.605	20.164	2.064	5.528
Combatant_fuel_Cap_700	9.337	2.464	20.066	1.835	4.915
Combatant_fuel_Cap_800	6.531	1.813	20.395	2.279	6.105
Combatant_fuel_Cap_900	2.476	1.777	4.124	0.210	0.563
Combatant_fuel_Cap_1000	19.054	10.190	20.164	0.897	2.401

Combatant_fuel_Cap_1500	19.052	9.736	20.164	0.919	2.462
Combatant_fuel_Cap_2000	15.812	7.516	20.158	1.396	3.739
Combatant_fuel_Cap_3000	15.954	7.018	20.158	1.354	3.627
Combatant_fuel_Cap_4000	15.911	8.061	20.158	1.355	3.630
1 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	9.770	5.952	14.265	0.845	2.264
Double_JHSV_600	12.405	5.031	20.164	1.892	5.066
Double_JHSV_700	8.353	2.443	17.622	1.388	3.719
Double_JHSV_800	4.809	1.892	20.434	1.940	5.197
Double_JHSV_900	2.433	1.882	4.694	0.249	0.668
Double_JHSV_1000	19.695	19.084	20.164	0.112	0.301
Double_JHSV_1500	19.695	19.084	20.164	0.112	0.301
Double_JHSV_2000	16.558	10.018	20.164	1.597	4.279
Double_JHSV_3000	16.872	10.252	20.164	1.539	4.122
Double_JHSV_4000	16.538	10.055	20.164	1.604	4.295
1 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	13.156	5.108	19.420	1.793	4.803
Double_Logistics_600	13.943	5.589	19.456	1.587	4.251
Double_Logistics_700	6.574	1.800	17.408	1.338	3.583
Double_Logistics_800	3.619	1.097	10.434	0.899	2.407
Double_Logistics_900	2.162	1.180	5.981	0.427	1.142
Double_Logistics_1000	17.575	15.555	19.730	0.563	1.507
Double_Logistics_1500	17.575	15.555	19.730	0.563	1.507
Double_Logistics_2000	17.282	10.921	19.725	0.703	1.884
Double_Logistics_3000	17.268	10.517	19.725	0.721	1.931
Double_Logistics_4000	17.282	10.928	19.725	0.703	1.883

2 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	7.703	0.205	20.119	3.091	8.278
Combatant_fuel_Cap_600	7.703	0.205	20.119	3.091	8.278
Combatant_fuel_Cap_700	4.985	0.309	11.852	1.830	4.901
Combatant_fuel_Cap_800	4.877	0.309	11.852	1.826	4.892
Combatant_fuel_Cap_900	4.926	0.309	11.792	1.829	4.899
Combatant_fuel_Cap_1000	5.618	0.456	17.030	2.235	5.878
Combatant_fuel_Cap_1500	3.429	0.320	10.696	1.275	3.414
Combatant_fuel_Cap_2000	2.054	0.653	6.915	0.594	1.591
Combatant_fuel_Cap_3000	1.383	0.774	1.946	0.172	0.461
Combatant_fuel_Cap_4000	1.496	1.257	2.008	0.074	0.199
2 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	9.968	0.200	20.133	3.484	9.332
Double_JHSV_600	9.968	0.200	20.133	3.484	9.332
Double_JHSV_700	4.477	0.242	19.685	1.736	4.650
Double_JHSV_800	4.492	0.241	19.685	1.737	4.652
Double_JHSV_900	4.473	0.240	19.685	1.736	4.650
Double_JHSV_1000	5.034	0.398	15.363	1.796	4.810
Double_JHSV_1500	3.401	0.323	9.234	1.139	3.050
Double_JHSV_2000	2.153	0.605	7.704	0.669	1.791
Double_JHSV_3000	1.391	0.806	1.906	0.165	0.441
Double_JHSV_4000	1.488	1.290	1.939	0.066	0.176
2 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	9.131	0.184	19.704	3.399	9.105
Double_Logistics_600	9.131	0.184	19.704	3.399	9.105
Double_Logistics_700	7.507	0.186	19.705	3.036	8.132
Double_Logistics_800	7.304	0.186	19.705	2.986	7.998
Double_Logistics_900	7.509	0.186	19.705	3.036	8.133
Double_Logistics_1000	3.995	0.204	12.404	1.615	4.324

Double_Logistics_1500	2.314	0.227	7.682	0.921	2.467
Double_Logistics_2000	1.882	0.278	8.305	0.816	2.186
Double_Logistics_3000	0.757	0.522	1.481	0.078	0.209
Double_Logistics_4000	0.878	0.670	1.097	0.046	0.123

3 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	0.627	0.536	0.729	0.020	0.053
Combatant_fuel_Cap_600	0.628	0.533	0.710	0.018	0.049
Combatant_fuel_Cap_700	0.679	0.482	0.984	0.042	0.112
Combatant_fuel_Cap_800	0.815	0.569	1.118	0.059	0.157
Combatant_fuel_Cap_900	0.822	0.544	1.122	0.065	0.173
Combatant_fuel_Cap_1000	1.129	0.767	1.693	0.072	0.192
Combatant_fuel_Cap_1500	1.751	1.480	1.976	0.071	0.190
Combatant_fuel_Cap_2000	1.940	1.702	2.462	0.075	0.200
Combatant_fuel_Cap_3000	2.547	2.024	2.825	0.114	0.304
Combatant_fuel_Cap_4000	3.360	2.519	3.619	0.104	0.280
3 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	0.509	0.437	0.591	0.016	0.042
Double_JHSV_600	0.507	0.422	0.591	0.016	0.044
Double_JHSV_700	0.633	0.411	0.843	0.025	0.068
Double_JHSV_800	0.684	0.523	0.939	0.043	0.115
Double_JHSV_900	0.688	0.509	0.952	0.048	0.128
Double_JHSV_1000	1.080	0.713	1.458	0.056	0.151
Double_JHSV_1500	1.740	1.385	1.900	0.055	0.148
Double_JHSV_2000	1.906	1.419	2.289	0.076	0.202
Double_JHSV_3000	2.588	1.711	3.212	0.147	0.392
Double_JHSV_4000	3.312	2.551	3.578	0.116	0.311
3 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation

Double_Logistics_500	0.324	0.256	0.413	0.013	0.035
Double_Logistics_600	0.323	0.263	0.412	0.013	0.036
Double_Logistics_700	0.355	0.270	0.464	0.018	0.049
Double_Logistics_800	0.389	0.283	0.529	0.021	0.057
Double_Logistics_900	0.385	0.293	0.568	0.022	0.060
Double_Logistics_1000	0.528	0.374	0.658	0.029	0.077
Double_Logistics_1500	0.804	0.632	1.062	0.042	0.114
Double_Logistics_2000	0.917	0.784	1.257	0.047	0.126
Double_Logistics_3000	1.294	0.903	1.722	0.093	0.249
Double_Logistics_4000	1.717	1.236	2.459	0.133	0.356

4 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	0.331	0.251	0.410	0.017	0.046
Combatant_fuel_Cap_600	0.331	0.251	0.410	0.017	0.046
Combatant_fuel_Cap_700	0.453	0.380	0.543	0.017	0.046
Combatant_fuel_Cap_800	0.452	0.380	0.543	0.017	0.045
Combatant_fuel_Cap_900	0.451	0.376	0.543	0.017	0.044
Combatant_fuel_Cap_1000	0.646	0.567	0.723	0.013	0.035
Combatant_fuel_Cap_1500	0.743	0.555	0.933	0.036	0.098
Combatant_fuel_Cap_2000	1.182	0.876	1.633	0.054	0.145
Combatant_fuel_Cap_3000	3.087	1.640	3.649	0.056	0.149
Combatant_fuel_Cap_4000	27.207	4.636	42.964	0.097	0.261
4 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	0.335	0.275	0.417	0.015	0.041
Double_JHSV_600	0.335	0.275	0.417	0.015	0.041
Double_JHSV_700	0.335	0.276	0.416	0.014	0.038
Double_JHSV_800	0.335	0.276	0.416	0.014	0.037
Double_JHSV_900	0.334	0.276	0.416	0.014	0.038
Double_JHSV_1000	0.520	0.455	0.608	0.016	0.043
Double_JHSV_1500	0.674	0.495	0.801	0.032	0.086

Double_JHSV_2000	1.151	0.876	1.806	0.057	0.153
Double_JHSV_3000	3.049	1.980	3.591	0.053	0.143
Double_JHSV_4000	27.811	5.168	42.901	0.065	0.173
4 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	0.321	0.243	0.406	0.016	0.042
Double_Logistics_600	0.321	0.243	0.406	0.016	0.042
Double_Logistics_700	0.318	0.232	0.404	0.016	0.042
Double_Logistics_800	0.318	0.231	0.404	0.016	0.042
Double_Logistics_900	0.318	0.231	0.404	0.016	0.042
Double_Logistics_1000	0.327	0.256	0.413	0.015	0.039
Double_Logistics_1500	0.361	0.260	0.485	0.020	0.055
Double_Logistics_2000	0.529	0.364	0.644	0.030	0.079
Double_Logistics_3000	1.194	0.615	2.005	0.042	0.112
Double_Logistics_4000	3.527	1.643	9.619	0.045	0.122

5 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	0.335	0.256	0.411	0.017	0.046
Combatant_fuel_Cap_600	0.335	0.252	0.411	0.017	0.046
Combatant_fuel_Cap_700	0.465	0.403	0.560	0.020	0.054
Combatant_fuel_Cap_800	0.465	0.392	0.546	0.020	0.054
Combatant_fuel_Cap_900	0.465	0.393	0.546	0.020	0.054
Combatant_fuel_Cap_1000	0.651	0.560	0.744	0.017	0.044
Combatant_fuel_Cap_1500	0.830	0.630	0.981	0.033	0.088
Combatant_fuel_Cap_2000	1.334	0.828	1.815	0.051	0.137
Combatant_fuel_Cap_3000	4.470	2.766	5.306	0.028	0.075
Combatant_fuel_Cap_4000	51.617	8.542	83.544	0.076	0.203
5 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	0.340	0.280	0.419	0.015	0.041

Double_JHSV_600	0.339	0.280	0.419	0.015	0.041
Double_JHSV_700	0.338	0.281	0.418	0.014	0.039
Double_JHSV_800	0.338	0.284	0.418	0.014	0.038
Double_JHSV_900	0.338	0.280	0.418	0.014	0.038
Double_JHSV_1000	0.539	0.467	0.629	0.017	0.046
Double_JHSV_1500	0.728	0.567	0.889	0.035	0.093
Double_JHSV_2000	1.278	0.964	1.746	0.056	0.150
Double_JHSV_3000	4.354	2.700	5.260	0.050	0.135
Double_JHSV_4000	52.413	7.322	83.527	0.057	0.154
5 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	0.327	0.246	0.435	0.017	0.046
Double_Logistics_600	0.327	0.246	0.435	0.017	0.046
Double_Logistics_700	0.323	0.248	0.431	0.016	0.044
Double_Logistics_800	0.323	0.248	0.431	0.016	0.044
Double_Logistics_900	0.323	0.248	0.431	0.016	0.044
Double_Logistics_1000	0.329	0.266	0.428	0.016	0.042
Double_Logistics_1500	0.354	0.270	0.493	0.023	0.061
Double_Logistics_2000	0.544	0.402	0.684	0.026	0.071
Double_Logistics_3000	1.660	0.648	3.151	0.047	0.127
Double_Logistics_4000	6.953	2.313	27.545	0.041	0.109

6 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	42.095	41.932	42.169	0.024	0.064
Combatant_fuel_Cap_600	42.095	41.932	42.169	0.024	0.064
Combatant_fuel_Cap_700	42.175	42.009	42.247	0.025	0.066
Combatant_fuel_Cap_800	42.174	42.009	42.247	0.024	0.065
Combatant_fuel_Cap_900	42.175	42.014	42.248	0.024	0.065
Combatant_fuel_Cap_1000	42.266	42.145	42.338	0.018	0.047
Combatant_fuel_Cap_1500	42.114	41.960	42.252	0.028	0.076
Combatant_fuel_Cap_2000	42.363	42.192	42.668	0.037	0.100

Combatant_fuel_Cap_3000	43.906	42.681	44.401	0.031	0.084
Combatant_fuel_Cap_4000	67.499	45.315	83.512	0.048	0.129
6 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	42.098	41.941	42.173	0.024	0.065
Double_JHSV_600	42.098	41.941	42.173	0.024	0.065
Double_JHSV_700	42.100	41.943	42.171	0.022	0.060
Double_JHSV_800	42.100	41.943	42.171	0.022	0.060
Double_JHSV_900	42.100	41.943	42.171	0.022	0.060
Double_JHSV_1000	42.198	42.079	42.275	0.017	0.046
Double_JHSV_1500	42.083	41.936	42.215	0.021	0.055
Double_JHSV_2000	42.343	42.138	42.686	0.033	0.090
Double_JHSV_3000	43.915	43.006	44.394	0.042	0.113
Double_JHSV_4000	67.055	46.171	83.559	0.044	0.119
6 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	42.091	41.936	42.177	0.019	0.051
Double_Logistics_600	42.091	41.936	42.177	0.019	0.051
Double_Logistics_700	42.101	41.941	42.177	0.019	0.052
Double_Logistics_800	42.101	41.941	42.177	0.019	0.052
Double_Logistics_900	42.101	41.941	42.177	0.019	0.052
Double_Logistics_1000	42.106	41.994	42.176	0.015	0.040
Double_Logistics_1500	41.721	41.422	42.084	0.017	0.044
Double_Logistics_2000	41.801	41.495	42.167	0.029	0.078
Double_Logistics_3000	42.529	42.102	43.294	0.031	0.084
Double_Logistics_4000	44.912	43.126	51.930	0.030	0.081

7 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	83.855	83.612	83.927	0.024	0.064
Combatant_fuel_Cap_600	83.855	83.612	83.927	0.024	0.064

Combatant_fuel_Cap_700	42.095	41.933	42.169	0.022	0.058
Combatant_fuel_Cap_800	83.863	83.610	83.925	0.019	0.050
Combatant_fuel_Cap_900	83.863	83.610	83.925	0.019	0.050
Combatant_fuel_Cap_1000	83.900	83.863	83.927	0.006	0.016
Combatant_fuel_Cap_1500	83.408	83.329	83.551	0.022	0.059
Combatant_fuel_Cap_2000	83.402	83.324	83.544	0.020	0.055
Combatant_fuel_Cap_3000	83.409	83.255	83.546	0.028	0.076
Combatant_fuel_Cap_4000	83.396	83.246	83.547	0.026	0.070
7 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	83.857	83.600	83.926	0.017	0.045
Double_JHSV_600	83.856	83.600	83.926	0.017	0.045
Double_JHSV_700	42.098	41.940	42.173	0.024	0.065
Double_JHSV_800	83.855	83.595	83.925	0.013	0.036
Double_JHSV_900	83.854	83.595	83.924	0.013	0.035
Double_JHSV_1000	83.902	83.862	83.929	0.007	0.017
Double_JHSV_1500	83.419	83.317	83.543	0.020	0.053
Double_JHSV_2000	83.416	83.337	83.515	0.015	0.041
Double_JHSV_3000	83.406	83.269	83.535	0.029	0.079
Double_JHSV_4000	83.400	83.237	83.585	0.027	0.072
7 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	83.857	83.620	83.925	0.020	0.055
Double_Logistics_600	83.857	83.620	83.925	0.020	0.055
Double_Logistics_700	42.091	41.942	42.176	0.019	0.052
Double_Logistics_800	83.875	83.617	83.926	0.019	0.050
Double_Logistics_900	83.874	83.617	83.926	0.019	0.050
Double_Logistics_1000	83.901	83.863	83.929	0.007	0.019
Double_Logistics_1500	83.110	82.306	83.730	0.015	0.039
Double_Logistics_2000	83.111	82.341	83.725	0.027	0.072
Double_Logistics_3000	83.525	83.413	83.627	0.020	0.053
Double_Logistics_4000	83.511	83.432	83.641	0.022	0.058

8 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.864	90.613	90.927	0.021	0.056
Combatant_fuel_Cap_600	90.864	90.613	90.927	0.021	0.056
Combatant_fuel_Cap_700	90.872	90.611	90.925	0.019	0.050
Combatant_fuel_Cap_800	90.872	90.611	90.925	0.019	0.051
Combatant_fuel_Cap_900	90.872	90.610	90.925	0.019	0.050
Combatant_fuel_Cap_1000	90.901	90.868	90.930	0.006	0.016
Combatant_fuel_Cap_1500	90.662	90.601	90.737	0.014	0.039
Combatant_fuel_Cap_2000	90.657	90.600	90.739	0.013	0.035
Combatant_fuel_Cap_3000	90.650	90.559	90.723	0.016	0.044
Combatant_fuel_Cap_4000	90.401	90.272	90.729	0.026	0.068
8 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.859	90.609	90.926	0.019	0.051
Double_JHSV_600	90.859	90.609	90.926	0.019	0.051
Double_JHSV_700	90.860	90.605	90.924	0.016	0.042
Double_JHSV_800	90.860	90.605	90.924	0.016	0.042
Double_JHSV_900	90.860	90.605	90.924	0.016	0.042
Double_JHSV_1000	90.902	90.863	90.931	0.006	0.017
Double_JHSV_1500	90.661	90.598	90.753	0.014	0.037
Double_JHSV_2000	90.659	90.581	90.749	0.014	0.037
Double_JHSV_3000	90.653	90.563	90.729	0.018	0.048
Double_JHSV_4000	90.413	90.275	90.759	0.026	0.070
8 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.877	90.625	90.926	0.020	0.053
Double_Logistics_600	90.877	90.625	90.926	0.020	0.053
Double_Logistics_700	90.880	90.624	90.928	0.018	0.048
Double_Logistics_800	90.880	90.624	90.927	0.018	0.048

Double_Logistics_900	90.880	90.624	90.927	0.018	0.048
Double_Logistics_1000	90.902	90.864	90.929	0.007	0.019
Double_Logistics_1500	90.586	90.203	90.822	0.013	0.035
Double_Logistics_2000	90.581	90.224	90.820	0.017	0.046
Double_Logistics_3000	90.721	90.629	90.794	0.015	0.040
Double_Logistics_4000	90.551	90.429	90.686	0.022	0.059

9 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.864	90.624	90.927	0.018	0.049
Combatant_fuel_Cap_600	90.873	90.634	90.927	0.019	0.050
Combatant_fuel_Cap_700	90.892	90.635	90.926	0.018	0.048
Combatant_fuel_Cap_800	90.892	90.635	90.926	0.018	0.048
Combatant_fuel_Cap_900	90.892	90.635	90.926	0.018	0.048
Combatant_fuel_Cap_1000	90.901	90.871	90.931	0.006	0.016
Combatant_fuel_Cap_1500	90.899	90.869	90.929	0.006	0.016
Combatant_fuel_Cap_2000	90.896	90.858	90.923	0.006	0.016
Combatant_fuel_Cap_3000	90.890	90.854	90.918	0.006	0.016
Combatant_fuel_Cap_4000	90.405	90.273	90.803	0.025	0.067
9 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.861	90.606	90.926	0.021	0.056
Double_JHSV_600	90.868	90.630	90.926	0.023	0.061
Double_JHSV_700	90.876	90.626	90.931	0.015	0.039
Double_JHSV_800	90.876	90.626	90.931	0.015	0.039
Double_JHSV_900	90.876	90.626	90.931	0.015	0.039
Double_JHSV_1000	90.902	90.863	90.932	0.007	0.018
Double_JHSV_1500	90.900	90.862	90.930	0.007	0.020
Double_JHSV_2000	90.897	90.858	90.924	0.007	0.020
Double_JHSV_3000	90.892	90.853	90.919	0.007	0.019
Double_JHSV_4000	90.409	90.272	90.588	0.023	0.061

9 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.879	90.624	90.927	0.019	0.050
Double_Logistics_600	90.884	90.629	90.930	0.019	0.052
Double_Logistics_700	90.885	90.620	90.929	0.019	0.050
Double_Logistics_800	90.885	90.620	90.929	0.019	0.050
Double_Logistics_900	90.885	90.620	90.929	0.019	0.050
Double_Logistics_1000	90.901	90.863	90.930	0.007	0.018
Double_Logistics_1500	90.896	90.858	90.926	0.007	0.019
Double_Logistics_2000	90.893	90.855	90.923	0.007	0.020
Double_Logistics_3000	90.887	90.849	90.918	0.007	0.018
Double_Logistics_4000	90.550	90.442	90.669	0.021	0.056

10 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.875	90.624	90.927	0.018	0.048
Combatant_fuel_Cap_600	90.873	90.632	90.927	0.018	0.049
Combatant_fuel_Cap_700	90.885	90.411	90.926	0.028	0.074
Combatant_fuel_Cap_800	90.885	90.411	90.926	0.028	0.074
Combatant_fuel_Cap_900	90.885	90.412	90.926	0.028	0.074
Combatant_fuel_Cap_1000	90.901	90.864	90.930	0.006	0.016
Combatant_fuel_Cap_1500	90.899	90.862	90.929	0.006	0.017
Combatant_fuel_Cap_2000	90.897	90.858	90.923	0.006	0.017
Combatant_fuel_Cap_3000	90.421	90.238	90.553	0.030	0.081
Combatant_fuel_Cap_4000	90.890	90.847	90.914	0.006	0.017
10 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.861	90.605	90.926	0.017	0.045
Double_JHSV_600	90.868	90.629	90.926	0.019	0.050
Double_JHSV_700	90.858	90.383	90.930	0.013	0.035
Double_JHSV_800	90.858	90.383	90.931	0.013	0.034
Double_JHSV_900	90.858	90.383	90.930	0.013	0.035

Double_JHSV_1000	90.902	90.864	90.930	0.007	0.017
Double_JHSV_1500	90.900	90.863	90.928	0.007	0.019
Double_JHSV_2000	90.896	90.858	90.924	0.007	0.020
Double_JHSV_3000	90.405	90.283	90.582	0.025	0.068
Double_JHSV_4000	90.885	90.852	90.913	0.007	0.019
10 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.879	90.620	90.927	0.019	0.051
Double_Logistics_600	90.890	90.629	90.930	0.017	0.045
Double_Logistics_700	90.858	89.933	90.929	0.017	0.046
Double_Logistics_800	90.863	89.937	90.929	0.016	0.044
Double_Logistics_900	90.858	89.933	90.929	0.017	0.046
Double_Logistics_1000	90.902	90.864	90.929	0.007	0.018
Double_Logistics_1500	90.898	90.860	90.930	0.007	0.019
Double_Logistics_2000	90.896	90.858	90.924	0.007	0.019
Double_Logistics_3000	90.599	90.455	90.700	0.022	0.058
Double_Logistics_4000	90.888	90.850	90.917	0.007	0.018

11 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.885	90.634	90.927	0.019	0.050
Combatant_fuel_Cap_600	90.885	90.633	90.927	0.019	0.050
Combatant_fuel_Cap_700	90.903	90.865	90.931	0.006	0.016
Combatant_fuel_Cap_800	90.903	90.865	90.931	0.006	0.016
Combatant_fuel_Cap_900	90.902	90.864	90.931	0.006	0.016
Combatant_fuel_Cap_1000	90.902	90.867	90.931	0.006	0.016
Combatant_fuel_Cap_1500	90.899	90.861	90.928	0.006	0.017
Combatant_fuel_Cap_2000	90.896	90.858	90.923	0.006	0.017
Combatant_fuel_Cap_3000	90.890	90.854	90.918	0.007	0.017
Combatant_fuel_Cap_4000	90.407	90.286	90.804	0.028	0.074
11 Ship Endurance Patrol					

Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.872	90.635	90.928	0.021	0.055
Double_JHSV_600	90.872	90.635	90.928	0.021	0.055
Double_JHSV_700	90.903	90.864	90.931	0.007	0.018
Double_JHSV_800	90.903	90.864	90.931	0.007	0.018
Double_JHSV_900	90.903	90.864	90.931	0.007	0.018
Double_JHSV_1000	90.902	90.864	90.932	0.007	0.017
Double_JHSV_1500	90.900	90.861	90.928	0.007	0.019
Double_JHSV_2000	90.896	90.858	90.924	0.007	0.019
Double_JHSV_3000	90.892	90.853	90.919	0.007	0.019
Double_JHSV_4000	90.413	90.319	90.580	0.020	0.055
11 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.884	90.647	90.930	0.017	0.045
Double_Logistics_600	90.884	90.647	90.930	0.017	0.045
Double_Logistics_700	90.903	90.864	90.931	0.007	0.018
Double_Logistics_800	90.902	90.864	90.931	0.007	0.018
Double_Logistics_900	90.902	90.864	90.930	0.007	0.018
Double_Logistics_1000	90.902	90.864	90.930	0.007	0.017
Double_Logistics_1500	90.896	90.858	90.926	0.007	0.019
Double_Logistics_2000	90.893	90.854	90.922	0.007	0.020
Double_Logistics_3000	90.888	90.849	90.917	0.007	0.018
Double_Logistics_4000	90.558	90.420	90.702	0.022	0.060

12 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.886	90.634	90.928	0.018	0.049
Combatant_fuel_Cap_600	90.886	90.634	90.928	0.018	0.049
Combatant_fuel_Cap_700	90.903	90.865	90.932	0.006	0.017
Combatant_fuel_Cap_800	90.903	90.865	90.932	0.006	0.017
Combatant_fuel_Cap_900	90.903	90.865	90.932	0.006	0.017
Combatant_fuel_Cap_1000	90.902	90.865	90.931	0.006	0.017

Combatant_fuel_Cap_1500	90.899	90.862	90.929	0.006	0.017
Combatant_fuel_Cap_2000	90.896	90.858	90.924	0.006	0.017
Combatant_fuel_Cap_3000	90.654	90.566	90.846	0.018	0.048
Combatant_fuel_Cap_4000	90.421	90.292	90.868	0.026	0.069
12 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.880	90.639	90.929	0.020	0.053
Double_JHSV_600	90.880	90.639	90.929	0.020	0.053
Double_JHSV_700	90.903	90.864	90.931	0.007	0.018
Double_JHSV_800	90.903	90.864	90.931	0.007	0.018
Double_JHSV_900	90.903	90.864	90.930	0.007	0.018
Double_JHSV_1000	90.902	90.865	90.931	0.007	0.017
Double_JHSV_1500	90.900	90.861	90.926	0.007	0.019
Double_JHSV_2000	90.896	90.858	90.923	0.007	0.019
Double_JHSV_3000	90.653	90.576	90.738	0.015	0.041
Double_JHSV_4000	90.412	90.305	90.752	0.022	0.059
12 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.891	90.648	90.930	0.017	0.046
Double_Logistics_600	90.891	90.648	90.930	0.017	0.046
Double_Logistics_700	90.903	90.865	90.930	0.007	0.018
Double_Logistics_800	90.903	90.865	90.930	0.007	0.018
Double_Logistics_900	90.903	90.865	90.930	0.007	0.018
Double_Logistics_1000	90.902	90.866	90.929	0.006	0.017
Double_Logistics_1500	90.898	90.860	90.925	0.007	0.018
Double_Logistics_2000	90.895	90.856	90.922	0.007	0.019
Double_Logistics_3000	90.742	90.657	90.820	0.015	0.039
Double_Logistics_4000	90.561	90.440	90.741	0.023	0.061

13 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation

Combatant_fuel_Cap_500	90.889	90.618	90.928	0.018	0.047
Combatant_fuel_Cap_600	90.891	90.635	90.929	0.018	0.049
Combatant_fuel_Cap_700	90.903	90.865	90.931	0.006	0.017
Combatant_fuel_Cap_800	90.903	90.864	90.931	0.006	0.017
Combatant_fuel_Cap_900	90.903	90.864	90.931	0.006	0.017
Combatant_fuel_Cap_1000	90.902	90.864	90.931	0.006	0.017
Combatant_fuel_Cap_1500	90.899	90.861	90.929	0.007	0.018
Combatant_fuel_Cap_2000	90.896	90.858	90.924	0.007	0.018
Combatant_fuel_Cap_3000	90.657	90.529	90.852	0.018	0.049
Combatant_fuel_Cap_4000	90.418	90.258	90.891	0.025	0.066
13 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.881	90.632	90.930	0.016	0.042
Double_JHSV_600	90.890	90.652	90.930	0.016	0.043
Double_JHSV_700	90.903	90.865	90.931	0.006	0.017
Double_JHSV_800	90.903	90.865	90.931	0.006	0.017
Double_JHSV_900	90.903	90.865	90.931	0.006	0.017
Double_JHSV_1000	90.902	90.865	90.931	0.006	0.017
Double_JHSV_1500	90.898	90.860	90.926	0.007	0.018
Double_JHSV_2000	90.895	90.857	90.923	0.007	0.018
Double_JHSV_3000	90.653	90.563	90.734	0.014	0.039
Double_JHSV_4000	90.413	90.310	90.759	0.021	0.056
13 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.892	90.639	90.930	0.017	0.046
Double_Logistics_600	90.892	90.648	90.930	0.018	0.049
Double_Logistics_700	90.903	90.865	90.930	0.007	0.018
Double_Logistics_800	90.903	90.865	90.930	0.007	0.018
Double_Logistics_900	90.903	90.865	90.930	0.007	0.018
Double_Logistics_1000	90.902	90.866	90.929	0.006	0.017
Double_Logistics_1500	90.900	90.860	90.924	0.007	0.018
Double_Logistics_2000	90.897	90.856	90.922	0.007	0.019

Double_Logistics_3000	90.742	90.653	90.817	0.013	0.035
Double_Logistics_4000	90.568	90.468	90.748	0.019	0.051

14 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.891	90.635	90.929	0.018	0.047
Combatant_fuel_Cap_600	90.891	90.635	90.929	0.018	0.047
Combatant_fuel_Cap_700	90.903	90.865	90.932	0.006	0.017
Combatant_fuel_Cap_800	90.903	90.865	90.931	0.006	0.017
Combatant_fuel_Cap_900	90.903	90.865	90.931	0.007	0.018
Combatant_fuel_Cap_1000	90.901	90.864	90.930	0.006	0.017
Combatant_fuel_Cap_1500	90.898	90.860	90.927	0.007	0.018
Combatant_fuel_Cap_2000	90.893	90.855	90.921	0.007	0.018
Combatant_fuel_Cap_3000	90.883	90.846	90.911	0.007	0.019
Combatant_fuel_Cap_4000	90.397	90.285	90.900	0.024	0.063
14 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.890	90.653	90.930	0.016	0.044
Double_JHSV_600	90.890	90.652	90.930	0.016	0.044
Double_JHSV_700	90.903	90.865	90.932	0.006	0.017
Double_JHSV_800	90.903	90.865	90.932	0.006	0.017
Double_JHSV_900	90.903	90.866	90.931	0.006	0.017
Double_JHSV_1000	90.902	90.864	90.931	0.006	0.017
Double_JHSV_1500	90.898	90.860	90.927	0.007	0.018
Double_JHSV_2000	90.893	90.855	90.921	0.007	0.018
Double_JHSV_3000	90.882	90.844	90.913	0.007	0.018
Double_JHSV_4000	90.400	90.293	90.750	0.020	0.054
14 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.892	90.641	90.931	0.016	0.043
Double_Logistics_600	90.892	90.641	90.931	0.016	0.043

Double_Logistics_700	90.903	90.865	90.931	0.007	0.018
Double_Logistics_800	90.903	90.865	90.931	0.007	0.018
Double_Logistics_900	90.903	90.865	90.931	0.007	0.018
Double_Logistics_1000	90.902	90.864	90.930	0.006	0.017
Double_Logistics_1500	90.899	90.858	90.926	0.007	0.018
Double_Logistics_2000	90.893	90.853	90.921	0.007	0.018
Double_Logistics_3000	90.882	90.841	90.909	0.007	0.018
Double_Logistics_4000	90.550	90.429	90.767	0.023	0.060

15 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.885	90.634	90.927	0.019	0.050
Combatant_fuel_Cap_600	90.885	90.633	90.927	0.019	0.050
Combatant_fuel_Cap_700	90.903	90.865	90.931	0.006	0.016
Combatant_fuel_Cap_800	90.903	90.865	90.931	0.006	0.016
Combatant_fuel_Cap_900	90.902	90.864	90.931	0.006	0.016
Combatant_fuel_Cap_1000	90.902	90.867	90.931	0.006	0.016
Combatant_fuel_Cap_1500	90.899	90.861	90.928	0.006	0.017
Combatant_fuel_Cap_2000	90.896	90.858	90.923	0.006	0.017
Combatant_fuel_Cap_3000	90.890	90.854	90.918	0.007	0.017
Combatant_fuel_Cap_4000	90.407	90.286	90.804	0.028	0.074
15 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.872	90.635	90.928	0.021	0.055
Double_JHSV_600	90.872	90.635	90.928	0.021	0.055
Double_JHSV_700	90.903	90.864	90.931	0.007	0.018
Double_JHSV_800	90.903	90.864	90.931	0.007	0.018
Double_JHSV_900	90.903	90.864	90.931	0.007	0.018
Double_JHSV_1000	90.902	90.864	90.932	0.007	0.017
Double_JHSV_1500	90.900	90.861	90.928	0.007	0.019
Double_JHSV_2000	90.896	90.858	90.924	0.007	0.019
Double_JHSV_3000	90.892	90.853	90.919	0.007	0.019

Double_JHSV_4000	90.413	90.319	90.580	0.020	0.055
15 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.884	90.647	90.930	0.017	0.045
Double_Logistics_600	90.884	90.647	90.930	0.017	0.045
Double_Logistics_700	90.903	90.864	90.931	0.007	0.018
Double_Logistics_800	90.902	90.864	90.931	0.007	0.018
Double_Logistics_900	90.902	90.864	90.930	0.007	0.018
Double_Logistics_1000	90.902	90.864	90.930	0.007	0.017
Double_Logistics_1500	90.896	90.858	90.926	0.007	0.019
Double_Logistics_2000	90.893	90.854	90.922	0.007	0.020
Double_Logistics_3000	90.888	90.849	90.917	0.007	0.018
Double_Logistics_4000	90.558	90.420	90.702	0.022	0.060

16 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.895	90.636	90.929	0.017	0.046
Combatant_fuel_Cap_600	90.895	90.636	90.929	0.017	0.046
Combatant_fuel_Cap_700	90.891	90.635	90.929	0.017	0.046
Combatant_fuel_Cap_800	90.903	90.865	90.931	0.006	0.017
Combatant_fuel_Cap_900	90.903	90.865	90.931	0.007	0.018
Combatant_fuel_Cap_1000	90.901	90.864	90.930	0.006	0.017
Combatant_fuel_Cap_1500	90.898	90.860	90.927	0.007	0.018
Combatant_fuel_Cap_2000	90.893	90.855	90.921	0.007	0.018
Combatant_fuel_Cap_3000	90.883	90.846	90.911	0.007	0.019
Combatant_fuel_Cap_4000	90.639	90.568	90.899	0.014	0.039
16 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.894	90.652	90.931	0.016	0.042
Double_JHSV_600	90.894	90.652	90.931	0.016	0.042
Double_JHSV_700	90.892	90.672	90.929	0.013	0.034

Double_JHSV_800	90.904	90.866	90.931	0.006	0.017
Double_JHSV_900	90.903	90.866	90.930	0.006	0.017
Double_JHSV_1000	90.902	90.867	90.930	0.006	0.017
Double_JHSV_1500	90.898	90.862	90.925	0.006	0.017
Double_JHSV_2000	90.893	90.855	90.920	0.007	0.018
Double_JHSV_3000	90.882	90.844	90.911	0.007	0.017
Double_JHSV_4000	90.637	90.571	90.898	0.014	0.037
16 Ship Endurance Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.895	90.641	90.931	0.016	0.044
Double_Logistics_600	90.895	90.641	90.931	0.016	0.044
Double_Logistics_700	90.895	90.664	90.931	0.016	0.043
Double_Logistics_800	90.904	90.866	90.931	0.007	0.018
Double_Logistics_900	90.903	90.865	90.931	0.007	0.018
Double_Logistics_1000	90.902	90.866	90.929	0.006	0.017
Double_Logistics_1500	90.899	90.861	90.925	0.007	0.018
Double_Logistics_2000	90.894	90.856	90.920	0.007	0.019
Double_Logistics_3000	90.884	90.843	90.911	0.007	0.018
Double_Logistics_4000	90.716	90.654	90.822	0.014	0.038

2. Combat Patrol Simulation Results

1 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	19.375	10.388	20.164	0.643	1.723
Combatant_fuel_Cap_600	19.374	10.360	20.164	0.645	1.728
Combatant_fuel_Cap_700	16.020	9.897	20.158	1.316	3.526
Combatant_fuel_Cap_800	15.168	10.268	20.158	1.257	3.366
Combatant_fuel_Cap_900	15.231	7.087	20.158	1.415	3.790
Combatant_fuel_Cap_1000	12.278	6.306	18.597	1.299	3.480

Combatant_fuel_Cap_1500	13.749	6.822	20.158	1.871	5.011
Combatant_fuel_Cap_2000	10.398	4.794	20.171	1.439	3.854
Combatant_fuel_Cap_3000	9.501	1.741	20.363	2.290	6.134
Combatant_fuel_Cap_4000	5.206	2.261	13.747	1.091	2.922
1 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	19.695	19.084	20.164	0.112	0.301
Double_JHSV_600	19.695	19.084	20.164	0.112	0.301
Double_JHSV_700	16.599	8.474	20.164	1.683	4.509
Double_JHSV_800	17.358	9.759	20.164	1.500	4.016
Double_JHSV_900	17.299	7.471	20.164	1.692	4.533
Double_JHSV_1000	9.902	4.807	19.383	1.046	2.801
Double_JHSV_1500	12.842	6.910	20.164	1.888	5.058
Double_JHSV_2000	9.614	4.681	16.814	1.253	3.295
Double_JHSV_3000	7.339	1.904	19.671	1.582	4.236
Double_JHSV_4000	4.549	2.200	14.900	1.020	2.733
1 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	17.575	15.555	19.730	0.563	1.507
Double_Logistics_600	17.575	15.555	19.730	0.563	1.507
Double_Logistics_700	17.273	10.666	19.725	0.715	1.914
Double_Logistics_800	17.273	10.647	19.725	0.715	1.916
Double_Logistics_900	17.262	10.331	19.725	0.730	1.954
Double_Logistics_1000	13.550	4.518	19.648	1.937	5.187
Double_Logistics_1500	14.626	6.745	19.725	1.605	4.300
Double_Logistics_2000	7.512	1.279	17.408	1.591	4.261

Double_Logistics_3000	5.462	1.372	15.109	1.330	3.562
Double_Logistics_4000	3.875	1.265	11.391	1.046	2.801

2 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	7.621	0.194	20.116	3.078	8.243
Combatant_fuel_Cap_600	7.390	0.194	20.116	2.979	7.979
Combatant_fuel_Cap_700	4.725	0.299	11.671	1.762	4.720
Combatant_fuel_Cap_800	4.580	0.289	11.963	1.713	4.587
Combatant_fuel_Cap_900	4.683	0.283	11.390	1.746	4.677
Combatant_fuel_Cap_1000	5.797	0.414	18.236	2.349	6.290
Combatant_fuel_Cap_1500	3.459	0.305	9.677	1.243	3.329
Combatant_fuel_Cap_2000	2.326	0.668	7.228	0.699	1.872
Combatant_fuel_Cap_3000	1.392	0.727	2.044	0.190	0.509
Combatant_fuel_Cap_4000	1.802	1.297	2.890	0.195	0.522
2 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	9.110	0.182	19.741	3.196	8.559
Double_JHSV_600	9.109	0.182	19.741	3.196	8.560
Double_JHSV_700	5.772	0.192	16.966	2.239	5.997
Double_JHSV_800	5.424	0.191	15.829	2.071	5.548
Double_JHSV_900	5.637	0.188	16.966	2.209	5.916
Double_JHSV_1000	3.707	0.213	13.795	1.455	3.898
Double_JHSV_1500	2.294	0.231	8.243	0.847	2.270
Double_JHSV_2000	1.781	0.303	7.326	0.660	1.769

Double_JHSV_3000	0.726	0.467	1.711	0.100	0.269
Double_JHSV_4000	0.935	0.546	2.058	0.118	0.315
2 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	9.126	0.177	19.704	3.401	9.109
Double_Logistics_600	9.126	0.176	19.704	3.401	9.110
Double_Logistics_700	7.678	0.174	19.705	3.089	8.274
Double_Logistics_800	7.690	0.173	19.705	3.092	8.282
Double_Logistics_900	7.475	0.173	19.705	3.035	8.129
Double_Logistics_1000	3.777	0.186	15.468	1.620	4.338
Double_Logistics_1500	2.314	0.187	9.693	0.987	2.645
Double_Logistics_2000	1.612	0.244	5.653	0.612	1.639
Double_Logistics_3000	0.682	0.448	1.505	0.078	0.208
Double_Logistics_4000	0.882	0.598	1.382	0.078	0.206

3 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	0.308	0.237	0.395	0.016	0.042
Combatant_fuel_Cap_600	0.307	0.236	0.394	0.016	0.042
Combatant_fuel_Cap_700	0.403	0.304	0.529	0.023	0.059
Combatant_fuel_Cap_800	0.399	0.316	0.491	0.021	0.056
Combatant_fuel_Cap_900	0.396	0.308	0.506	0.022	0.058
Combatant_fuel_Cap_1000	0.611	0.520	0.709	0.018	0.048
Combatant_fuel_Cap_1500	0.643	0.461	0.767	0.032	0.086
Combatant_fuel_Cap_2000	1.158	0.788	1.497	0.064	0.171
Combatant_fuel_Cap_3000	1.769	1.483	1.922	0.070	0.188

Combatant_fuel_Cap_4000	1.960	1.535	3.345	0.280	0.751
3 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	0.306	0.245	0.390	0.014	0.039
Double_JHSV_600	0.301	0.239	0.383	0.015	0.039
Double_JHSV_700	1.290	1.027	1.481	0.047	0.126
Double_JHSV_800	0.328	0.265	0.397	0.014	0.037
Double_JHSV_900	0.325	0.269	0.390	0.013	0.034
Double_JHSV_1000	0.657	0.558	0.764	0.019	0.051
Double_JHSV_1500	0.310	0.256	0.402	0.014	0.037
Double_JHSV_2000	0.307	0.249	0.396	0.014	0.036
Double_JHSV_3000	0.486	0.340	0.582	0.017	0.046
Double_JHSV_4000	1.348	0.988	1.747	0.072	0.192
3 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	0.299	0.230	0.391	0.014	0.036
Double_Logistics_600	0.299	0.229	0.390	0.014	0.036
Double_Logistics_700	0.291	0.224	0.385	0.014	0.038
Double_Logistics_800	0.290	0.223	0.384	0.014	0.038
Double_Logistics_900	0.289	0.222	0.383	0.014	0.038
Double_Logistics_1000	0.298	0.241	0.384	0.013	0.034
Double_Logistics_1500	0.330	0.229	0.435	0.022	0.058
Double_Logistics_2000	0.485	0.306	0.602	0.029	0.077
Double_Logistics_3000	0.712	0.531	0.950	0.041	0.111
Double_Logistics_4000	0.988	0.617	1.804	0.145	0.388

4 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	0.315	0.239	0.395	0.017	0.045
Combatant_fuel_Cap_600	0.315	0.238	0.394	0.017	0.045
Combatant_fuel_Cap_700	0.430	0.348	0.513	0.016	0.043
Combatant_fuel_Cap_800	0.429	0.343	0.524	0.017	0.047
Combatant_fuel_Cap_900	0.430	0.337	0.527	0.017	0.044
Combatant_fuel_Cap_1000	0.614	0.524	0.722	0.020	0.055
Combatant_fuel_Cap_1500	0.690	0.520	0.869	0.033	0.089
Combatant_fuel_Cap_2000	1.243	0.889	1.671	0.053	0.141
Combatant_fuel_Cap_3000	3.075	1.991	3.780	0.063	0.167
Combatant_fuel_Cap_4000	14.815	3.140	46.711	3.997	10.705
4 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	0.319	0.260	0.399	0.015	0.040
Double_JHSV_600	0.318	0.260	0.398	0.015	0.040
Double_JHSV_700	0.312	0.262	0.392	0.013	0.035
Double_JHSV_800	0.312	0.258	0.391	0.014	0.037
Double_JHSV_900	0.312	0.252	0.390	0.014	0.037
Double_JHSV_1000	0.509	0.430	0.602	0.017	0.046
Double_JHSV_1500	0.610	0.452	0.727	0.027	0.072
Double_JHSV_2000	1.192	0.871	1.615	0.047	0.125
Double_JHSV_3000	3.114	2.146	3.822	0.059	0.157
Double_JHSV_4000	12.927	3.142	46.683	4.100	10.980
4 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half	Standard

				Width	Deviation
Double_Logistics_500	0.307	0.232	0.391	0.015	0.041
Double_Logistics_600	0.306	0.231	0.390	0.015	0.041
Double_Logistics_700	0.299	0.214	0.385	0.016	0.042
Double_Logistics_800	0.298	0.214	0.384	0.016	0.042
Double_Logistics_900	0.297	0.213	0.383	0.016	0.042
Double_Logistics_1000	0.300	0.224	0.385	0.015	0.039
Double_Logistics_1500	0.319	0.224	0.439	0.019	0.052
Double_Logistics_2000	0.488	0.310	0.618	0.029	0.079
Double_Logistics_3000	1.066	0.532	2.031	0.041	0.107
Double_Logistics_4000	2.690	1.313	9.598	0.788	2.110

5 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	0.319	0.240	0.395	0.017	0.045
Combatant_fuel_Cap_600	0.319	0.239	0.395	0.017	0.045
Combatant_fuel_Cap_700	0.439	0.374	0.515	0.019	0.052
Combatant_fuel_Cap_800	0.435	0.373	0.521	0.021	0.055
Combatant_fuel_Cap_900	0.437	0.378	0.519	0.020	0.053
Combatant_fuel_Cap_1000	0.626	0.543	0.729	0.020	0.055
Combatant_fuel_Cap_1500	0.740	0.457	0.928	0.039	0.105
Combatant_fuel_Cap_2000	1.376	1.067	1.832	0.062	0.165
Combatant_fuel_Cap_3000	4.463	2.775	5.652	0.041	0.110
Combatant_fuel_Cap_4000	29.342	4.128	90.449	0.274	0.733
5 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	0.323	0.266	0.399	0.015	0.041

Double_JHSV_600	0.323	0.265	0.396	0.015	0.041
Double_JHSV_700	0.317	0.263	0.393	0.014	0.038
Double_JHSV_800	0.316	0.262	0.392	0.014	0.038
Double_JHSV_900	0.316	0.262	0.389	0.014	0.038
Double_JHSV_1000	0.667	0.560	0.784	0.023	0.061
Double_JHSV_1500	0.995	0.746	1.241	0.040	0.107
Double_JHSV_2000	1.777	1.486	2.022	0.041	0.109
Double_JHSV_3000	4.474	2.843	5.646	0.069	0.186
Double_JHSV_4000	24.625	4.513	90.477	0.271	0.727
5 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	0.313	0.235	0.417	0.017	0.045
Double_Logistics_600	0.312	0.234	0.416	0.016	0.042
Double_Logistics_700	0.301	0.229	0.408	0.016	0.042
Double_Logistics_800	0.300	0.228	0.407	0.016	0.042
Double_Logistics_900	45.580	45.420	45.663	0.019	0.052
Double_Logistics_1000	0.311	0.243	0.404	0.017	0.046
Double_Logistics_1500	0.409	0.304	0.569	0.026	0.070
Double_Logistics_2000	0.733	0.548	0.970	0.031	0.082
Double_Logistics_3000	1.524	0.604	2.891	0.041	0.110
Double_Logistics_4000	5.021	1.648	19.514	0.134	0.358

6 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	55.960	10.224	90.442	0.191	0.513
Combatant_fuel_Cap_600	45.586	45.425	45.660	0.024	0.064
Combatant_fuel_Cap_700	45.661	45.476	45.728	0.025	0.067

Combatant_fuel_Cap_800	45.663	45.483	45.727	0.024	0.065
Combatant_fuel_Cap_900	45.662	45.475	45.725	0.024	0.064
Combatant_fuel_Cap_1000	45.751	45.624	45.829	0.017	0.046
Combatant_fuel_Cap_1500	45.594	45.465	45.757	0.027	0.071
Combatant_fuel_Cap_2000	45.898	45.628	46.173	0.041	0.109
Combatant_fuel_Cap_3000	47.405	46.374	48.105	0.034	0.092
Combatant_fuel_Cap_4000	55.960	10.224	90.442	0.191	0.513
6Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	55.283	11.320	90.496	0.162	0.435
Double_JHSV_600	45.589	45.433	45.660	0.024	0.064
Double_JHSV_700	45.587	45.431	45.658	0.022	0.059
Double_JHSV_800	45.588	45.430	45.656	0.022	0.059
Double_JHSV_900	45.586	45.429	45.659	0.022	0.059
Double_JHSV_1000	45.762	45.632	45.848	0.018	0.049
Double_JHSV_1500	45.706	45.437	45.909	0.024	0.063
Double_JHSV_2000	46.092	45.842	46.282	0.036	0.096
Double_JHSV_3000	47.404	46.459	48.055	0.047	0.127
Double_JHSV_4000	55.283	11.320	90.496	0.162	0.435
6 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	32.112	4.372	56.207	0.077	0.207
Double_Logistics_600	45.583	45.429	45.663	0.019	0.051
Double_Logistics_700	45.590	45.430	45.662	0.019	0.051
Double_Logistics_800	45.589	45.429	45.661	0.019	0.051
Double_Logistics_900	90.870	90.624	90.921	0.020	0.053

Double_Logistics_1000	45.594	45.483	45.668	0.015	0.040
Double_Logistics_1500	45.229	44.904	45.631	0.017	0.046
Double_Logistics_2000	45.385	45.062	45.775	0.034	0.091
Double_Logistics_3000	45.971	45.531	46.854	0.032	0.085
Double_Logistics_4000	32.112	4.372	56.207	0.077	0.207

7 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	83.853	83.610	83.925	0.024	0.064
Combatant_fuel_Cap_600	83.853	83.610	83.925	0.024	0.064
Combatant_fuel_Cap_700	83.859	83.606	83.921	0.019	0.050
Combatant_fuel_Cap_800	83.858	83.605	83.920	0.019	0.050
Combatant_fuel_Cap_900	83.858	83.605	83.920	0.019	0.050
Combatant_fuel_Cap_1000	83.892	83.855	83.920	0.006	0.016
Combatant_fuel_Cap_1500	83.395	83.316	83.537	0.021	0.057
Combatant_fuel_Cap_2000	83.382	83.305	83.536	0.021	0.055
Combatant_fuel_Cap_3000	83.371	83.236	83.512	0.028	0.074
Combatant_fuel_Cap_4000	76.480	12.624	83.456	0.112	0.300
7 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	83.855	83.599	83.924	0.017	0.045
Double_JHSV_600	83.855	83.598	83.924	0.017	0.045
Double_JHSV_700	83.850	83.591	83.920	0.013	0.034
Double_JHSV_800	83.850	83.590	83.920	0.013	0.034
Double_JHSV_900	83.849	83.590	83.919	0.014	0.036
Double_JHSV_1000	83.894	83.854	83.921	0.007	0.017
Double_JHSV_1500	83.406	83.319	83.527	0.019	0.050

Double_JHSV_2000	83.398	83.326	83.508	0.016	0.043
Double_JHSV_3000	83.365	83.237	83.503	0.028	0.076
Double_JHSV_4000	76.833	15.655	83.515	0.074	0.198
7 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	83.856	83.618	83.923	0.020	0.055
Double_Logistics_600	83.856	83.618	83.923	0.020	0.055
Double_Logistics_700	83.870	83.613	83.922	0.019	0.050
Double_Logistics_800	83.870	83.612	83.922	0.019	0.050
Double_Logistics_900	83.869	83.612	83.921	0.019	0.050
Double_Logistics_1000	83.893	83.855	83.921	0.007	0.019
Double_Logistics_1500	83.095	82.295	83.717	0.014	0.038
Double_Logistics_2000	83.093	82.322	83.706	0.025	0.067
Double_Logistics_3000	83.490	83.382	83.604	0.020	0.053
Double_Logistics_4000	56.522	10.946	83.589	0.047	0.126

8 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	83.853	83.610	83.925	0.024	0.064
Combatant_fuel_Cap_600	83.853	83.610	83.925	0.024	0.064
Combatant_fuel_Cap_700	83.859	83.606	83.921	0.019	0.050
Combatant_fuel_Cap_800	83.858	83.605	83.920	0.019	0.050
Combatant_fuel_Cap_900	83.858	83.605	83.920	0.019	0.050
Combatant_fuel_Cap_1000	83.892	83.855	83.920	0.006	0.016
Combatant_fuel_Cap_1500	83.395	83.316	83.537	0.021	0.057
Combatant_fuel_Cap_2000	83.382	83.305	83.536	0.021	0.055
Combatant_fuel_Cap_3000	83.371	83.236	83.512	0.028	0.074

Combatant_fuel_Cap_4000	76.480	12.624	83.456	0.112	0.300
8 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	83.855	83.599	83.924	0.017	0.045
Double_JHSV_600	83.855	83.598	83.924	0.017	0.045
Double_JHSV_700	83.850	83.591	83.920	0.013	0.034
Double_JHSV_800	83.850	83.590	83.920	0.013	0.034
Double_JHSV_900	83.849	83.590	83.919	0.014	0.036
Double_JHSV_1000	83.894	83.854	83.921	0.007	0.017
Double_JHSV_1500	83.406	83.319	83.527	0.019	0.050
Double_JHSV_2000	83.398	83.326	83.508	0.016	0.043
Double_JHSV_3000	83.365	83.237	83.503	0.028	0.076
Double_JHSV_4000	76.833	15.655	83.515	0.074	0.198
8 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	83.856	83.618	83.923	0.020	0.055
Double_Logistics_600	83.856	83.618	83.923	0.020	0.055
Double_Logistics_700	83.870	83.613	83.922	0.019	0.050
Double_Logistics_800	83.870	83.612	83.922	0.019	0.050
Double_Logistics_900	83.869	83.612	83.921	0.019	0.050
Double_Logistics_1000	83.893	83.855	83.921	0.007	0.019
Double_Logistics_1500	83.095	82.295	83.717	0.014	0.038
Double_Logistics_2000	83.093	82.322	83.706	0.025	0.067
Double_Logistics_3000	83.490	83.382	83.604	0.020	0.053
Double_Logistics_4000	56.522	10.946	83.589	0.047	0.126
9 Ship Combat Patrol					

Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.896	90.863	90.925	0.006	0.016
Combatant_fuel_Cap_600	90.895	90.862	90.924	0.006	0.016
Combatant_fuel_Cap_700	90.655	90.596	90.737	0.014	0.038
Combatant_fuel_Cap_800	90.651	90.589	90.734	0.013	0.035
Combatant_fuel_Cap_900	90.650	90.583	90.732	0.013	0.036
Combatant_fuel_Cap_1000	90.640	90.581	90.722	0.013	0.035
Combatant_fuel_Cap_1500	90.619	90.531	90.688	0.015	0.041
Combatant_fuel_Cap_2000	90.359	90.234	90.682	0.026	0.069
Combatant_fuel_Cap_3000	90.260	89.835	90.425	0.083	0.223
Combatant_fuel_Cap_4000	89.954	89.690	90.337	0.079	0.210
9 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.897	90.858	90.926	0.006	0.017
Double_JHSV_600	90.896	90.858	90.925	0.006	0.017
Double_JHSV_700	90.654	90.589	90.745	0.014	0.038
Double_JHSV_800	90.646	90.577	90.750	0.015	0.041
Double_JHSV_900	90.645	90.575	90.748	0.015	0.040
Double_JHSV_1000	90.642	90.564	90.733	0.014	0.037
Double_JHSV_1500	90.620	90.538	90.701	0.018	0.049
Double_JHSV_2000	90.369	90.253	90.698	0.025	0.066
Double_JHSV_3000	89.272	74.827	90.405	0.124	0.332
Double_JHSV_4000	89.945	89.701	90.329	0.062	0.167
9 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation

Double_Logistics_500	90.897	90.859	90.924	0.007	0.019
Double_Logistics_600	90.896	90.858	90.923	0.007	0.019
Double_Logistics_700	90.576	90.188	90.814	0.012	0.032
Double_Logistics_800	90.572	90.203	90.801	0.009	0.025
Double_Logistics_900	90.571	90.212	90.800	0.009	0.024
Double_Logistics_1000	90.564	90.201	90.803	0.018	0.047
Double_Logistics_1500	90.687	90.599	90.765	0.015	0.040
Double_Logistics_2000	90.510	90.390	90.651	0.023	0.061
Double_Logistics_3000	89.435	75.000	90.601	0.050	0.134
Double_Logistics_4000	90.063	89.875	90.266	0.050	0.135

10 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.877	90.631	90.926	0.019	0.050
Combatant_fuel_Cap_600	90.871	90.630	90.925	0.018	0.049
Combatant_fuel_Cap_700	90.882	90.424	90.923	0.028	0.074
Combatant_fuel_Cap_800	90.882	90.430	90.923	0.028	0.074
Combatant_fuel_Cap_900	90.881	90.430	90.922	0.028	0.074
Combatant_fuel_Cap_1000	90.893	90.859	90.922	0.006	0.016
Combatant_fuel_Cap_1500	90.885	90.851	90.914	0.006	0.017
Combatant_fuel_Cap_2000	90.874	90.836	90.902	0.006	0.017
Combatant_fuel_Cap_3000	90.609	90.501	90.691	0.019	0.050
Combatant_fuel_Cap_4000	90.325	90.076	90.790	0.051	0.136
10 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.868	90.630	90.925	0.021	0.056

Double_JHSV_600	90.866	90.627	90.924	0.019	0.050
Double_JHSV_700	90.854	90.385	90.927	0.013	0.034
Double_JHSV_800	90.853	90.386	90.926	0.013	0.034
Double_JHSV_900	90.853	90.386	90.926	0.013	0.034
Double_JHSV_1000	90.894	90.855	90.923	0.007	0.018
Double_JHSV_1500	90.886	90.847	90.915	0.007	0.019
Double_JHSV_2000	90.874	90.836	90.902	0.007	0.019
Double_JHSV_3000	90.605	90.519	90.699	0.016	0.043
Double_JHSV_4000	90.338	90.201	90.651	0.020	0.053
10 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.885	90.638	90.929	0.019	0.051
Double_Logistics_600	90.882	90.627	90.928	0.017	0.045
Double_Logistics_700	90.857	89.932	90.925	0.017	0.045
Double_Logistics_800	90.856	89.931	90.925	0.017	0.045
Double_Logistics_900	90.856	89.931	90.924	0.017	0.045
Double_Logistics_1000	90.893	90.855	90.922	0.007	0.018
Double_Logistics_1500	90.884	90.845	90.914	0.007	0.018
Double_Logistics_2000	90.872	90.834	90.901	0.007	0.019
Double_Logistics_3000	90.698	90.621	90.761	0.014	0.038
Double_Logistics_4000	90.487	90.353	90.636	0.022	0.059

11 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.880	90.628	90.922	0.019	0.050
Combatant_fuel_Cap_600	90.878	90.627	90.921	0.019	0.050
Combatant_fuel_Cap_700	90.900	90.862	90.928	0.006	0.016

Combatant_fuel_Cap_800	90.899	90.861	90.928	0.006	0.016
Combatant_fuel_Cap_900	90.899	90.861	90.927	0.006	0.016
Combatant_fuel_Cap_1000	90.893	90.857	90.922	0.006	0.016
Combatant_fuel_Cap_1500	90.884	90.847	90.913	0.006	0.017
Combatant_fuel_Cap_2000	90.879	90.841	90.907	0.006	0.017
Combatant_fuel_Cap_3000	90.619	90.521	90.699	0.018	0.048
Combatant_fuel_Cap_4000	90.362	90.215	90.760	0.026	0.070
11 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.870	90.634	90.926	0.021	0.055
Double_JHSV_600	90.870	90.634	90.926	0.021	0.055
Double_JHSV_700	90.899	90.860	90.927	0.007	0.018
Double_JHSV_800	90.899	90.860	90.926	0.007	0.018
Double_JHSV_900	90.898	90.859	90.926	0.007	0.018
Double_JHSV_1000	90.894	90.857	90.923	0.006	0.017
Double_JHSV_1500	90.885	90.846	90.913	0.007	0.019
Double_JHSV_2000	90.874	90.836	90.901	0.007	0.019
Double_JHSV_3000	90.607	90.533	90.689	0.016	0.042
Double_JHSV_4000	90.340	90.225	90.514	0.020	0.053
11 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.883	90.645	90.929	0.017	0.045
Double_Logistics_600	90.882	90.645	90.928	0.017	0.045
Double_Logistics_700	90.899	90.860	90.927	0.007	0.018
Double_Logistics_800	90.898	90.859	90.926	0.007	0.018
Double_Logistics_900	90.898	90.859	90.926	0.007	0.018

Double_Logistics_1000	90.894	90.857	90.920	0.007	0.018
Double_Logistics_1500	90.882	90.844	90.911	0.007	0.019
Double_Logistics_2000	90.870	90.832	90.899	0.007	0.020
Double_Logistics_3000	90.701	90.629	90.772	0.015	0.039
Double_Logistics_4000	90.490	90.380	90.654	0.023	0.061

12 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.884	90.633	90.926	0.018	0.049
Combatant_fuel_Cap_600	90.884	90.633	90.926	0.018	0.049
Combatant_fuel_Cap_700	90.899	90.861	90.928	0.006	0.017
Combatant_fuel_Cap_800	90.898	90.860	90.927	0.006	0.017
Combatant_fuel_Cap_900	90.898	90.860	90.927	0.006	0.017
Combatant_fuel_Cap_1000	90.894	90.857	90.922	0.006	0.017
Combatant_fuel_Cap_1500	90.885	90.847	90.914	0.006	0.017
Combatant_fuel_Cap_2000	90.874	90.836	90.902	0.006	0.017
Combatant_fuel_Cap_3000	90.610	90.522	90.801	0.018	0.047
Combatant_fuel_Cap_4000	90.336	90.077	90.791	0.050	0.133
12 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.878	90.638	90.927	0.020	0.053
Double_JHSV_600	90.878	90.637	90.927	0.020	0.053
Double_JHSV_700	90.899	90.860	90.927	0.007	0.018
Double_JHSV_800	90.899	90.860	90.926	0.007	0.018
Double_JHSV_900	90.898	90.859	90.926	0.007	0.018
Double_JHSV_1000	90.894	90.857	90.922	0.007	0.017
Double_JHSV_1500	90.886	90.847	90.912	0.007	0.019

Double_JHSV_2000	90.874	90.836	90.901	0.007	0.019
Double_JHSV_3000	90.611	90.541	90.697	0.014	0.038
Double_JHSV_4000	90.333	90.199	90.668	0.021	0.057
12 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.889	90.646	90.928	0.017	0.046
Double_Logistics_600	90.889	90.646	90.928	0.017	0.046
Double_Logistics_700	90.899	90.861	90.926	0.007	0.018
Double_Logistics_800	90.898	90.860	90.925	0.007	0.018
Double_Logistics_900	90.898	90.860	90.925	0.007	0.018
Double_Logistics_1000	90.893	90.857	90.920	0.006	0.017
Double_Logistics_1500	90.884	90.845	90.910	0.007	0.018
Double_Logistics_2000	90.872	90.834	90.899	0.007	0.019
Double_Logistics_3000	90.696	90.614	90.775	0.015	0.041
Double_Logistics_4000	90.491	90.380	90.669	0.021	0.057

13 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.886	90.619	90.927	0.018	0.048
Combatant_fuel_Cap_600	90.886	90.619	90.926	0.018	0.048
Combatant_fuel_Cap_700	90.899	90.861	90.927	0.006	0.017
Combatant_fuel_Cap_800	90.898	90.860	90.927	0.006	0.017
Combatant_fuel_Cap_900	90.898	90.860	90.926	0.006	0.017
Combatant_fuel_Cap_1000	90.894	90.855	90.922	0.006	0.017
Combatant_fuel_Cap_1500	90.885	90.847	90.915	0.006	0.017
Combatant_fuel_Cap_2000	90.875	90.836	90.902	0.006	0.017
Combatant_fuel_Cap_3000	90.609	90.483	90.808	0.018	0.050

Combatant_fuel_Cap_4000	90.331	89.930	90.829	0.077	0.205
13 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.886	90.640	90.928	0.016	0.043
Double_JHSV_600	90.886	90.639	90.928	0.016	0.043
Double_JHSV_700	90.899	90.861	90.927	0.006	0.017
Double_JHSV_800	90.898	90.860	90.926	0.006	0.017
Double_JHSV_900	90.898	90.860	90.926	0.007	0.017
Double_JHSV_1000	90.894	90.855	90.923	0.006	0.017
Double_JHSV_1500	90.885	90.847	90.912	0.007	0.018
Double_JHSV_2000	90.874	90.836	90.901	0.007	0.018
Double_JHSV_3000	90.609	90.531	90.694	0.015	0.041
Double_JHSV_4000	90.332	90.202	90.537	0.021	0.055
13 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.890	90.645	90.929	0.017	0.047
Double_Logistics_600	90.889	90.645	90.928	0.017	0.047
Double_Logistics_700	90.899	90.861	90.926	0.007	0.018
Double_Logistics_800	90.899	90.860	90.925	0.007	0.018
Double_Logistics_900	90.898	90.859	90.926	0.007	0.017
Double_Logistics_1000	90.894	90.856	90.921	0.006	0.017
Double_Logistics_1500	90.886	90.844	90.911	0.006	0.017
Double_Logistics_2000	90.874	90.832	90.901	0.007	0.018
Double_Logistics_3000	90.699	90.610	90.774	0.014	0.038
Double_Logistics_4000	90.492	90.325	90.679	0.024	0.064

14 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.818	90.674	90.842	0.014	0.038
Combatant_fuel_Cap_600	90.892	90.647	90.928	0.018	0.048
Combatant_fuel_Cap_700	90.884	90.616	90.926	0.019	0.052
Combatant_fuel_Cap_800	90.899	90.861	90.927	0.006	0.017
Combatant_fuel_Cap_900	90.898	90.860	90.926	0.006	0.017
Combatant_fuel_Cap_1000	90.894	90.857	90.922	0.006	0.017
Combatant_fuel_Cap_1500	90.885	90.847	90.914	0.007	0.018
Combatant_fuel_Cap_2000	90.875	90.836	90.902	0.007	0.018
Combatant_fuel_Cap_3000	90.847	90.811	90.877	0.007	0.018
Combatant_fuel_Cap_4000	90.813	90.774	90.841	0.007	0.018
14 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.346	90.260	90.822	0.019	0.052
Double_JHSV_600	90.865	90.621	90.924	0.016	0.043
Double_JHSV_700	90.893	90.665	90.929	0.016	0.042
Double_JHSV_800	90.890	90.670	90.927	0.013	0.034
Double_JHSV_900	90.899	90.860	90.927	0.007	0.017
Double_JHSV_1000	90.898	90.864	90.925	0.007	0.017
Double_JHSV_1500	90.894	90.855	90.923	0.006	0.017
Double_JHSV_2000	90.886	90.846	90.916	0.007	0.018
Double_JHSV_3000	90.872	90.837	90.900	0.007	0.019
Double_JHSV_4000	90.842	90.804	90.874	0.007	0.017
14 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half	Standard

				Width	Deviation
Double_Logistics_500	90.843	90.803	90.872	0.007	0.018
Double_Logistics_600	90.487	90.313	90.699	0.022	0.059
Double_Logistics_700	90.893	90.639	90.929	0.016	0.043
Double_Logistics_800	90.890	90.633	90.928	0.016	0.043
Double_Logistics_900	90.899	90.860	90.928	0.007	0.019
Double_Logistics_1000	90.899	90.861	90.928	0.006	0.017
Double_Logistics_1500	90.898	90.860	90.925	0.006	0.017
Double_Logistics_2000	90.889	90.855	90.917	0.006	0.017
Double_Logistics_3000	90.886	90.845	90.913	0.007	0.018
Double_Logistics_4000	90.870	90.832	90.901	0.007	0.019

15 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.892	90.647	90.928	0.017	0.047
Combatant_fuel_Cap_600	90.892	90.647	90.927	0.017	0.047
Combatant_fuel_Cap_700	90.894	90.650	90.929	0.017	0.046
Combatant_fuel_Cap_800	90.899	90.861	90.927	0.006	0.017
Combatant_fuel_Cap_900	90.898	90.860	90.926	0.006	0.017
Combatant_fuel_Cap_1000	90.893	90.858	90.923	0.006	0.017
Combatant_fuel_Cap_1500	90.885	90.848	90.915	0.006	0.017
Combatant_fuel_Cap_2000	90.875	90.836	90.902	0.007	0.017
Combatant_fuel_Cap_3000	90.846	90.810	90.875	0.007	0.018
Combatant_fuel_Cap_4000	90.339	90.190	90.829	0.023	0.063
15 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.891	90.662	90.929	0.016	0.044

Double_JHSV_600	90.890	90.662	90.928	0.016	0.044
Double_JHSV_700	90.894	90.650	90.929	0.016	0.042
Double_JHSV_800	90.899	90.860	90.926	0.006	0.017
Double_JHSV_900	90.898	90.860	90.926	0.006	0.017
Double_JHSV_1000	90.894	90.858	90.923	0.006	0.017
Double_JHSV_1500	90.886	90.848	90.913	0.007	0.017
Double_JHSV_2000	90.874	90.836	90.901	0.007	0.018
Double_JHSV_3000	90.847	90.808	90.875	0.007	0.017
Double_JHSV_4000	90.341	90.233	90.824	0.019	0.050
15 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.892	90.642	90.929	0.017	0.045
Double_Logistics_600	90.891	90.642	90.929	0.017	0.045
Double_Logistics_700	90.893	90.640	90.929	0.016	0.044
Double_Logistics_800	90.899	90.861	90.926	0.007	0.017
Double_Logistics_900	90.898	90.860	90.926	0.007	0.017
Double_Logistics_1000	90.894	90.857	90.921	0.006	0.017
Double_Logistics_1500	90.886	90.847	90.914	0.007	0.017
Double_Logistics_2000	90.875	90.836	90.902	0.007	0.018
Double_Logistics_3000	90.846	90.806	90.874	0.007	0.018
Double_Logistics_4000	90.492	90.417	90.702	0.021	0.055

16 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Combatant_fuel_Cap_500	90.819	90.782	90.844	0.007	0.019
Combatant_fuel_Cap_600	90.895	90.649	90.928	0.017	0.046
Combatant_fuel_Cap_700	90.895	90.650	90.929	0.017	0.047

Combatant_fuel_Cap_800	90.899	90.861	90.928	0.006	0.017
Combatant_fuel_Cap_900	90.898	90.860	90.926	0.006	0.017
Combatant_fuel_Cap_1000	90.893	90.858	90.921	0.006	0.017
Combatant_fuel_Cap_1500	90.885	90.847	90.914	0.007	0.018
Combatant_fuel_Cap_2000	90.875	90.836	90.902	0.007	0.017
Combatant_fuel_Cap_3000	90.846	90.809	90.874	0.007	0.019
Combatant_fuel_Cap_4000	90.812	90.774	90.842	0.007	0.018
16 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_JHSV_500	90.814	90.674	90.845	0.013	0.035
Double_JHSV_600	90.895	90.669	90.928	0.016	0.044
Double_JHSV_700	90.896	90.672	90.929	0.016	0.044
Double_JHSV_800	90.899	90.861	90.927	0.006	0.017
Double_JHSV_900	90.899	90.861	90.927	0.006	0.017
Double_JHSV_1000	90.894	90.859	90.921	0.006	0.017
Double_JHSV_1500	90.885	90.851	90.911	0.007	0.018
Double_JHSV_2000	90.876	90.841	90.900	0.006	0.017
Double_JHSV_3000	90.845	90.809	90.871	0.007	0.018
Double_JHSV_4000	90.812	90.777	90.836	0.007	0.019
16 Ship Combat Patrol					
Scenario	Average	Minimum	Maximum	Half Width	Standard Deviation
Double_Logistics_500	90.818	90.785	90.844	0.007	0.019
Double_Logistics_600	90.895	90.672	90.929	0.017	0.045
Double_Logistics_700	90.893	90.662	90.929	0.017	0.046
Double_Logistics_800	90.899	90.861	90.928	0.007	0.018
Double_Logistics_900	90.899	90.860	90.926	0.007	0.017

Double_Logistics_1000	90.894	90.857	90.922	0.007	0.018
Double_Logistics_1500	90.886	90.847	90.914	0.007	0.019
Double_Logistics_2000	90.878	90.837	90.903	0.007	0.019
Double_Logistics_3000	90.847	90.808	90.875	0.007	0.018
Double_Logistics_4000	90.816	90.776	90.840	0.007	0.019

3. Logistic Improvement Analysis

Values such as speeds and transfer times were fixed, removing any variability to the simulation. The following values were adjusted:

- T-AKE speed from 12 kts. to 24 kts.
- JHSV speed from 20 kts. to 40 kts.
- T-AKE capacity to 1,800,000 gallons
- Fuel ferry capacity to 420,000
- Guam to first transfer point reduced to 800 miles
- Guam to first transfer point reduced to 400 mile
- Ship numbers to: eight T-AKE and four fuel ferry
- Ship numbers to: eight fuel ferry and four T-AKE
- Ship numbers to: eight T-AKE and eight fuel ferry

a. Baseline of Eight T-AKE and Eight Fuel Ferries

1500 ton		
Scenario	**Days Idle**	**Percent**
Baseline: 4 T-AKE, 4 Fuel Ferry, 15 SSC	91	50%
Increase Speed of T-AKE to 24 kts.	91	50%
Increase Speed of JHSV to 40 kts.	19	10%
Increase Capacity of T-AKE to 1,800,000	91	50%
Increase Capacity of Fuel Ferry to 420,000	60	33%
T-AKE Leg Reduced to 800 miles	91	50%
T-AKE Leg Reduced to 400 mile	91	50%
8 T-AKE, 4 Fuel Ferry	91	50%
8 Fuel Ferry, 4 T-AKE	91	50%
8 T-AKE, 8 Fuel Ferry	90	50%

Scenario	**Days Idle**	**Percent**
Baseline: 8 T-AKE, 8 Fuel Ferry, 15 SSC	91	50%
Increase Speed of T-AKE to 24 kts.	91	50%

Increase Speed of JHSV to 40 kts.	12	6%
Increase Capacity of T-AKE to 1,800,000	91	50%
Increase Capacity of Fuel Ferry to 420,000	29	16%
T-AKE Leg Reduced to 800 miles	91	50%
T-AKE Leg Reduced to 400 mile	91	50%
16 T-AKE, 8 Fuel Ferry	91	50%
16 Fuel Ferry, 8 T-AKE	44	25%
16 T-AKE, 16 Fuel Ferry	44	25%

b. Baseline of 4 T-AKE and 4 Fuel Ferries

600 ton		
Scenario	**Days Idle**	**Percent**
Baseline: 4 T-AKE, 4 Fuel Ferry, 15 SSC	2	1%
Increase Speed of T-AKE to 24kts	2	1%
Increase Speed of JHSV to 40 kts.	6	3%
Increase Capacity of T-AKE to 1,800,000	2	1%
Increase Capacity of Fuel Ferry to 420,000	5	3%

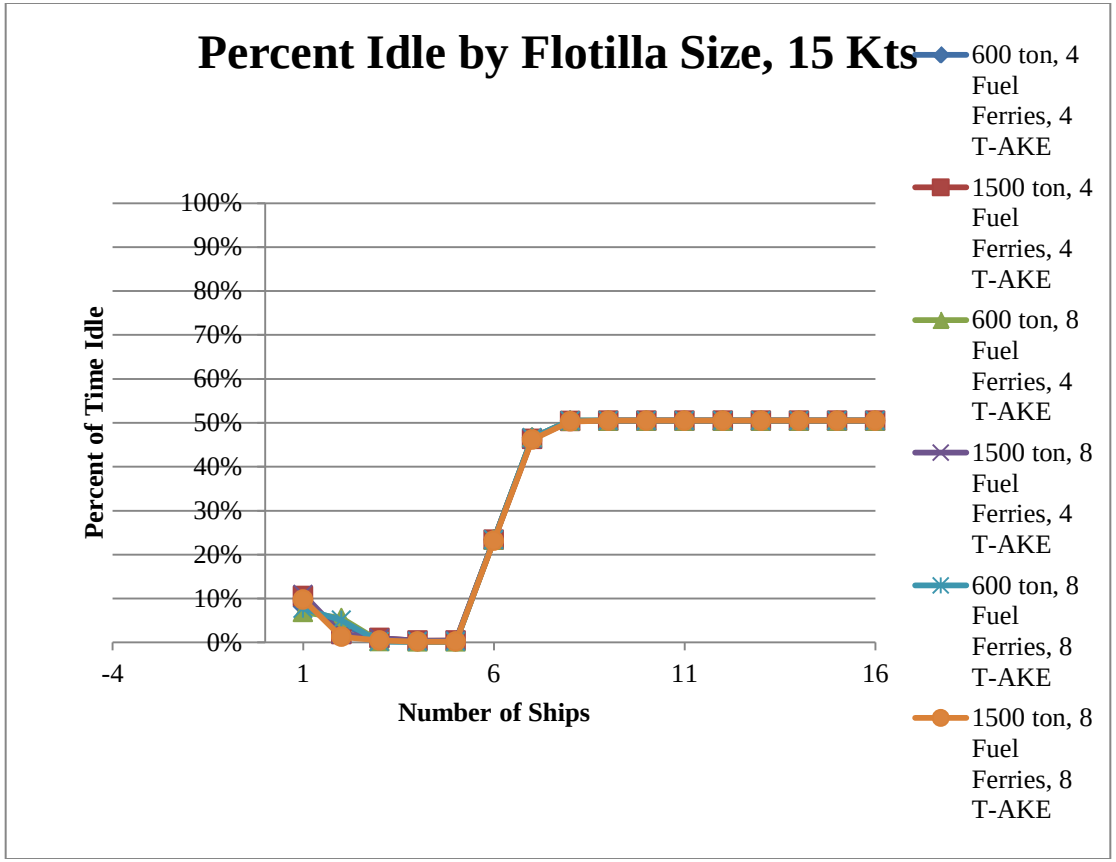
T-AKE Leg Reduced to 800 miles	2	1%
T-AKE Leg Reduced to 400 mile	3	2%
8 T-AKE, 4 Fuel Ferry	2	1%
8 Fuel Ferry, 4 T-AKE	2	1%
8 Both	1	1%

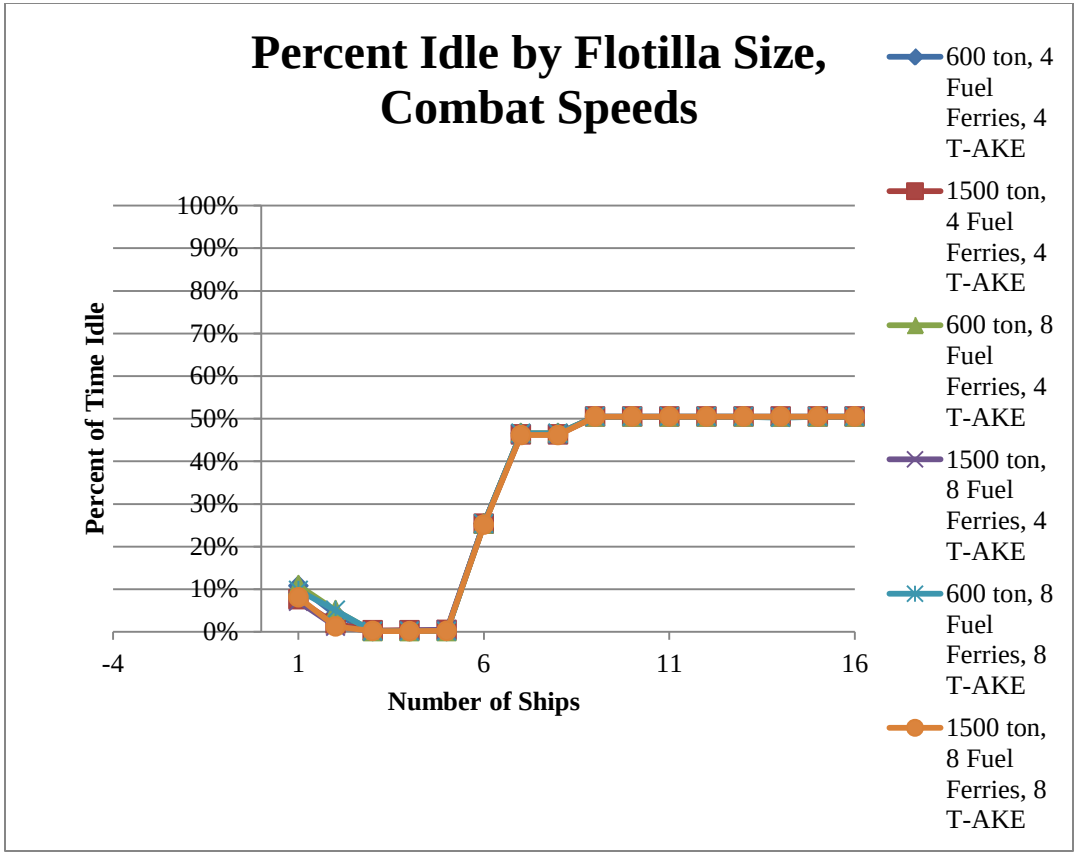
Scenario	Days Idle	Percent
Baseline: 8 T-AKE, 8 Fuel Ferry, 15 SSC	1	1%
Increase Speed of T-AKE to 24 kts.	2	1%
Increase Speed of JHSV to 40 kts.	4	2%
Increase Capacity of T-AKE to 1,800,000	7	4%
Increase Capacity of Fuel Ferry to 420,000	3	2%
T-AKE Leg Reduced to 800 miles	2	1%
T-AKE Leg Reduced to 400 mile	2	1%
16 T-AKE, 8 Fuel Ferry	3	2%
16 Fuel Ferry, 8 T-AKE	2	1%

16 Both	3	2%

4. Percent Idle Time for Flotilla

These graphs represent the idle time derived from SIMIO based on the ships operating to a 50% capacity and returning to the replenishment point.


Percent Idle by Flotilla Size, 15 Kts
Percent of Time Idle
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-4
1
6
11
16
Number of Ships
600 ton, 4 Fuel Ferries, 4 T-AKE
1500 ton, 4 Fuel Ferries, 4 T-AKE
600 ton, 8 Fuel Ferries, 4 T-AKE
1500 ton, 8 Fuel Ferries, 4 T-AKE
600 ton, 8 Fuel Ferries, 8 T-AKE
1500 ton, 8 Fuel Ferries, 8 T-AKE


Percent Idle by Flotilla Size, Combat Speeds
Percent of Time Idle
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
-4
1
6
11
16
Number of Ships
600 ton, 4 Fuel Ferries, 4 T-AKE
1500 ton, 4 Fuel Ferries, 4 T-AKE
600 ton, 8 Fuel Ferries, 4 T-AKE
1500 ton, 8 Fuel Ferries, 4 T-AKE
600 ton, 8 Fuel Ferries, 8 T-AKE
1500 ton, 8 Fuel Ferries, 8 T-AKE

C. COMBAT XXI

This work was performed in an educational/research setting using representative performance data and is not endorsed by either the U.S. Army TAADOC Analysis Center (TRAC) or Marine Corps Combat Development Command (MCCDC). COMBAT XXI was modified to model naval engagements.

Red Casualties		*BLUE Casualties*	
Mean	16	Mean	1.45
Standard Error	0	Standard Error	0.226691
Median	16	Median	0
Mode	16	Mode	0
Standard Deviation	0	Standard Deviation	2.266912
Sample Variance	0	Sample Variance	5.138889
Range	0	Range	9
Minimum	16	Minimum	0
Maximum	16	Maximum	9
Sum	1600	Sum	145
Count	100	Count	100
Confidence Level (95.0%)	0	Confidence Level (95.0%)	0.449804

Run Number	Red Casualties	BLUE Casualties
1	16	0
2	16	0
3	16	0
4	16	0
5	16	0
6	16	0
7	16	0
8	16	0
9	16	6
10	16	0
11	16	4
12	16	0
13	16	7
14	16	0
15	16	1
16	16	2
17	16	0

18	16	6
19	16	0
20	16	0
21	16	3
22	16	0
23	16	1
24	16	2
25	16	0
26	16	1
27	16	0
28	16	0
29	16	0
30	16	0
31	16	0
32	16	0
33	16	0
34	16	0
35	16	0
36	16	2
37	16	2
38	16	0
39	16	0
40	16	5
41	16	5
42	16	0
43	16	0
44	16	0
45	16	3
46	16	0
47	16	0
48	16	2
49	16	2
50	16	0
51	16	0
52	16	6
53	16	2
54	16	3
55	16	0
56	16	0
57	16	3
58	16	0
59	16	0
60	16	0

61	16	7
62	16	0
63	16	1
64	16	0
65	16	0
66	16	1
67	16	0
68	16	0
69	16	5
70	16	1
71	16	3
72	16	0
73	16	0
74	16	0
75	16	0
76	16	0
77	16	0
78	16	5
79	16	0
80	16	2
81	16	0
82	16	4
83	16	0
84	16	6
85	16	0
86	16	7
87	16	0
88	16	9
89	16	5
90	16	4
91	16	0
92	16	4
93	16	5
94	16	0
95	16	1
96	16	0
97	16	0
98	16	0
99	16	0
100	16	7

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SUPPLEMENTALS

All supplemental appendices are available upon request through the Dudley Knox Library located at the Naval Postgraduate School upon request.

A. SEA-20A INITIAL PROGRESS REVIEW BRIEF #1

This is the initial presentation outlining SEA-20A's tasking statement, mission, vision, goals, project team organization, systems engineering process, capability analysis, modeling tools, project timeline and milestones, and the way ahead. Each slide contains notes and description of the slides for future use.

B. SEA-20A INITIAL PROGRESS REVIEW BRIEF #2

The second presentation refined SEA-20A's first IPR, and furthered the systems engineering process, design concept, combat modeling, logistical support, and cost estimates. Each slide contains notes and description of the slides for future use.

C. SEA-20A FINAL PROGRESS REVIEW BRIEF

This is the final Powerpoint presentation given to stakeholders and faculty members regarding the distributed force concept. Each slide contains notes and description of the slides for future use.

D. TRADE SPACE DISCUSSION

These Powerpoint slides contain the various weapons and platforms used to determine threat capabilities and force structure as well as the weapons and platforms used to derive the capabilities for the distributed force platforms. Additionally, there are slides for discussions on the definitions of littoral waters and A2AD environments, possible areas of conflict, and possible adversary nations, and scenario development.

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