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THESIS

**IMPLEMENTATION OF UNMANNED SURFACE
VEHICLES IN THE DISTRIBUTED MARITIME
OPERATIONS CONCEPT**

by

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December 2018

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**IMPLEMENTATION OF UNMANNED SURFACE VEHICLES IN THE
DISTRIBUTED MARITIME OPERATIONS CONCEPT**

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Submitted in partial fulfillment of the
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ABSTRACT

This thesis investigates the integration of unmanned surface vehicles into the order of battle for Distributed Maritime Operations. The purpose is to design a cost effective and operationally effective unmanned system of systems capable of contributing the DMO concept in the 2030–2035 timeframe. This thesis determines the mission set and combination of USVs that is both operationally impactful and cost effective in the conventional carrier strike group, expeditionary strike group and/or surface action group, and whether unmanned systems could potentially replace or supplement a number of current manned systems mission sets. The primary finding is that USVs can significantly supplement manned assets in the following two mission areas: (1) Intelligence, surveillance and reconnaissance mission set, and (2) the anti-missile defense mission set. The secondary finding is an initial \$500 million investment into building approximately 10 USV platforms, with the aforementioned mission sets, is paramount to meet the measures of effectiveness described in this thesis. The author's recommendation for the U.S. Navy is to implement a standardized USV design, focusing on an AMD and ISR mission package. Secondly, the investment of approximately \$500 million to build 10 of these platforms and integrate them into one of the current CSGs, ESGs, or SAGs, would be the stepping stone for transition to implementing USVs into the future fleet.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAM	Air-to-Air Missiles
ACE	Aviation Combat Element
ACTUV	ASW Continuous Trail Unmanned Vessel
ADL	Adaptative Deck Launcher
ADM	Admiral
AFP	Adaptive Force Package
AIS	Automatic Identification System
AMD	Anti-Missile Defense
AMW	Amphibious Warfare
AOR	Area of Responsibility
AOU	Area of Uncertainty
ASCM	Anti-Ship Cruise Missile
ASW	Anti-Submarine Warfare
AW	Air Warfare
BAM	Buque de Accion Maritima (Offshore Patrol Vessels of the Spanish Navy)
BIC	Bayesian Information Criterion
BMD	Ballistic Missile Defense
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CC	Command and Control
CDR	Commander
CG	Guided Missile Cruisers
CNO	Chief of Naval Operations
CONOPS	Concept of Operations
C-RAM	Counter-Rocket, Artillery and Mortar Defense System
CSG	Carrier Strike Group
CUSV	Common Unmanned Surface Vehicle
CVN	Aircraft Carriers
CVW	Carrier Air Wing

DARPA	Defense Advanced Research Projects Agency
DDG	Guided Missile Destroyer
DES	Discrete Event Simulation
DL	Distributed Lethality
DMO	Distributed Maritime Operations
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DOE	Design of Experiments
EA	Electronic Attack
EMCON	Emission Control
ER	Extended Range
ESG	Expeditionary Strike Group
ESM	Electronic Support Measures
ESSM	Evolved Sea Sparrow Missile
EW	Electronic Warfare
F2T2EA	Find, Fix, Track, Target, Engage, and Assess
FC	Fire Control
FOB	Foreign Operating Base
FSA	Force Structure Assessment
FTE	Find, Target, Engage
FY	Fiscal Year
INT	Intelligence
IO	Information Operations
IR	Infra-Red
ISR	Intelligence, Surveillance, and Reconnaissance
LCAC	Landing Craft Air Cushion
LCM	Landing Craft Maintenance
LCS	Littoral Combat Ship
LCU	Landing Craft Utility
LHD/LHA	Amphibious Assault Ships
LPD	Landing Platform/Dock
LRASM	Long Range Anti-Ship Missile

MCM	Mine Countermeasures
MD	Military Deception
MS	Maritime Security
MDUSV	Medium Displaced Unmanned Surface Vehicle
MFS	Mono-hull Fast Sealift
MIO	Maritime Interdiction Operations
MIW	Mine Warfare
MOE	Measures of Effectiveness
MOP	Measures of Performance
MST	Maritime Strike Tomahawk
NDRI	National Defense Research Institute
NM	Nautical Mile
NOB	Nearly Orthogonal Balanced
NPS	Naval Postgraduate School
NSWCDD	Naval Surface Warfare Center Dahlgren Division
NWDC	Navy Warfare Development Command
ONR	Office of Naval Research
OOB	Order of Battle
OODA	Observe, Orient, Decide, Act
OPV	Offshore Patrol Vessel
PACOM	Pacific Command
PMS	Program Office
PRC	People's Republic of China
R&D	Research and Development
RAND	Research AND Development (National Defense Research Institute)
RCS	Radar Cross Section
RDT&E	Research Development Testing & Evaluation
RF	Radio Frequency
RHIB	Rigid Hulled Inflatable Boat
SAG	Surface Action Group
SAR	Search And Rescue
SCS	South China Sea

SEA	Systems Engineering Analysis
SEBok	Systems Engineering Body of Knowledge
SEWIP	Surface Electronic Warfare Improvement Program
SM	Standard Missile
SOC	Special Operations Craft
SOF	Special Operations Forces
SRBOC	Super Rapid Blooms Offboard Countermeasures
SSM	Surface-to-Surface Missile
STW	Strike Warfare
SUW	Surface Warfare
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UMS	Unmanned Maritime System
UMV	Unmanned Maritime Vehicle
US	United States
USIR	Unmanned Systems Integrated Roadmap
USSV–HS	Unmanned Sea Surface Vehicle – High Speed
USV	Unmanned Surface Vehicle
UUV	Unmanned Undersea Vehicle
VLRAAM	Very Long Range Air-to-Air Missile
VLS	Vertical Launching System

EXECUTIVE SUMMARY

This thesis examines the integration of Unmanned Surface Vehicles (USV) into the Distributed Maritime Operations (DMO) concept via a development of a systems architecture and an associated discrete event simulation. The goal is to research potential mission areas for unmanned surface forces in the DMO concept and then construct a functional and physical architecture of a standardized USV. The author uses a similar concept as the Littoral Combat Ship (LCS) by providing external mission module packages to be installed on the standardized USV for the identified mission areas. Following the architectural definition, a model was developed by using a discrete event simulation software. The model's scenario is defined as a fleet-on-fleet engagement against a near peer adversary in the 2030–2035 timeframe. Measures of effectiveness were used to analyze the operational impact that the proposed USVs provide throughout the simulation. Upon completion of the model analysis, the author concludes with a cost analysis of the proposed USV platforms versus their overall operational impact on the outcome of the fleet-on-fleet engagement.

A. OVERVIEW OF DMO AND USVS

In 2017, the Navy Warfare Development Command created the phrase “Distributed Maritime Operations,” which was derived from ADM Rowden’s (2017) “Distributed Lethality” (DL). DMO looks at distributed forces in more of an all-encompassing fleet-centric fighting power, rather than small force packages as described in the DL definition. The supreme goal of the DMO concept is to allow commanders greater diversity of options or combinations of sensors/platforms/weapon employment availability and adequate time that outpaces the adversaries. DMO takes into account the merging of resources, information and technologies with key decision makers at all levels of an organization. This encapsulates the DMO concept well when the U.S. Navy views a system as a distributed network. A distributed network that has the integration capability of all available platforms across all operational domains will enhance the U.S. Navy’s offensive and defensive capability. The focus of this thesis toward the design and acquisition of unmanned surface vehicles in this distributed network will not only provide a cost effective

alternative to manned assets, but also provide a much lower risk-management scenario due to the limited human intervention.

Unmanned Systems have the potential to be a key force multiplier in the future force structure of the U.S. Navy. The Chief of Naval Operations, ADM Richardson (2016), lays out four key “lines of effort” in his strategic vision for the Navy. One of the lines is to “Strengthen Naval Power at and from Sea,” which encourages exploration of “alternative fleet designs, including kinetic and non-kinetic payloads and both manned and unmanned systems” (6). This thesis covers the basic tenants of unmanned surface vehicles including the hierarchy, classes, and mission types that are currently available. The thesis also addresses the potential contribution that USVs could bring to the DMO concept in the future construct of fleet forces, as well as touches on key enabling technologies that are essential for future research and development of unmanned surface vehicles.

For the purpose of this thesis, three alternatives USVs, with their three applicable mission packages, were analyzed through modeling and simulation. The chosen platforms to be investigated were the USV ISR mission platform, USV Surface Warfare mission platform and the USV Anti-Missile Defense mission platform, since they were identified as the most relevant in the context of DMO. The author notes that these three alternatives are not readily available on the current market, as prescribed in this thesis, but the objective of proposing a functional and physical architecture was to shape the development of future work to be feasible and congruent with the U.S. Navy’s vision and objectives concerning unmanned systems.

Table 1 summarizes the three alternative USVs that the author analyzes using modeling and simulation with their applicable class type and payloads as annotated.

Table 1. Three Alternative USV Specifications

	USV ISR	USV SUW	USV AMD
Class Type	E-G	G	F-G
Payload	None	LRASM/ MST	SM-6/ESSM
Missile #	None	4 - 4	8 - 16

B. MODEL DEFINITION

To facilitate analysis of the alternative USVs, the author developed a simulation model. To ensure that the DMO concept was analyzed in a realistic scenario and operational environment, the focus was geared towards a littoral conflict in the South China Sea. The model is broken down into four primary phases; the threat generation phase, the finding phase, the targeting phase, and the engagement phase. The three alternative USVs, presented in Table 1, were implemented in the model. The USV AMD was split into two unique platforms: AIR and MISSILE; these configurations were meant to defend against air platforms and incoming missiles, respectively. All alternative USVs brought additional countermeasures to the friendly order of battle, including chaff, active and passive decoys, flares, and IR and visual smoke. The missile carrying USVs also brought their specific payloads, as annotated in Table 1, which provided additional ordnance in the distributed resource pool of friendly forces. The USV ISR provided a capability unique to the rest of the USV alternatives. This platform's capability was added during the enemy's targeting and engagement phase and allowed every potential friendly missile an extended range to hit incoming enemy platforms or missiles.

C. OPERATIONAL EFFECTIVENESS ANALYSIS

Data analysis showed that, with respect to multiple different measures of effectiveness (MOEs), some of the conceptualized USVs not only were statistically significant, but operationally significant as well. The three measures of effectiveness that turned out to be interesting when analyzing how USVs contributed to the DMO concept

where: (1) MOE #2: Surviving Enemy Forces, (2) MOE #4: Percentage of Enemy Missiles within 10 Nautical Miles, and (3) MOE #6: Defensive Measure Success (note that the numbering convention corresponds to the full text of the thesis). The alternative USVs that were the most operationally impactful were the USV ISR platform, USV AMD AIR platform, and the USV AMD MISSILE platform, whereas the USV SUW platform proved to be not operationally significant throughout the entire analysis. The results of the analysis were inconclusive: unmanned surface vehicles were most effective by supplementing the manned naval assets in two primary mission sets in the confines of the DMO concept: (1) intelligence, surveillance and reconnaissance mission set, and (2) anti-missile defense mission set (for both anti-air and anti-missile defense). This envisions more of a defensive posture approach for the implementation of USVs, either by counter-engaging enemy platforms or missiles in the defense-in-depth layered strategy.

D. COST ANALYSIS

To augment the operational effectiveness analysis, the author chose to use a parametric approach to derive a cost model that predicts the cost of the alternative USVs described in this thesis. The author identified 40 platforms that had historical procurement costs and researched their design specifications for the parametric approach. Contour maps were generated to facilitate a trade-off analysis between operational effectiveness and cost for multiple investment scenarios. The analysis suggested that a minimum investment of \$500 million, to enable acquisition of approximately 10 capable USVs, was necessary to realize operationally significant gains of effectiveness. An additional investment of \$1000 million (for a total of \$1500 million) resulted in a potential increase to a total of 35 USVs, which is associated with a 31.2% improvement from the baseline investment scenario for the percentage of enemy missiles within 10 nm of friendly forces (MOE #4) and a 9.9% improvement from the baseline investment scenario for the percentage of successful countermeasures (MOE #6).

E. CONCLUSIONS

The incorporation of USVs in DMO provides both a cost effective and operationally effective order of battle compared to the conventional force structures of the

U.S. Navy's CSG, ESG and SAG. The Intelligence, Surveillance and Reconnaissance mission as well as the Anti-missile Defense mission proved to have the most statistical significance and operational impact in regard to the prescribed measures of effectiveness annotated in the section C of this summary. The following bullet points explain the three most interesting measures in the context of the operational impact from USVs:

- * MOE #2: Surviving Enemy Force. This MOE was significantly impacted by whether an USV ISR platform was present or not. A maximum decrease of approximately 5.9% of the enemy force survivability can be expected if the USV ISR platform is present.

- * MOE #4: Percentage of Enemy Missiles within 10 NM. This MOE was significantly impacted by the number of USV AMD MISSILE and USV AMD AIR platforms present in the model. A maximum decrease in approximately 8.5% of the number of enemy missiles reaching 10 nautical miles is expected when given the correct composition of USV AMD platforms.

- * MOE #6: Defensive Measure Success. This MOE was significantly impacted by the number of USV AMD MISSILE and USV AMD AIR platforms present in the model. A maximum increase of approximately 4% of the defensive measure success is expected when given the correct composition of USV AMD platforms.

For the cost effectiveness aspect, described in section D of this summary, it was shown that the only USVs worth investing in were the USV ISR, USV AMD AIR and the USV AMD MISSILE platforms. For the specified concept of operations and the fixed order of battle, in regard to manned assets, the author believes that implementing specific combinations of USVs in the order of battle is a cost effective approach in achieving the desired measures of effectiveness.

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I. INTRODUCTION

A. AREA OF RESEARCH

Rowden (2015), prior Commander of Naval Surface Forces, published an article in January of 2015 titled, “Distributed Lethality.” His concept describes a force shift and change in ideology that moves toward taking the offensive and increasing the lethality of surface action groups. This would in turn “provide more strike options, provide another method to seize the initiative, and add battlespace complexity to an adversary’s calculus” (Rowden 2015) and their Observation, Orient, Decide and Act (OODA) Loop. Kline (2016), the Systems Engineering Analysis (SEA) chair at Naval Postgraduate School (NPS), summarizes the concept well: “In broad terms, distributed lethality proposes creating offensive adaptive force packages comprised of surface action groups with a variety of support elements that operate across a wide region and under an adversary’s anti-access sea denial umbrella.”

To contribute to the concept further, in 2017 the Navy Warfare Development Command (NWDC) deemed the phrase “Distributed Maritime Operations,” which looks at distributed forces in more of an all-encompassing fleet-centric fighting power rather than small force packages as described in the Distributed Lethality definition. In a recent Fleet Design Brief in 2017, CDR Canfield from NWDC said, “This concept uses all available assets, including unmanned systems, to empower warfighters at all echelons by providing synchronized operations and employment of multi-domain and cross-component capabilities in order to fight and win in complex, contested environments.” This, in turn, triggered a coordinated Naval Postgraduate School Cross-Campus Project FY17-18, termed: “Distributed Maritime Operations: Joint, Combined, and Coalition Warfare at Sea” (Kline 2017). Synchronized by OPNAV N91 Chair of Systems Engineering Analysis, the focus of this project was to develop concepts, technologies, tactics, and relations to advance the DMO concept.

Systems Engineering Analysis Cohort 27 further developed the DMO concept by “designing a cost effective, and resilient unmanned and manned system of systems capable

of contributing to the Distributed Maritime Operation concept in the 2030–2035 timeframe. Focusing on design contributions in counter-targeting, decoys, deception, electromagnetic warfare and the manned-unmanned tactics associated in achieving desired effects in supporting tactical offensive operations in the air, surface, undersea and cyber domains” (Kline 2017).

This thesis will continue the work that the SEA 27 team started, to further explore the functionality of the Distributed Maritime Operations (DMO) concept. It will use a substantial amount of information gathered from SEA 27’s work and will use the baseline model with modifications for the analysis portion. The principal topic of research will be one component of DMO: Unmanned Surface Vehicle (USV) integration into the order of battle. The research will consist of an analysis of USVs operational effectiveness, as well as a cost analysis of different USV configurations.

The supreme goal of the DMO concept is to allow commanders greater diversity of options or combinations of sensors/platforms/weapon employment availability and adequate time that outpaces the adversaries. DMO takes into account the merging of resources, information and technologies with key decision makers at all levels of an organization. This encapsulates the DMO concept well when the U.S Navy views a system as a distributed network, as explained by Paul Baran of the RAND Corporation in his distributed network concept (Baran 1964). The basis of modern internet data routing architecture is the distributed network paradigm. Having an undisrupted distributed network is the key to DMO’s success, having everything interconnected and the potential to utilize all the strengths of each platform even from over the horizon distances. Baran addresses the alternative networks as centralized, whereby one commander receives all inputs to make a decision, and decentralized, whereby multiple commanders are interconnected and the decision making process is delegated from the key decision maker. A graphic depicting generic nodes and network configurations are shown in Figure 1.

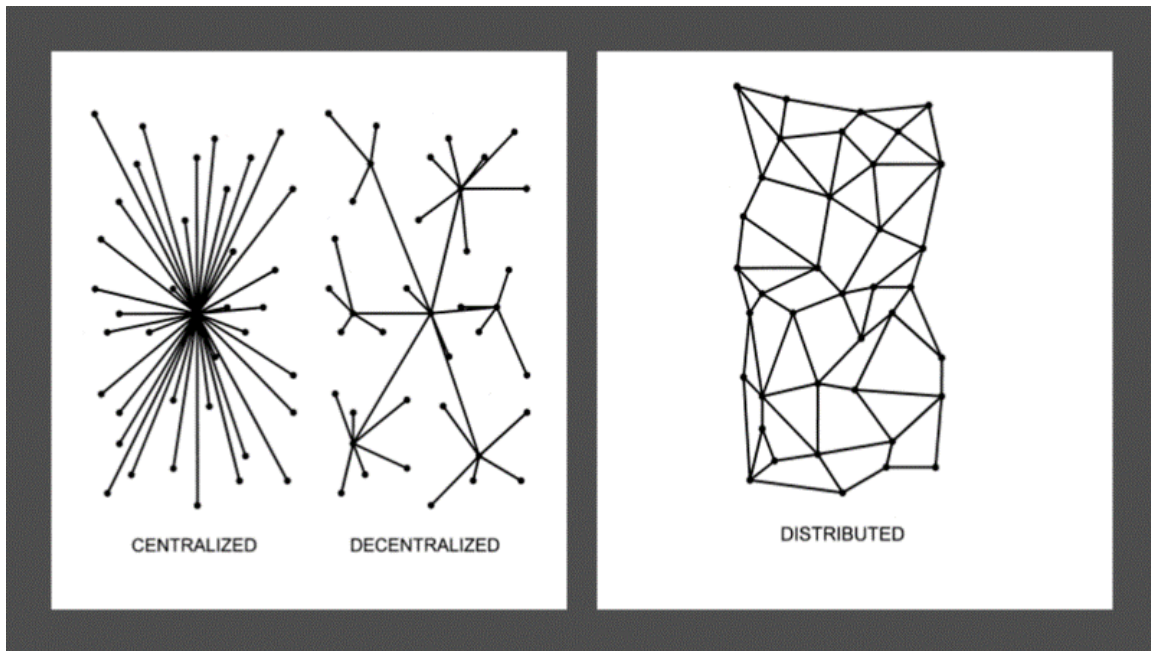


Figure 1. Distributed Network versus Centralized and Decentralized Networks. Adapted from Baran (1964).

Distributed Maritime Operations will emphasize the importance of counter-targeting, decoys, deception, electromagnetic warfare and the manned-unmanned tactics in support of tactical offensive operations in the air, surface, undersea and cyber domains. Ultimately, the critical measure of effectiveness for the DMO concept is how well the U.S. Navy can deter, distract, disrupt, deceive and distribute the adversary's forces and resources in such a manner that it will cause an offensive advantage in the U.S. Navy's favor.

B. BENEFITS OF STUDY

The DMO concept is new in the arena of Navy terms and has not been implemented into the operational Navy. Hence, the study of the DMO concept, specifically using unmanned surface vehicles, has the potential to influence the future force structure of the U.S. Navy, as well as help define requirements needed to fill the gap in the current configurations of the Carrier Strike Group (CSG), Expeditionary Strike Group (ESG) and Surface Action Group (SAG). The current Unmanned Systems Integrated Roadmap (USIR) for FY2013-2038 states, "recent combat operations in Southwest Asia have

demonstrated the military utility of unmanned systems in today's combat environment,” and that “rapid integration of unmanned technologies into the joint force structure” is paramount for the future of our Naval Forces (USIR 2013). The USIR (2013) specifically predicts that unmanned systems may be required to operate in areas where freedom to operate is contested and seeks to determine “levels of effectiveness...affordability...and other key parameters needed to meet future operational requirements” (v).

The ultimate goal is to leverage unmanned systems to enhance cross domain operations. Currently the future naval warfighting scenarios point to contested environments in close proximity to land masses. The open ocean “blue navy” seems to be drifting away, which requires a new force to supplement the dynamic environment of today's threat. According to the Office of the Chief of Naval Operations (2018), “In December 2016, the CNO completed a Force Structure Assessment (FSA) to determine the correct mix of platforms needed to address the evolving and increasingly complex responsibilities of the Navy. The FSA detailed a requirement of 355 ships based upon analysis and acceptable strategic and operational risk” (3). Interestingly, the FSA findings also showed that unmanned systems were integral in the analysis and could be key enablers in the coming decades for the fleet architecture (Office of the Chief of Naval Operations 2018). Also, the FY2016 National Defense Authorization Act required three fleet architecture studies to be conducted to project what the Navy force structure should look like in 2030. All three studies were conclusive in determining that unmanned systems played a key role in the force structure of the U.S. Navy's 355 ship fleet, with two of the studies estimating that the Naval fleet required 321 manned ships with 136 large unmanned vehicles, and 340 manned ships with 90 unmanned vehicles, respectively (O'Rourke 2018a). To follow up with the FSA study, in May 2017 ADM Richardson stated in the Navy's vision plan, “The Future Navy,” that there is, “no question that unmanned systems must be an integral part of the future fleet. The advantages such systems offer are even greater when they incorporate autonomy and machine learning” (Richardson 2017). Due to the never-ending fiscal budget constraints that the Navy has to deal with, the topic that late Senator John McCain examined in 2017 was imperative. Can the Navy consider moving away from the conventional high value units, like the carrier, to a more robust

inventory of smaller cheaper maritime vessels? McCain (2017) describes the end state of our future 355 ship fleet, “The goal should be a future fleet and air wing comprised of larger numbers of small relatively cheaper systems [possibly unmanned systems] that can operate in denied environments, rather than smaller numbers of larger and more expensive systems that are adversaries can increasingly locate and target” (9).

C. SCOPE

The scope of this thesis includes: (1) an examination of USVs in the context of the DMO concept; (2) identifying the capabilities that USVs provide in the DMO force structure; (3) a proposed future USV configurations for DMO; and (4) a tradeoff of operational effectiveness and cost for USV configurations.

D. RESEARCH QUESTIONS

- (1) Does the incorporation of unmanned surface vehicles, in the context of Distributed Maritime Operations, provide a more cost- and operationally-effective order of battle compared to the conventional United States (U.S.) Navy Carrier Strike Group (CSG) configuration, Expeditionary Strike Group (ESG) configuration or the Surface Action Group (SAG) configuration?
 - i) What is the tradeoff analysis in cost versus overall operational effectiveness in DMO when reconfiguring unmanned surface vehicles to support different mission sets, specifically in the Anti-Missile Defense (AMD), Surface Warfare (SUW) and Intelligence, Surveillance, and Reconnaissance (ISR) capable mission roles?
 - ii) What realistic combination of unmanned surface vehicles provides the most operationally effective scenario in the context of DMO?
- (2) What are the critical parameters that need to be met in the future designs of unmanned surface vehicles specific to the DMO concept?

E. METHODOLOGY

The methodology used in this thesis research consisted of the following steps:

(1) Review SEA 27's capstone project, including the tasking statement, DMO breakdown, focus of research effort, mathematical model and analysis, and recommendations and future work.

(2) Conduct a literature search of books, online articles, Navy reports, related theses (USV, Unmanned Systems, Autonomous systems), the internet, and other library information resources on the topic.

(3) Conduct a summary of current USV platforms.

(4) Conduct a requirements analysis of capability gaps in the DMO concept, and how USVs could fill those gaps.

(5) Perform a functional and physical decomposition of a desired USV to fit the requirements analysis from the capability gaps.

(6) Revise SEA 27's mathematical model and conduct a design of experiments for proposed USV configurations.

(7) Conduct a model analysis from the output data.

(8) Conduct a cost analysis of the proposed USV configurations.

(9) Provide recommendations and conclusions from the research findings.

F. THESIS ORGANIZATION

Chapter I: INTRODUCTION. This chapter provides the research questions, a brief discussion of the topic and benefits that could be gained from this thesis.

Chapter II: BACKGROUND. The chapter describes the concept of Distributed Maritime Operations and breaks down what exactly unmanned systems are, specifically focusing on unmanned surface vehicles. Later in the chapter, the thesis discusses what USVs could provide to the DMO concept as well as the technologies and platforms that are currently available.

Chapter III: ARCHITECTURE. This chapter considers the surface domain mission sets and how USVs could either supplement or replace current naval force configurations. The Chapter decomposes both the functional and physical side of a proposed USV design and addresses the mission module packages that could be incorporated into the DMO concept.

Chapter IV: MODEL DESCRIPTION. This chapter looks at the SEA 27 capstone concept of operations and describes the mathematical model in depth. The model was implemented in ExtendSim, which is a standard simulation modeling tool. The chapter also addresses the changes made to incorporate the potential USV alternatives and the model's assumptions and limitations.

Chapter V: DATA ANALYSIS. This chapter discusses how the author measured operational effectiveness for the implemented USVs and then analyzes the output data derived from the ExtendSim model using statistical analysis software. Throughout the chapter, insights and conclusions from the data analysis are conferred for each measure of effectiveness provided.

Chapter VI: COST ANALYSIS AND CONCLUSIONS. This chapter concludes the thesis with a cost analysis versus operational effectiveness of the alternative USVs discussed throughout the report. The chapter provides reasonable expectations of what the outcome will be in the specified scenario given different sums of investment in regard to future acquisition of USVs. The remainder of the chapter introduces recommendations as well as future research in the development of the DMO concept.

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II. BACKGROUND

This chapter presents the background information relevant to this research. Specifically, it reviews both the DL and DMO concepts, presents a high-level overview of USVs as well as the role that USVs may play in the DMO concept, and identifies key technological enablers for USVs.

A. WHAT IS DISTRIBUTED MARITIME OPERATIONS?

Before getting into the explicit definition of DMO, it is important to reflect on the influencer that was the root for the exploration of this new concept: Distributed Lethality (DL). DL is a paradigm shift for the conventional U.S. Navy’s “defense in depth” concept. Currently, the maritime arsenal is made up of mostly surface-to-air defensive missiles, the Standard Missiles series, as well as close-in weapons systems to protect the Navy’s high value units. Initially introduced in 1977, with the latest upgrade in 2015, the last surface-to-surface (SSM) missile designed to fire from a naval surface platform was the Harpoon, termed the “only offensive SSM of the surface fleet.” A look at the cost breakdown of what the DoD requested in Fiscal Year 2016 for the development of offensive Surface-to-surface missiles shows their priority. The amount requested was only 285.5 million in RDT&E according to the Program Acquisition Cost by Weapon System (Office of the Under Secretary of Defense 2015). This is only 11.3% of the total amount requested from the Navy for their missiles and munitions allotment. Only recently has the shift in research and development for more offensive type missiles begun, including the Maritime Strike Tomahawk variant (MST) and the Long Range Anti-Ship Missile (LRASM). The U.S. Navy has been focused on defending their assets rather than developing an offensive “strike first” mentality. This development has been a transition from World War II battleship vs battleship to the more conventional carrier strike group approach that uses the strike mission and air superiority as their main deterrence, with the carrier as the center of gravity and the rest of the combatants defending the carrier-based air operations.

ADM Rowden describes DL as “increasing surface-force lethality – particularly in our offensive weapons and the concept of operations for surface action groups – will

provide more strike options to joint-force commanders, provide another method to seize the initiative, and add battlespace complexity to an adversary's calculus" (Rowden 2015, 8). This concept moves away from a defensive approach to a more offensive strike first mentality. DL provides more power in more places, providing a dispersed force to make it more difficult for the adversary to allocate their critical and limited resources. Again, ADM Rowden states that the DL doctrine is simply "the condition gained by increasing the offensive power of individual components of the surface force (cruisers, destroyers, littoral combat ships, amphibious ships, and logistic ships) and then employing them in dispersed offensive formations known as 'hunter-killer SAGs'" (Rowden 2015, 10).

The DMO concept was then developed by the U.S. Naval Warfare Development Command with the DL model as the main influencer. As DMO is an emerging concept in modern naval warfare, the fighting doctrine and open literature discussions are very limited. Mark Coffman, NWDC's DMO concept writing team lead, described the desired end state of DMO: "DMO will describe the fleet-centric warfighting capabilities necessary to gain and maintain sea control through the employment of synchronized kinetic/non-kinetic mission execution that may be distributed over vast distances, multiple domains, and a wide array of platforms in order to fight, and win in complex contested environments" (Navy Warfare Development Command 2017).

The SEA 27 capstone team, tasked to develop a system of systems that encompassed the DMO paradigm, took the NWDC's broad definition and scoped and bounded the concept into a functioning system that was easily comprehensible. They defined DMO as the ability to distribute offensive capability across all domains and platforms in a contested environment (SEA 27 2018). Their main effort of development is described in the following paragraphs.

The SEA 27 tasking statement bounded the time horizon to the 2030 – 2035 timeframe. This allowed the team to narrow the scope of the project based off the projected type of platforms, technologies, tactics and possible domains that would be key in the DMO concept in the next couple of decades. Through the iterative process of a modified systems engineering v-model methodology, the SEA 27 team developed a scenario and concept of operations, determined requirements and performance parameters, conducted a stakeholder

analysis, and decomposed the DMO concept into five operational domains with five focus areas. The five focus areas specified for consideration in the system of systems design were counter-targeting, decoys, deception, electromagnetic warfare, and manned-unmanned tactics (SEA 27, 2018). Each of these subsets of DMO could be a focus area of study by itself. Figure 2 depicts the breakdown of the areas that the SEA 27 team set out to investigate.

		DOMAINS				
		AIR	SURFACE	SUBSURFACE	LAND	CYBER
FOCUS AREAS	COUNTER-TARGETING	Air Counter-Targeting	Surface Counter-Targeting	Subsurface Counter-Targeting	Land Counter-Targeting	Cyber Counter-Targeting
	DECOYS	Air Decoys	Surface Decoys	Subsurface Decoys	Land Decoys	Cyber Decoys
	DECEPTION	Air Deception	Surface Deception	Subsurface Deception	Land Deception	Cyber Deception
	ELECTRO-MAGNETIC WARFARE	Air EMW	Surface EMW	Subsurface EMW	Land EMW	Cyber EMW
	MANNED/UNMANNED TACTICS	Air Manned/Unmanned Tactics	Surface Manned/Unmanned Tactics	Subsurface Manned/Unmanned Tactics	Land Manned/Unmanned Tactics	Cyber Manned/Unmanned Tactics

Figure 2. DMO Domains and Focus Areas. Source: SEA 27 (2018).

The SEA 27 team then created a functional description of the DMO concept with the primary function decomposed into sub functions that considers each operational domain; see Figure 3. The primary function of DMO is to “Perform Distributed Maritime Operations,” and the subset functions are performing DMO in each specified domain. This encompasses the distributed aspect of DMO, making available all the resources that each platform brings for a combined cross-domain effort to win the fight.

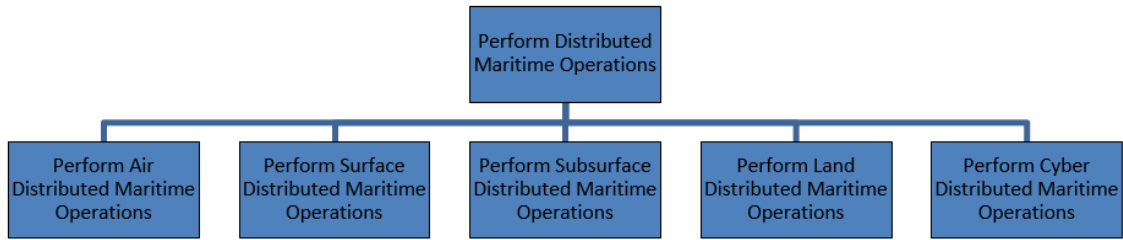


Figure 3. DMO Functions. Adapted from SEA 27 (2018).

SEA 27 further constructed an additional functional decomposition based off the direction of focus they chose; the employment of tactics within the Distributed Maritime Operations concept (see Figure 4). The primary tactics considered for DMO across all specified domains were grouped into four main categories: swarming tactics, mechanical and physical decoy and counter-measures, management of electromagnetic emissions, and electronic jamming tactics.

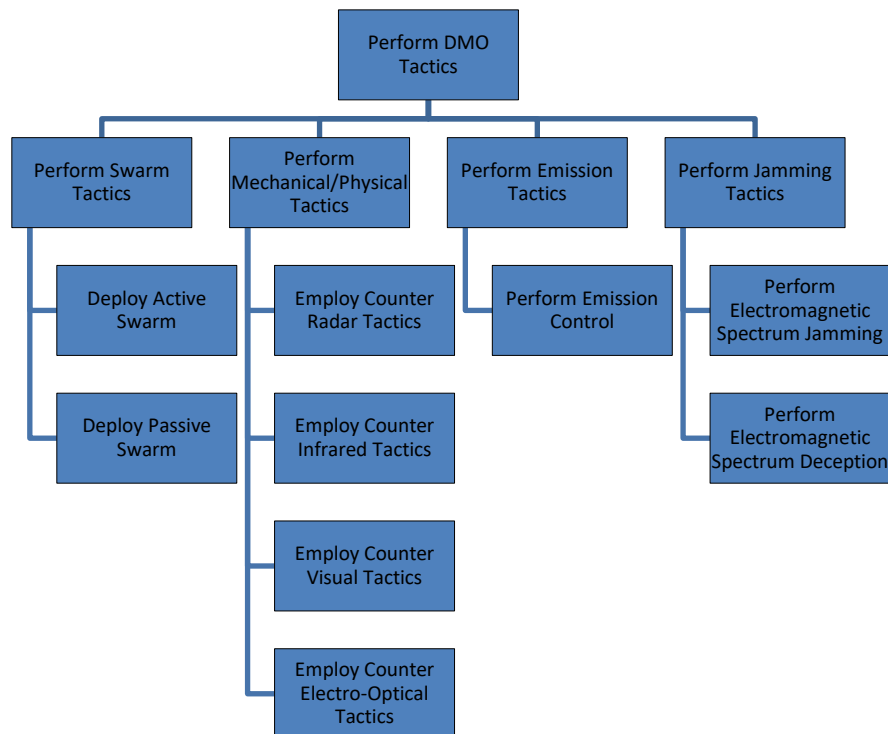


Figure 4. DMO Tactics. Adapted from SEA 27 (2018).

For the purpose of this thesis, the tactics functional architecture as well as the top-level architecture will be further investigated, decomposed and modified to include unmanned surface vehicles and how they specifically integrate into the DMO construct. The objective is to determine how operationally effective USVs can perform in the DMO paradigm as well as a cost analysis of the implementation of USVs in the conventional U.S. Navy fleet.

1. SEA 27 Summary

The SEA 27 (2018) team developed a complex model, similar to the one described in Chapter IV of this thesis, using the four primary tactics employed in the DMO concept as well as the rearrangement of force structure of the current fleet. The goal of the model was to simulate a balanced fleet-on-fleet engagement between a near-peer adversary in the context of the DMO concept. The team then identified specific measures of effectiveness (MOE) and measures of performance (MOP) to analyze so that they could address the most significant factors that contributed to the overall DMO success. The primary MOEs were survivability of both friendly and enemy forces, as well as the enemy forces effectiveness throughout their kill chain. They created two design of experiments (DOE) to implement into the model. The first DOE was based on a dynamic friendly force structure, which changed the input variables for all friendly platforms as well as the employment of DMO tactics for the simulation. The second DOE fixed the friendly force structure and varied only the DMO tactics that were employed for the simulation. The remaining paragraphs of this section will briefly describe SEA 27's significant findings from both sets of DOEs and will put into perspective this thesis' attempt for further analysis on the DMO concept. For further discussion on the findings of SEA 27 capstone report, refer to chapter 7 of the SEA 27 capstone report.

2. SEA 27 Results and Conclusions

It was found that the most significant factor in both the fixed and variable force structures was the use of jamming tactics, specifically spot and barrage jamming. These two tactics were "consistently noticed as key performance enablers in measuring friendly force success" (SEA 27 2018, 115). SEA 27 (2018) states, "The jamming tactics have an

evident impact due to the ability for the tactic to degrade the adversary in the critical phases of targeting and engagement within the kill chain. Additionally, with a minimal penalty imposed on friendly forces for employing jamming, it is apparent that this tactic demonstrates the greatest impact on the survivability and associated ability to conduct offensive engagements against degraded enemy threats” (115). In Chapter III, regarding the Functional and Physical architecture, the author identified the significance of jamming to be useful in the creation of a standardized physical architecture of future USVs. Chapter III will address alternative USVs with self-defense suites, that have applicable jamming capabilities, which add more available Electronic Warfare (EW) platforms and extend the effectiveness of the EW mission.

Other factors considered significant were the missile carrying platforms. In the variable force structure DOE, the destroyer and cruiser, both having numerous VLS cells, brought the only effective strike capability. This allowed for both offensive and defensive postures since the two platforms brought a balanced payload of LRASMs, MSTs, Standard Missiles, and ESSMs. This was significant for the author to observe and was the sole reason to design and implement a more offensive strike USV platform described in Chapter III. The other significant factors are listed in Table 1. They are broken up between the two force structures analyzed and show that most DMO tactics played a role in the success of the specified MOEs and MOPs.

Table 1. Ranking of the Significant Factors for Fixed and Variable Force Structure. Source: SEA 27 (2018).

Fixed Baseline Force Structure	DMO Variable Force Structure
Spot Jamming	Barrage Jamming
Barrage Jamming	Spot Jamming
DRFM Jamming	Quantity of DDG-51
Sweep Jamming	DRFM Jamming
Swarm	Sweep Jamming
EMCON (DDG-51)	Quantity of CG
Quantity of Passive Decoys	Quantity of F-35 (Air)
Quantity of Active Decoys	Quantity of F/A-18 (Air)
	Quantity of MDUSV
	Quantity of TERN

SEA 27’s “model and analysis provided fundamental insights for the architectures of various force structure and the relative employment of offensive counter-targeting assets and defensive counter-measures with respect to survivability and lethality of the friendly forces” (SEA 27 2018, 117). One of the capstone team’s recommendations was the further study and development of the employment of jamming techniques to ensure a more realistic scenario. Model simplifications resulted in an overly optimistic representation of the impact of jamming. They also identified that the Navy should continue the efforts in the development of new unmanned systems. SEA 27 (2018) states, “Moving towards what DMO brings to the fight: allowing time for decision makers, counter-targeting, deception, and confusing the adversary; the integration of the tactics discussed...provide an effective alternative vice relying solely on our missile carriers to win the fight” (120). Since the missile-carrying platforms serve as the primary force multiplier in the DMO concept, adding additional unmanned platforms with similar capabilities could be a major cost advantage as well as reduction in risk to friendly forces. Adding more unmanned systems is a much more feasible option, in the context of financial constraints, then it is to build and outfit more destroyers and cruisers. A cost analysis of unmanned surface vehicles will be addressed in Chapter VI after the initial model analysis is complete.

B. WHAT ARE UNMANNED SURFACE VEHICLES?

Unmanned systems have the potential to be key force multipliers in the future force structure of the U.S. Navy. The Chief of Naval Operations, ADM Richardson (2016), lays out four key “lines of effort” in his strategic vision for the Navy. One of the lines is to “Strengthen Naval Power at and from Sea,” which encourages exploration of “alternative fleet designs, including kinetic and non-kinetic payloads and both manned and unmanned systems” (6). The U.S. military has already introduced multiple unmanned systems, ranging from aerial vehicles like the Triton to unmanned robotics that support the Explosive Ordnance Disposal teams. They have already shown and continue to show potential in providing reduced risk to our high value units as well as manned forces, performing tasks that manned vehicles cannot, and do this at a typically much lower cost than manned systems. The bulk of the information about unmanned surface vehicles can be found in just a few references: The Navy Unmanned Surface Vehicle Master Plan and the Unmanned Systems Integrated Roadmap FY2013-2038 are the primary sources that date back from 2007 and 2013, respectively. Since 2013, there have been additional and updated information from the Unmanned Surface Vehicle Program Office PMS-406, and other more recent articles that have contributed to the scope of research about unmanned surface vehicles and will be addressed as needed. Figure 5 provides the the physical hierarchy of the different types of unmanned systems.

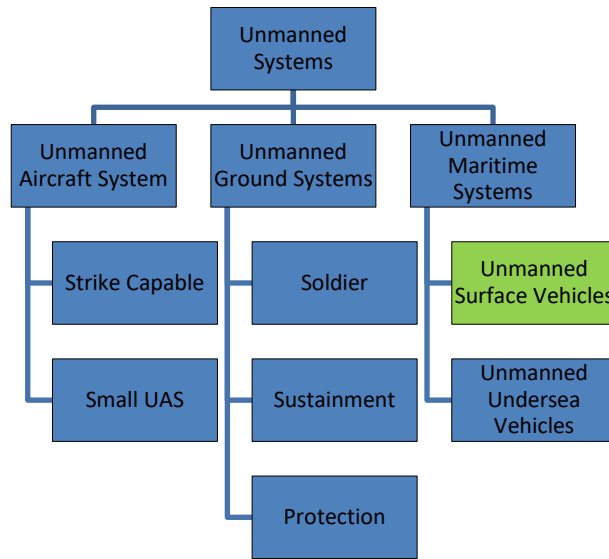


Figure 5. Unmanned Systems Physical Hierarchy. Adapted from USIR (2013).

This thesis focuses on Unmanned Surface Vehicles (highlighted in green in Figure 5) and what capabilities they bring in the context of the DMO concept; therefore, the following terms were extracted from both primary sources and were deemed essential to define.

- Unmanned: “Capable of unmanned operation. Can be manned for dual use or for testing and evaluation. Has varying degrees of autonomy” (Department of the Navy [DoN] 2007, xi).
- Unmanned Maritime Systems: “UMS comprise unmanned maritime vehicles (UMVs), which include both unmanned surface vehicles (USVs) and unmanned undersea vehicles (UUVs), all necessary support components, and the fully integrated sensors and payloads necessary to accomplish the required missions” (USIR 2013,8).
- Surface Vehicle: “Displaces water at rest. Operates with near continuous contact with the surface of the water” (DoN 2007, xi).

- Semi-autonomous: “Some vehicle behaviors are completely autonomous (e.g., transit to station, activate sensors). Vehicle refers to its operator when directed by the operator or by its own awareness of the situation (e.g., for permission to fire)” (DoN 2007, xi).
- Autonomous: “The vehicle governs its own decisions and makes its own decision from launch point to recovery point” (DoN 2007, xi).

As shown in Figures 6–7, Unmanned Surface Vehicles are categorized into class and craft type. The Class Type decomposition is updated from current development given by PMS-406 as well as from a recent RAND National Defense Research Institute (NDRI) study. The proposed classes E, F and G are added, which considers larger USVs that are greater than the Fleet Class that has a maximum length of 11 meters.

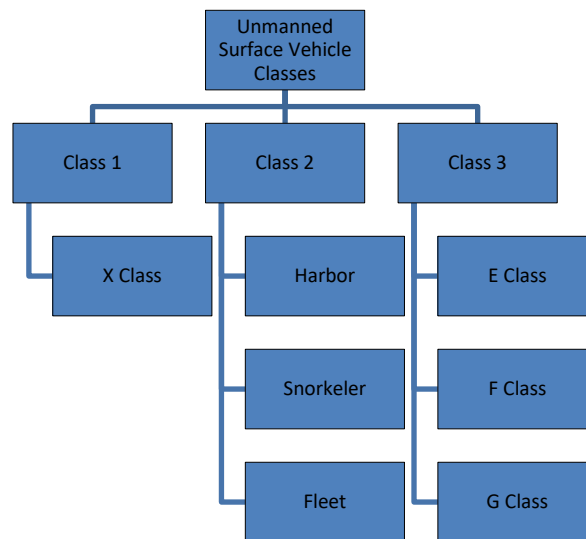


Figure 6. Unmanned Surface Vehicle Classes. Adapted from Savitz et al. (2013).

In Table 2, the seven classes of USVs can be compared to the following craft that are currently in the U.S. Navy’s inventory.

Table 2. Unmanned Surface Vehicle Class Comparison. Adapted from Savitz et al. (2013).

Unmanned Surface Vehicle Class:	Similar in Size to:	Size Range:
X	Modular Unmanned Surface Craft Littoral	3 meters or less
Harbor	7 Meter Rigid Hulled Inflatable Boat (RHIB)	4-10 meters
Snorkeler	Semi-Submersible	4-10 meters
Fleet	11 Meter RHIB	11 meters
E	Special Operations Craft (MARK V SOC)	12-25 meters
F	Landing Craft Air Cushion (LCAC)	25-40 meters
G	Landing Craft Utility (LCU)	41 meters and above

Unmanned Surface Vehicles are currently categorized into five primary hull types, as shown in Figure 7. The “other craft type” category constitutes all the remaining hulls that could be used to design USVs. The most common in this category are trimarans craft, displacement hulls, and mono-hull fast sealift (MFS).

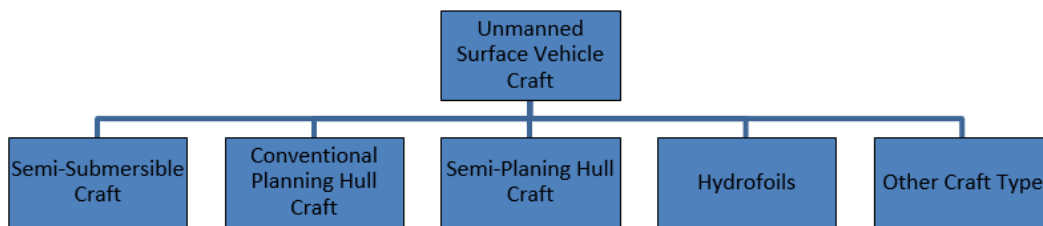


Figure 7. Unmanned Surface Vehicle Craft Types. Adapted from Savitz et al. (2013).

A relative comparison of waterline length versus maximum speed in knots is shown in Figure 8. This depicts a generic overview of how craft types perform in the context of speed through the water. The objective in showing this figure is to show the limitations and abilities that different lengths and hull types bring to the DMO concept. This will be

important when determining the required speed for USVs in the context of DMO, as well as the limitations that each hull type has when considering payload capacity, drag through the water, sea state stability, etc. Currently all USVs are in the upper left quadrant, ranging from planning hulls to MFS. However, larger craft with displacement hulls are currently in research and development, like the Rolls Royce USV prototype that Hutchison (2017) states is similar to the Nanuchka-class corvette, weighing 700 tons, as well as the current proposals from the Strategic Capabilities Office for the ghost fleet called the Overlord USV. The Defense Systems Information Analysis Center states that the Overlord concept seeks to develop and demonstrate the capability for larger USVs to independently deploy up to 90 days and conduct operations such as surface warfare, strike warfare, and electronic warfare (Berkof 2018). These USVs would be converted from previously manned ships like the Oliver Hazard Perry-class frigates (Hudson 2017).

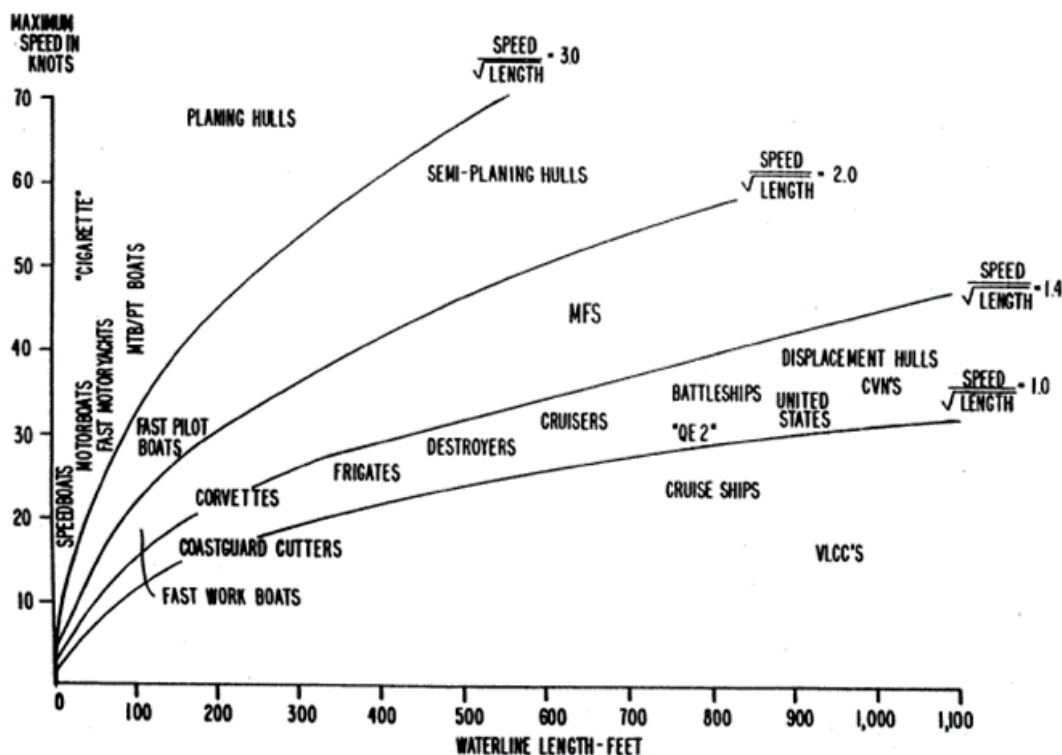


Figure 8. Maximum Speed in Knots versus Waterline Length Graphical Representation. Source: Pike (2011).

C. WHAT CAN USVs BRING TO THE DMO CONCEPT?

USVs are also categorized into different mission types, which directly relate to the type of capabilities they have. The USV Master Plan identified seven main mission sets in 2007; however, in 2013 the National Defense Research Institute expanded the mission sets to ten primary categories. Figure 9 shows the original set of capable missions that USVs were identified to perform defined by the USV roadmap, as well as the RAND contribution that revised the potential mission sets. Not all USVs can perform each mission set, therefore each USV class will be broken down into different mission set capabilities and what they could potentially provide to the DMO concept.

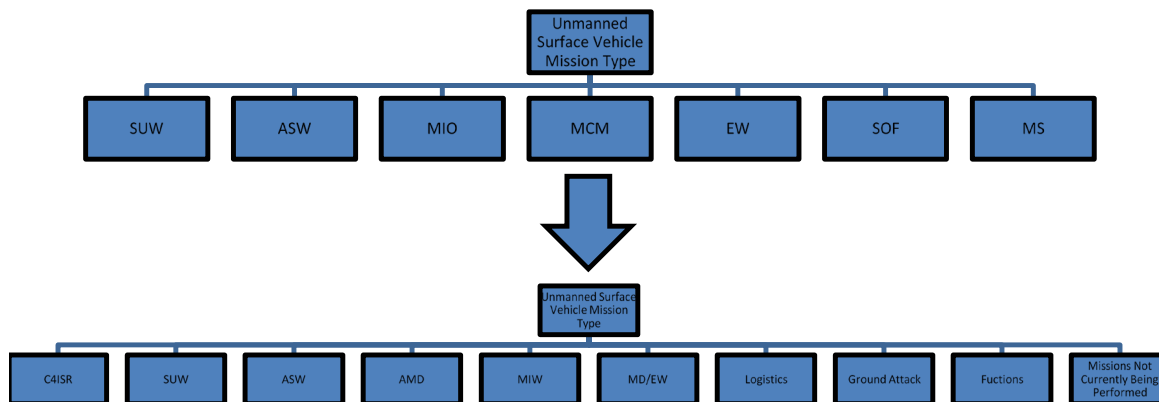


Figure 9. Unmanned Surface Vehicle Mission Types. Adapted from DoN (2007) and Savitz et al. (2013).

The mission sets are described in Table 3 with the potential Class of USV prescribed. The table also describes the technology maturity in a rating system called Technology Readiness Level (TRL). The mission sets require certain technologies to be mature to perform at the level desired. The Defense Acquisition University (2017) describes the rating system with a range from TRL 1 to TRL 9. TRL 1–3 tells that the research of the desired technology is proven feasible. TRL 4–7 tells that the technology has been developed and demonstrated. TRL 8–9 tells that the system is developed, and the technology is fully mature and able to complete a successful mission. The TRLs for each sub-mission set were derived from the RAND study conducted in 2013, *U.S. Navy*

Employment Options for Unmanned Surface Vehicles. This gives an idea of what technologies are currently available and what could be available during the next few decades that aligns well with the time horizon that this thesis focuses on, the 2030–2035 timeframe.

Table 3. Potential Mission Sets for USV Employment. Adapted from Savitz et al. (2013) and Joint Chiefs of Staff [JCS] (2016).

Mission Set	Description	Potential USV Class	TRL
C4ISR	An acronym for Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance.	All Classes	Persistent ISR: TRL 8-9 ISR Contested Environment: TRL 1-3 Communication Relay: TRL 4-7 Deploy Sensors/Networks: TRL 4-7
SUW	"The portion of maritime warfare in which operations are conducted to destroy or neutralize enemy naval surface forces and merchant vessels" (JCS 2016, 230).	Harbor and Above All Classes All Classes F and G Class Fleet and Above	Armed Escort: TRL 4-7 Counter-FAC (Autonomous): TRL 1-3 Counter-FAC (remote control): TRL 8-9 ASCM attack: TRL 1-3 Presence Patrol: TRL 4-7
ASW	"Operations Conducted with the intention of denying the enemy the effective use of submarines" (JCS 2016, 13).	Harbor and Above G Class F and G Class All Classes	ASW Sensor: TRL 4-7 ASW Tracking: TRL 1-3 Armed Wartime ASW: TRL 1-3 ASW Maritime Shield: TRL 8-9
AMD	"The integration of capabilities and overlapping operations to defend the homeland and United States national interests, protect the joint force, and enable freedom of action by negating an adversary's ability to create adverse effects from their air and missile capabilities" (JCS 2016, 113).	G class	Sensing and Warning: TRL 4-7 Non-Kinetic Defense: TRL 4-7 Kinetic Defense: TRL 1-3
Mine Warfare	"The strategic, operational, and tactical use of mines and mine countermeasures either by emplacing mines to degrade the enemy's capabilities to wage land, air, and maritime warfare or by countering of enemy-emplaced mines to permit friendly maneuver or use of selected land or sea areas" (JCS 2016, 154).	All Classes Harbor and Above Fleet and Above	Mine Hunting: TRL 4-7 Mine Sweeping: TRL 8-9 Mine Laying: TRL 1-3
Military Deception and EW	"Actions executed to deliberately mislead adversary military" (JCS 2016, 152). The purpose of EW is to deny the opponent an advantage in the EM spectrum and ensure friendly access to the EM spectrum.	All Classes	Communication Deception: TRL 4-7 Radar Deception: TRL 4-7 Decoy/countermeasures: TRL 4-7 Tactical Jamming: TRL 4-7 Computer Network Attack: TRL 4-7 Acoustic Deception: TRL 4-7
Logistics	"Planning and executing the movement and support of forces" (JCS 2016, 142).	Harbor and Above F and G Class	Unmanned Vehicle Support: TRL 4-7 Resupply of manned ships: TRL 1-3
Ground Attack	Kinetic or non-kinetic actions executed to degrade the adversaries ground positions, vehicles, supplies, and infrastructure	E Class and Above E Class and Above	Short/medium range: TRL 1-3 Long Range: TRL 1-3
Functions	Functions that USVs could perform to reduce manning requirements and allocation of resources	All Classes	Complex SAR: TRL 1-3 SOF Cargo Delivery: TRL 1-3 Test and Training: TRL 8-9
Missions Not Currently Being Performed	Missions that aren't currently being conducted by manned or unmanned systems	All Classes	Vehicle as a Surface Weapon: TRL 4-7 Blockship operations: TRL 1-3 Deliberately allowing capture: TRL 1-3 Impairing adversary sensors: TRL 1-3

As was shown in Figure 2: DMO Domains and Focus Areas, the area of research in this thesis narrows down the DMO concept to fit into a subdomain consisting of Unmanned Surface Vehicles. This is depicted below in Figure 10, which decomposes the Surface Domain into manned and unmanned assets, allowing both subdomain components to contribute to the overall DMO concept.

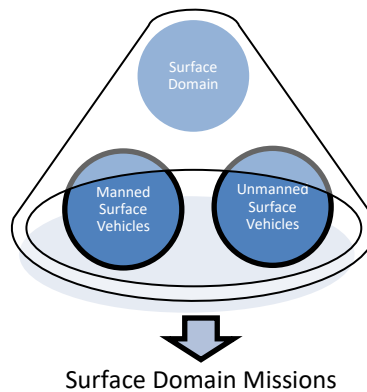


Figure 10. Decomposition of Surface Domain

The conclusions drawn from Table 3, specifically in the context of Distributed Maritime Operations mission areas, show that USVs have the potential to be effective across multiple different mission sets, bringing a number of invaluable additions to the force structures of conventional Carrier Strike Groups, Expeditionary Strike Groups and Surface Action Groups. Whether they replace current assets or provide a necessary supplement will be further addressed in the coming chapters. However, based off the potential missions that USVs provide, the most suitable missions from a DMO perspective were identified as Military Deception (MD) and Electronic Warfare (EW), Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR), Surface Warfare (SUW), Anti-Submarine Warfare (ASW) and Anti-Missile Defense (AMD). All of these align well with the focus areas that the SEA 27 team investigated, specifically the Military Deception, EW and C4ISR capable missions. These specific mission sets will be described below and will be further explored in Chapter III in the context of the functional and physical architecture of DMO.

- **Military Deception:** USVs of any type may provide a variety of physical or mechanical means of deceiving an adversary. They have potential in being deceptive targets by influencing the adversary to target and launch weapons at them instead of high value units, leading the enemy to misallocate important resources. This is normally termed a “missile sponge.” They could also introduce false information through deceptive radar, comms, or acoustics to further confuse the adversary. This ties into the EW mission set described in the following definition.
- **Electronic Warfare:** USVs could jam or spoof networks, conduct cyberattacks, as well as passively or actively receive electronic signatures to help identify locations of the adversary. The USVs required for this mission set can be all classes; however, there is a tradeoff when considering the power requirements as well as the size requirements for jamming and sensor equipment. The larger the EW payload, the more restrictive the class type due to the weight and sizing limitations of smaller class USVs.
- **C4ISR:** All USVs have the potential to gather and collect intelligence, conduct surveillance, and recon areas of interest in the maritime domain. ISR is defined as:

The capability to graphically display the current and future locations of intelligence, surveillance, and reconnaissance sensors, their projected platform tracks, vulnerability to threat capabilities and meteorological and oceanographic phenomena, fields of regard, tasked collection targets, and products to provide a basis for dynamic retasking and time-sensitive decision making. (JCS 2016, 116).

C4ISR could be done in a relatively stealthy, cost effective way, especially if all unmanned systems were networked into the same system of systems so they could relay all available information. This is a main contributor to the DMO concept, where one of the main assumptions is interconnectivity of all platforms amongst multiple domains.

- SUW: USVs have the potential for employment as armed escorts as well as countering fast attack craft, but one of the key capabilities that could be incorporated into the DMO concept would be the anti-ship cruise missile (ASCM) attack USV platform. This could be a key force multiplier in the context of offensive strike against surface adversaries. To have the SUW ASCM mission set, the USV platforms would need considerable payload capacity for the required sensors and combat systems, as well as significant range and endurance capabilities. The SUW mission set would fit into the realm of the F or G class USVs.
- ASW: The U.S. Navy has a significant advantage with using USVs for area sanitization in a specific area of operation. They could detect and classify enemy submarines while providing lower risk with less demand on manned assets. The endurance and range of sensing is directly related to the size of the platform, therefore, larger class type USVs would be more suitable for this mission type. Lastly, an armed ASW platform would take considerably more payload requirements due to adding torpedoes into the mix; F and G class USVs would be ideal for this type of mission set.
- AMD: USVs have the potential to be outfitted with air and missile defense modules and the applicable sensors to add an additional layer of defense against incoming adversary missiles and aircraft. This would allow a more distributed network of platforms able to defend our high value assets as well as provide a significant early warning sensing capability if the USVs are able to be dispersed at substantial distances from their assigned CSG, ESG, or SAG.

The Defense Advanced Research Projects Agency (DARPA) has conducted research in the area of potential contributions that USVs could provide that reinforces the above information, specifically in the AMD and ISR realms. A simplified graphic from DARPA is depicted in Figure 11 to show the concept of operations.

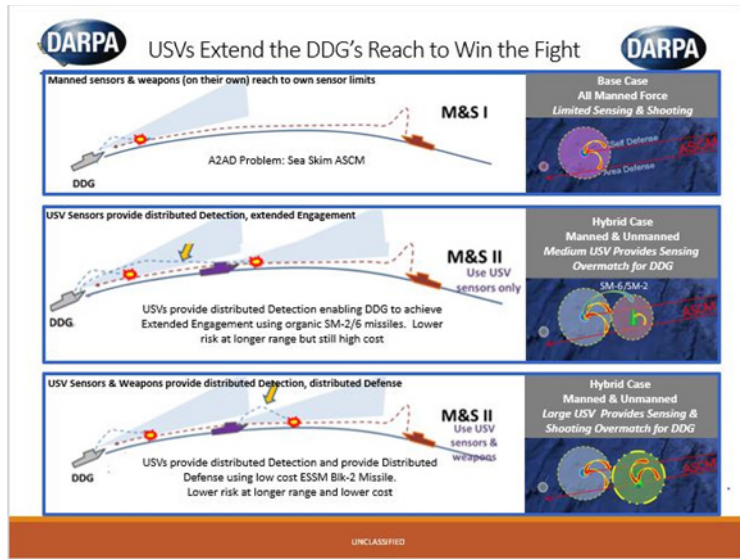


Figure 11. DARPA Proposed USV CONOPS. Source: Gallup (2018).

The top picture depicts a typical scenario of a sea skimming anti-ship cruise missile inbound from an adversary and the friendly destroyer having only its sensors to detect the incoming missile. The middle picture utilizes an unmanned surface vehicle to detect with its organic sensors and relay targeting information to the destroyer, this could be considered a C4ISR mission set. The bottom picture depicts the AMD mission set where the unmanned surface vehicle provides its own kinetic kill option while still providing relay targeting information to the destroyer. The last two cases provide an illustration of what a distributed network system could look like in the DMO concept of operations.

D. WHAT ARE KEY ENABLER TECHNOLOGIES FOR UNMANNED SURFACE VEHICLES?

The Unmanned Systems Integrated Roadmap FY2013-2035 determined that there were six areas of technology that were key for the DoD to research and develop (R&D) for future concept of operations involving unmanned systems. These technologies are different than the TRLs that were mentioned in the previous section. The mission sets with their specified TRLs were only considering the applicable operational capability, whereas, the six areas of technology are the baseline enablers for a resilient, trusting, operationally

effective unmanned system. The technologies are listed below with some insight into each area (USIR 2013).

- Interoperability and Modularity – USVs must have inter-platform and intra-platform congruency amongst other unmanned systems as well as current and future manned assets.
- Communications systems, spectrum and resilience – USVs must deal with the challenges of “available links, the amount of data that can be transmitted, and the resilience of all radio frequencies against interference” (USIR 2013, 39).
- Security: Research and Intelligence/Technology Protection – “USVs must include appropriate security measures...to prevent unauthorized access/control, unauthorized or unintentional disclosure of data, and the perseveration of technology superiority” (USIR 2013, 29).
- Persistent Resilience – USVs must have “improved reliability, maintainability, and survivability” (USIR 2013, 29).
- Autonomy and Cognitive Behavior – greater autonomy is a key driving force for USV technology in the context of reducing manpower involvement. Nearly all unmanned systems require active control in some way whether that is pre-determined mission parameters, refueling/recharging batteries, or reloading spent ordnance.
- Weaponry – full integration of the use of weapons is essential on unmanned systems.

In short, since the inception of the Roadmap in 2013, all of the key technologies have been further developed and most are mature and available for integration into USV platforms. The three technological areas that still remain a concern are fully autonomous and cognitive decision making, communications in a C4ISR denied or diminished environment, as well as the use of available weaponry, specifically in the realm of anti-

ship cruise missiles, strike capability, and anti-ship missiles defense. Many R&D programs are currently working on these items of concern as well as perfecting the other key enabler technologies listed above. Some of the leading companies currently in R&D of autonomous vehicles are ASV Global, DARPA, and Google. Whereas, for the weaponry and C4ISR concerns, multiple entities are working on R&D like PMS-406, Office of Naval Research (ONR), Naval Postgraduate School, and Lockheed Martin.

The Naval Surface Warfare Center Dahlgren Division (NSWCDD) points out that the use of Unmanned Surface Vehicles is only limited to people's imagination. The Navy and public companies have shown to be dedicated to collaborate, combine resources and integrate similar ideas into working concepts. Specifically, in the context of the interoperability and modularity technology, NSWCDD is developing a concept of a "mission package that could slide into a USV modular mission bay that provides a direct and indirect fire capability" (Joyce 2018). Joyce (2018), from NSWCDD corporate communications says: "For surface and expeditionary warfare mission, warfighters could use a modular, plug and play unit designed to fit [into the designed USV] mission bay. These mission modules include sensors for targeting, a weapon station with a gun and a launcher system for missiles. It could provide capabilities to enable a myriad of missions outlined in the Unmanned Surface Vehicle Master Plan."

These mission packages could be developed into many of the mission sets that were described in Table 3: Potential Mission Sets for USV Employment. Joyce (2018) expressed that, "other ideas in the works for mission packages include intelligence, surveillance and reconnaissance. We can [also] develop mission packages to support the carrying and launching of UAV's – armed and unarmed." For the purposes of this thesis, since the given time horizon of the DMO concept in 2030–2035, the desired capabilities and technology readiness levels that were given in Table 3 as well as the key technological areas discussed in this section will be assumed fully mature and ready for operational use and implementation.

1. Current USVs Available

The chosen USVs, depicted in Table 4, are not a comprehensive list of all the USVs currently available, but rather a list of current USVs that fit the role of the potential capable mission sets for DMO that were identified in Table 3. The objective in addressing some of the potential USVs is to determine if there are any capability gaps, requirements, and design issues. The desired outcome is not necessarily to choose 2 to 3 USVs and reconfigure them to fit the user requirements for the DMO concept. The idea is to determine what capabilities current USVs bring, and potentially provide a design solution of one or more USVs that can perform at an operationally effective level and to fill the gap of acceptable risk and cost savings that normal manned assets provide. As stated in Chapter I, the objective for this thesis is to determine the most operationally effective, cost effective and capable USV or combination of USVs to fit into the DMO force structure. This will be addressed throughout the data analysis in Chapter V and the cost analysis in Chapter VI.

Each USV is categorized by country, current mission set capability, class type, payload potential, and potential missions. A summary of the conclusions drawn from Table 4 is that, (1) most of the USVs currently have some form of ISR and ASW capability, (2) most USVs have the potential to fit into the MD mission set and the EW mission set, and (3) some of the bigger platforms have the potential to be reconfigured to a SUW and AMD mission set.

Table 4. Current USVs in the Industry. Source: Jane's by IHS Markit (2018e) and NavalDrones.com.

USV Name	Country	Mission Set	Class Type	Length	Payload	Potential Mission
ACTUV	USA	ISR, ASW	F Class	40 m	20,000 lbs	MD, EW, SUW, AMD
Spartan Scout	USA	ISR, SUW	Fleet Class	11 m	5,000 lbs	MD
Interceptor	USA	ISR	Harbor Class	8.1 m	2,400 lbs	MD, EW
USSV-HS	USA	EW	Harbor Class	10.9 m	4,500 lbs	MD, ISR
Hammerhead	Canada	ISR, EW	Harbor Class	5.2 m	~	MD
Venus	Singapore	ISR, ASW	Fleet/E Class	11/16 m	5,000/8,000 lbs	SUW, MD, EW, AMD
Katana	Israel	ISR, SUW	E Class	11.9 m	4,400 lbs	ASW, MD, EW
Seagull	Israel	ASW	E Class	12 m	5,500 lbs	MD, EW, SUW, ISR
Silver Marlin	Israel	ISR, SUW, EW	Harbor Class	10.7 m	5,500 lbs	MD, ASW
Protector	Israel	ISR, EW	Fleet Class	9-11 m	3,000 lbs	MD
Tamin	UAE	SUW	Fleet Class	11 m	5,500 lbs	MD, EW, ASW, ISR

2. Possible Modifications of Current USVs

The objective behind modifying current USVs on the market is to see if it is possible to combine multiple mission sets into one platform. Table 4: Current USVs in the Industry, shows that there is a wide variety of candidates, but most only provide ISR capabilities. The key enabler for combining mission sets is a mission module bay concept. The concept is a mission package that can fit into a predesignated compartment in the USV so that it can perform the required mission set. This technology is developed and mature for some

platforms and is similar to the Littoral Combat Ship (LCS) Mission Module and the proposed concept by NSWCCD. Just like the ASW, MCM, and SUW modules on the LCS, this thesis proposes a standardized design structure allowing USVs to perform mission types as shown in Figure 9.

For this to happen a functional and physical decomposition would need to take place, thereby identifying the required functions and components of a typical USV. If the physical architecture was standardized as a requirement for military operations specifically in the DMO concept, the way ahead would require communication of key stakeholders and industry leaders identifying the standards and specifications across industry in the context of payload capacity, sea state stability, size capacity, endurance and many other factors that would affect whether the USVs can physically handle certain mission packages. Henceforth, in Chapter III this thesis proposes a functional and physical architecture design addressing the potential mission sets that USVs could perform. It does not include specifications of all the parameters, but merely presents a broad, high level functional and physical architecture for a mission bay module concept.

A recent thesis, Casola 2017, considered a similar concept as mentioned in the preceding paragraphs, but focused on only one USV, the Medium Displacement Unmanned Surface Sea Hunter. The thesis analyzed the Medium Displacement Unmanned Surface Vehicles (MDUSV) potential contribution to the DL concept in the context of the SUW mission. Casola's idea of reconfiguring an already developed vessel into different mission sets gave a baseline to start with in this thesis and is summarized in the following paragraphs.

Casola (2017) described Adaptive Force Packages (AFP) comprised of MDUSVs consisting of a both offensive and defensive roles in the SUW mission set. The offensive MDUSV considered the Harpoon Block II Extended Range (ER) as the best missiles for the SUW-variant. This variant would be able to have a total of three Mk 141 Launchers configured on the MDUSV, for a total of 12 Harpoon Block II missiles available as the offensive munition. Casola considered two defensive MDUSV variants. One considered using counter missiles for the AMD mission set and the other used ship-launched countermeasures. The counter missile MDUSV used the RIM-116 Rolling Airframe

Missile, which was decided as the best counter-missile defense. This variant would be able to have a total of two Mk 49 missile launching systems for a total of 22 RIM-116 missiles per MDUSV. The ship-launched countermeasure MDUSV variant used the Mk 36 Super Rabid Blooms Offboard Countermeasures (SRBOC) Chaff and Decoy system.

Using ExtendSim modeling software, Casola created a simulation with a number of enemy ASCMs inbound to a variety of combinations of the above MDUSV offensive and defensive configurations. He determined that using the offensive variant with the defensive SRBOC variant was the most statistically significant in regard to number of friendly force ships killed. Casola gave a few recommendations for future research, (1) looking at larger hull USVs could allow for great payload capacity with the potential of vertical launch systems instead of just canister launched missiles systems, and (2) looking at advanced missile development specifically the LRASM and MST. Overall, his conclusions point out that the MDUSV can indeed be an effective SUW platform to support DL-based SUW. For the purposes of this thesis, a similar approach of using USVs will be made using the same simulation software; however, the scenario will be more complex, considering multiple platforms from both friendly and adversary forces, multiple domains interacting congruently, as well as multiple tactics and missiles in the confines of the DMO concept.

III. ARCHITECTURE

A. OVERALL SURFACE DOMAIN DMO CONCEPT

Based off the author's operational experience and his interpretation of the needs of the surface DMO domain, the potential mission areas as well as the applicable surface platforms were identified for the DMO surface domain missions as depicted in Figure 12: DMO Surface Missions and Platform Allocation. This figure demonstrates the full spectrum of surface platform missions ranging from Command and Control to Strike Warfare, and also illustrates the diversity of platforms that the surface fleet has in the U.S. Navy's inventory. Of note, this thesis suggests that USVs could potentially supplement or replace manned assets in certain areas as identified in Chapter 2, Figure 9; these areas are highlighted in green in Figure 12. This chapter does two things: it presents a systems architecture representation of USVs in a broad context from both a functional and physical perspective and presents the associated USV configurations that may have utility based on those architectural representations.

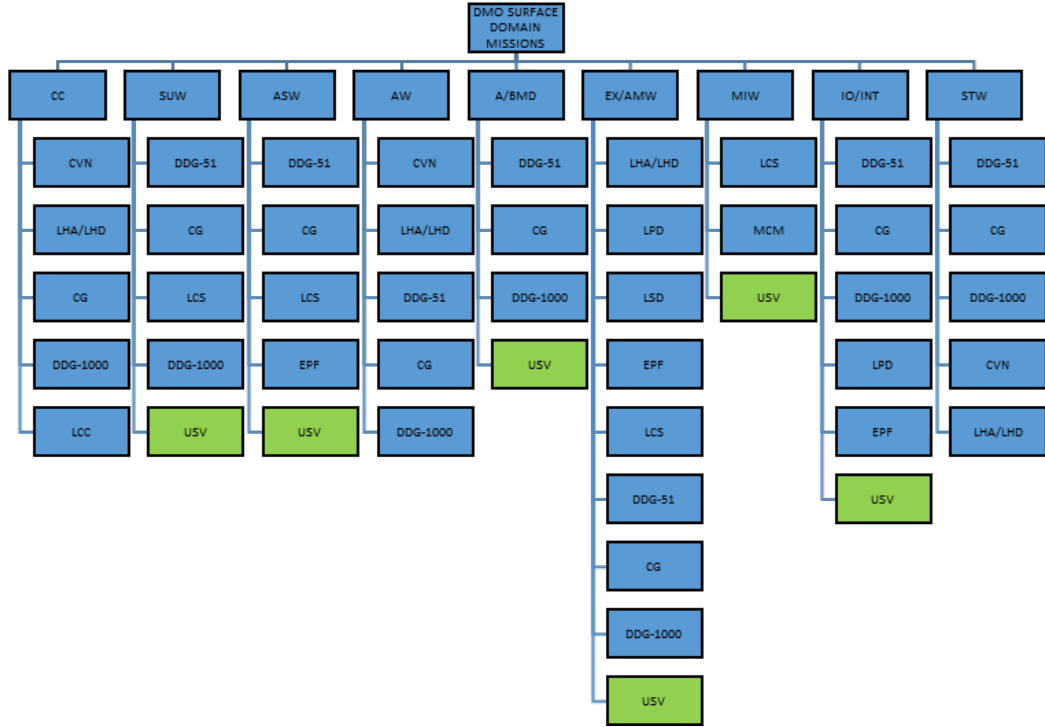


Figure 12. DMO Surface Missions and Platform Allocation

B. ARCHITECTURE OF UNMANNED SURFACE VEHICLES

A system’s architecture is the underlying structure of that system. In the context of unmanned surface vehicles, their architectures will serve as a powerful tool for requirements traceability from the basic “I want,” through functional analysis and physical allocation. The following two sections describes these two approaches, functional analysis and physical allocation.

1. Functional Architecture

To provide a foundation, a functional analysis was performed to present a high-level functional architecture for the DMO concept, incorporating the USVs and showing where they fit into the big picture of the system of systems. SEBok (2015a), states that the Functional Architecture is “a set of functions and their sub-functions that defines the transformations performed by the system to complete its mission.” Blanchard and Fabrycky (2011), describe that the functional architecture establishes “a functional baseline for all subsequent design and support activities, which in turn provide a foundation from

which all physical resource requirements are identified and justified” (86). Consistent with the intended purpose and utility of functional architectures, an SV-4: Systems Functionality Description, a methodology derived from the Department of Defense Architecture Framework (DoDAF), was designed showing the tentative functional decomposition that USVs will perform in Figure 13: Unmanned Surface DMO Functions. Of note, this functional decomposition is not considering all the functions and sub-functions that unmanned surface vehicles perform but is only considering the high-level functions in the context of the DMO concept.

There are a number of theses and publications that portray what the generic functions are for USVs, breaking down functions like the navigation of the system or the machinery of the system. Some of these ideas can be referenced in Cox (2011) or Johnson (2010) theses. For the purposes of this thesis, generic functions as described above will not be identified, but rather assumed in the functional decomposition of a generic USV in the DMO concept. It should be noted that all functions in a functional decomposition should be mapped to a physical component or multiple components of a system as well as all physical components mapped to functions of the system. The following section defines the physical decomposition of a generic USV in the confines of the requirements needed in the DMO concept. For the same reason as mentioned before, not all generic physical components of a typical USV are identified and not all physical components map to Figure 13. The six primary functions shown in Figure 13 are traced from the six mission areas identified in Figure 12.

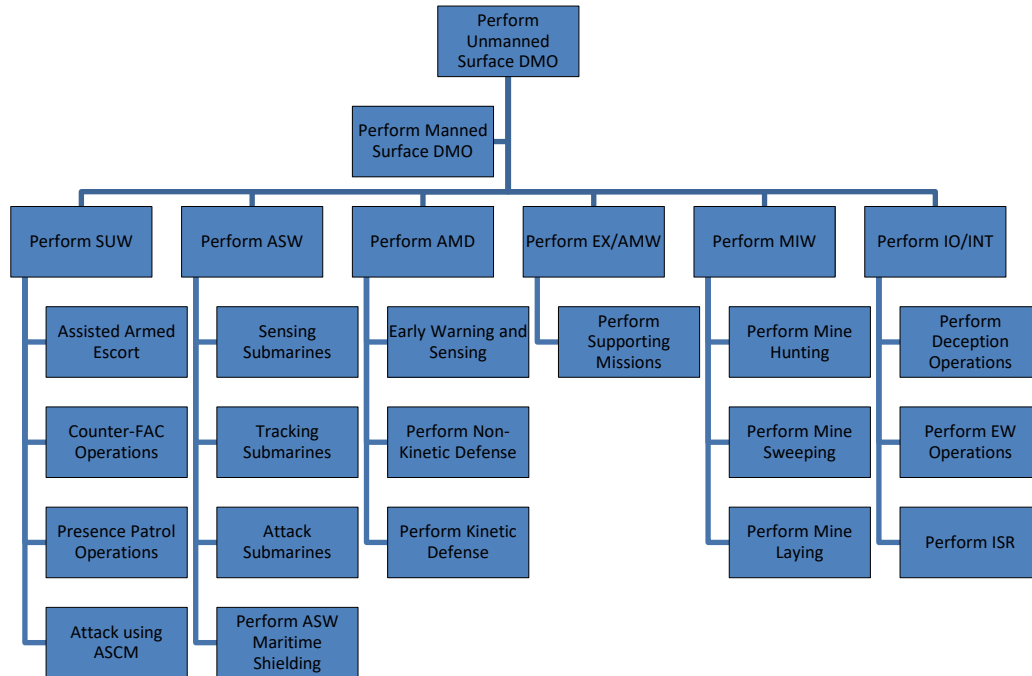


Figure 13. Functional Architecture of Unmanned Surface Vehicles

2. Physical Architecture

SEBoK (2015b) defines the physical architecture as “an arrangement of physical elements which provides the design solution for a consumer product or life-cycle process intended to satisfy the requirements of the functional architecture and the requirement baseline.” The physical architecture annotated in Figure 14 is a high-level conceptual architecture that is useful in moving forward with this thesis’ analysis. Current USVs in the international market are not designed explicitly as Figure 14 illustrates, but the objective in showing this is to give a future design model for the physical components of a typical USV in the context of the DMO concept.

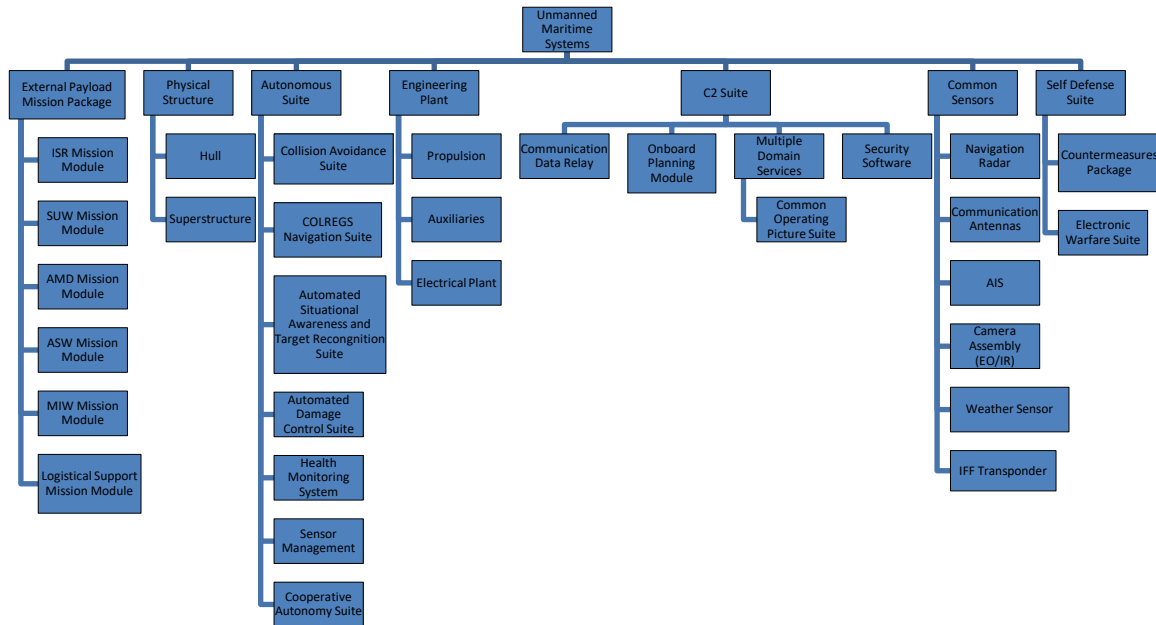


Figure 14. Physical Architecture of Unmanned Surface Vehicles

All USVs should have the basic physical components that make up the engineering plant, physical structure, C2 suite, and common sensors, but not all of today’s current USVs have the optional external payload mission packages, self-defense suite or the fully autonomous suite. As previously discussed in Chapter 2, NSWCDD and many industry manufacturers have accepted this concept of modular mission packages. Some examples of current industry leaders that have moved toward this concept of incorporating capacity and interoperability in their USV designs are Elbit, Israel Aerospace Industries, Textron Systems and Singapore Technologies Electronics, which make the Seagull, Katana, Common Unmanned Surface Vehicle (CUSV) and Venus, respectively. Ultimately, it would be ideal to have a standardized high-level physical architecture layout that conforms to the U.S. Navy’s requirements and expectations with which the USV industry could comply.

Each high-level physical component from Figure 14: Physical Architecture of Unmanned Surface Vehicles is described in the following paragraphs.

- External Payload Mission Packages: This component is external to the system and requires a decision maker to choose which package to configure to the specified USV. Each of the six mission packages are congruent with the Functional Architecture of Unmanned Surface Vehicles illustrated in Figure 13. The USV should be expected to support only one mission package at a time; it would be required to be docked and a team of personnel to change-out mission packages as applicable. The mission packages will be similar to the current Littoral Combat Ship Concept. They are illustrated in the simplified modular concept shown in Figure 15: Simplified Mission Package Modular Concept.

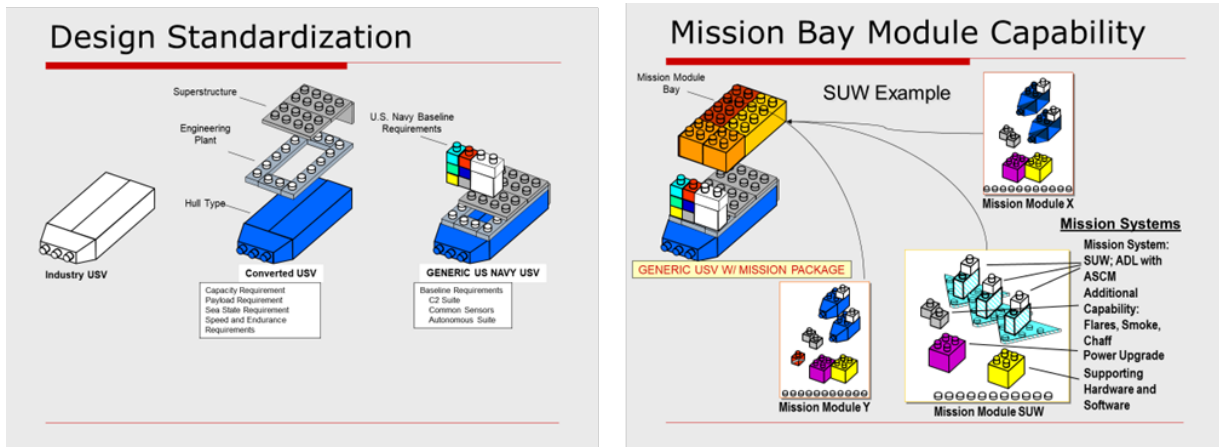


Figure 15. Simplified Mission Package Modular Concept. Adapted from Beery (2018).

- Physical Structure: The physical structure is made up of the hull and superstructure of the system that allow it to float and be watertight under specified sea state requirements. The left picture in Figure 15 shows that the hull and superstructure are configured to meet sea state, payload and capacity requirements specified by the U.S. Navy.
- Autonomous Suite: The autonomous suite is viewed as a key capability of this system and is the stepping stone for future cooperative and multi-

domain operations. The definition of autonomy can be referenced in Chapter 2 section B. Every USV will have an autonomous suite that consists of multiple software and hardware components. This is a baseline component as depicted in the left picture in Figure 15.

- Engineering Plant: The engineering plant consists of all the hardware and mechanical means of propulsion, auxiliaries, and electronics. All USVs will have a baseline engineering plant that will meet the specified requirements for endurance, speed and electrical power.
- C2 Suite: The C2 suite is another baseline component for all USVs. It will have the capability to receive and transmit information, have the necessary security measures, provide and receive a common operating picture, as well as an onboard planning module that allows for human interface, if necessary.
- Common Sensors: The common sensor components are made up of several generic over-the-counter sensors as well as some military standard sensors to perform the required functions of any maritime vessel. These sensors are integrated into the Autonomous Suite so they can be managed and the applicable information can be identified and interfaced into the decision making process of the system.
- Self Defense Suite: This thesis proposes that all USVs should be designed with a Self-Defense Suite. This Self-Defense Suite will have non-kinetic countermeasures like chaff, flares, and IR smoke, as well as a limited capability to utilize its EW suite with jamming tactics and active decoys. Research was conducted on feasible options to support this suite on the generic USVs operating in the DMO concept. The most practical and cost effective option identified for non-kinetic countermeasures is a system called the Centurion, developed by Chemring. The Centurion system has 12 barrels that can store multiple calibers of countermeasures, including

active decoys, IR and RF seduction countermeasures, as well as RF distraction countermeasure. It has a small deck footprint of less than 1,500 mm diameter, as well as weighs less than 1,000 kg and requires 440V 3 phase power (Jane's by IHS Markit 2018c). Figure 16 shows the Centurion System.



Figure 16. Centurion System. Source: Jane's by IHS Markit (2018c).

The EW suite will have to be something similar to Northrop Grumman's AN/SLQ-32(V)6, which is a part of the Surface Electronic Warfare Improvement Program (SEWIP) Electronic Attack (EA) variants. This system provides active-electronic attack capabilities, i.e., simultaneous jamming of multiple threats, along with passive measures "providing early warning, identification and direction finding capabilities of simultaneous multiple threats" (Jane's by IHS Markit 2018a). The SEA 27 (2018) analysis results, which were discussed in Chapter 2, noted that the employment of jamming tactics and the use of physical and mechanical countermeasures were significant in the operational success of the DMO concept. For this reason, all USVs will have a self-defense suite consisting of the previously discussed subsystems.

C. POTENTIAL USV VERSIONS THAT WILL BE ADDRESSED IN THIS THESIS

The objective of Chapter II was to present current USVs and their potential capabilities in the spectrum of possible mission areas. Chapter III has narrowed down the mission areas in the context of the Surface Domain Distributed Maritime Operations and has presented a functional and physical architecture for future USVs. For the purpose of this thesis, three alternatives will be analyzed through modeling and simulation. These three alternatives are not readily available on the current market, but the objective of proposing an architecture is to shape the development of future work to be feasible and congruent with the U.S. Navy's vision and objectives concerning unmanned systems. Chapter VI presents a cost analysis of these alternatives using the results from the modeling and simulation outputs to compare operational effectiveness to cost.

Before addressing each alternative, two major concerns need to be discussed in relation to the current configurations of most USV platforms; Vertical Launching System (VLS) support and sensing capability. Currently no unmanned system has the capability and hardware to support a VLS (known as the Mk 41), which is one of the main assets that the U.S. Navy has for firing its missiles. The VLS is very expensive and has huge payload requirements that current USVs cannot support. As mentioned in Chapter II, Casola (2017) determined that the only legitimate launching system that the U.S. Navy's biggest unmanned surface vehicle could currently support was the Mk 141, which launches Harpoons. The U.S. Navy has proven that one of its key force multipliers, in both the current and future maritime domain, is the capability of launching numerous missiles from their vertical launching systems. Both the destroyer and cruiser can hold upwards to 96 and 122 missiles, respectively. These missiles range from any of the Standard Missiles (SM-2, SM-3, and SM-6 versions), the Maritime Strike Tomahawk (MST), the Evolved Sea Sparrow Missile (ESSM), as well as the newly developed Long Range Anti-Ship Missile (LRASM). The desire for USV's is to have a similar capability, like the VLS, that can support firing the above mentioned missiles.

Until recently, the concept of having a similar system like the VLS on smaller platforms was unheard of; however, in early 2018, during the Surface Navy Association's

National Symposium, BAE unveiled its Adaptable Deck Launcher (ADL). The ADL is a deck-mounted launcher “that allows any number of launch cells to be configured at a low angle...for varying ship applications” (BAE System 2018). BAE has stated that the ADL can launch the same missiles as the MK 41 VLS, and benefits from a modular design that allows for multiple cell configurations. BAE has deemed that the ADL “answers the call for Distributed Lethality and Distributed Maritime Operations for platforms big and small” (BAE Systems 2018). Figures 17 and 18 illustrate the concept of the ADL; Figure 17 shows a design concept of a 4 canister ADL and Figure 18 shows a conceptualization of the MK VI with 4 LRASMs in the ADL.

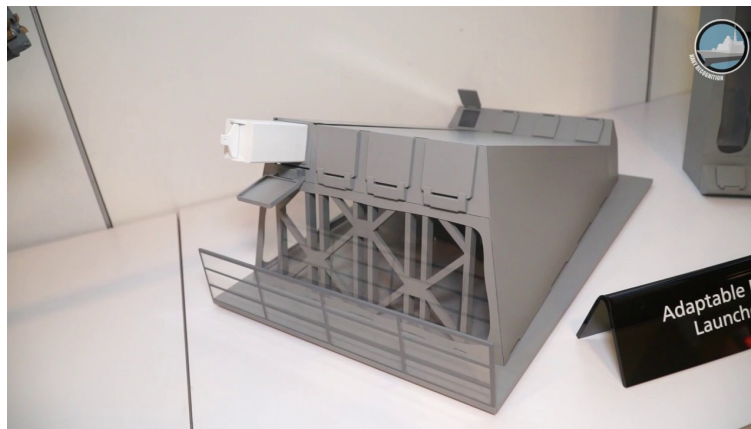


Figure 17. ADL Concept. Source: Navy Recognition (2018a).



Figure 18. Mk VI with ADL. Source: Navy Recognition (2018b).

The ADL is a much more feasible option than installing a Mk 41 VLS on an unmanned surface vehicle for more multiple reasons. The primary one being the Mk 41 VLS requires a certain depth in the hull greater than or equivalent to the length of the missile canister. Large warships have this design characteristic of beneath deck capacity, whereas, large USVs currently do not. A deck mounted launcher only requires the topside deck space vice the VLS requiring both the depth capacity and topside deck space. One of the other easily identifiable reasons that the ADL is a feasible option is that an empty ADL weighs 20,300 pounds and a fully loaded ADL with 16 ESSMs weighs 42,600 pounds (BAE Systems 2018). The VLS has a similar weight, approximately 20,000 pounds empty (Jane's by IHS Markit 2018d). The weights change depending on what missiles are installed and how many are carried, but the underlining fact is that USVs could support this concept.

This thesis is implementing BAE's ADL system into the USVs that will be analyzed. However, it is interesting that multiple sources are investigating and developing deck-mounted launchers similar to the ADL that support the same functions as described in the previous paragraphs. One industry leader is Lockheed Martin, which states that they will be developing a new topside or deck-mounted launcher that can go on multiple platforms. They recently received a contract to collaborate with the Office of Naval Research (ONR) and the Defense Advanced Project Research Agency (DARPA) in

developing the LRASM. They would like to develop a deck-mounted fire technology that would enable the LRASM to fire from more than just the Mk 41 VLS (Osborn 2016). Another industry leader is RAFAEL, which is developing their Iron Dome Counter-Rocket, Artillery and Mortar defense system (C-RAM) to the surface domain, termed “C-Dome” (Eshel 2014). These are just two examples of how the industry is moving toward interoperability of weapon systems in the surface domain.

Based on Chapter II’s USV classes in Figure 6, the F and G class could potentially fill the role with the payload requirements of the ADL. Concepts under development that were previously discussed, like the Rolls Royce USV and the Overlord USV, have the capacity to support the mission modules that would use the ADL. Figure 19 and 20 depict the conceptualization of the Rolls Royce USV and the potential conversion of previously manned ships, like the Monsoon Class, to autonomous unmanned surface vehicles. This new technology opens the door to concepts that could not be conceived previously.



Figure 19. Rolls Royce USV. Source: Hutchinson (2017).



Figure 20. Monsoon Class. Source: Navsource (n.d.).

The second major concern is the sensing capability for unmanned surface vehicles, specifically in regard to targeting, fire control solutions, size and power requirements. Currently the sensing capability is limited amongst known USV industry standards, and USVs that do have targeting and fire control data are constrained by range, power, and size and must rely on land based systems or manned systems supplementing targeting solutions. This thesis considered different radar configurations, keeping in mind the cost of the U.S. Navy's current radars being used for targeting and fire control data. The desire is to provide a reasonable tradeoff for the sensing capability to be cost effective but also operationally effective. The design concept would allow the installation of the necessary radar and equipment to the specified mission package module. For the purposes of this thesis, the most realistic radar that was considered for the three alternative mission modules was either a two or four fixed faced phased array radar similar to the proposed Aegis SPY-1K radar. The SPY-1K is described by Janes IHS Markit as, "a scaled-down version of the SPY-1F for corvette and light frigate applications," and is approximately "one quarter of the size and weight of the USN's SPY-1D(V) system, provides concurrent volume and horizon search, target tracking, fire-control target tracking, and uplink and downlink communications with mid-course guided missiles" (Janes IHS Markit 2018b). The Aegis weapons system and the associated SPY-1 E/F band radar family has shown to be key

enablers for the USN surface platforms. The costs of such systems are extremely high, but with the mitigation of reducing size, power, and the number of panels per USV could reduce the cost and provide a feasible targeting and fire control radar for the 2030–2035 timeframe. A cost estimate will be provided in Chapter VI and will incorporate both the ADL and the equivalent phased array mentioned in the above paragraphs.

1. USV ANTI-MISSILE DEFENSE Alternative

The AMD USV will supplement the existing surface platforms in the AMD mission set for the surface domain. The objective is to provide multiple USV platforms with the AMD mission module dispersed amongst the CSG, SAG or ESG. They will provide additional support, early warning sensors, as well as a cooperative engagement capability in conjunction with the friendly kill chain. This not only gives more available firepower but adds additional targets for the adversary to decide from, allowing more time for friendly forces to counter target or counter engage. The concept behind having multiple AMD USVs would be that it is a cost-effective alternative in the U.S. Navy's layered defense; having 5 to 6 AMD USV's destroyed in a maritime war vice having a manned cruiser destroyed is a colossal difference.

The AMD USV was outfitted with two different payloads for the discrete modeling and simulation. It is important to understand that these payloads are up to interpretation and can be configured however way the user wants, but for the purposes of this thesis the following alternatives were configured with specific quantities of missiles based off the author's operational experience and from a feasibility standpoint of what USVs could potentially hold due to payload capacity. Tables 5 and 6 illustrate the design specifications as well as the payloads for the two USV AMD platforms.

Table 5. USV AMD A (Air) Specifications

USV AMD A (Air)	
Class Type:	G
Mission Module Payload:	75 tons
ADL Footprint:	105 sqm
Missile Type:	SM-6
Number of Missiles:	8
Launch Cells:	8
Centurion System:	1
Countermeasures:	12
Centurion Footprint:	0.0012 sqm

Table 6. USV AMD M (Missile) Specifications

USV AMD M (Missile)	
Class Type:	F or G
Mission Module Payload:	45 tons
ADL Footprint:	85 sqm
Missile Type:	ESSM
Number of Missiles:	16
Launch Cells:	4
Centurion System:	1
Countermeasures:	12
Centurion Footprint:	0.0012 sqm

2. USV SURFACE WARFARE Alternative

The SUW USV will supplement the existing surface platforms in the SUW mission set for the surface domain. The objective is to provide multiple USV platforms, with the SUW mission module, dispersed in the maritime area of operation providing forward projection and deterrence. The SUW USV will solely be an offensive strike asset carrying several ASCMs. This is similar to the PLA's Type 055 Houbai, which carries a heavy

punch at a low cost of approximately \$17 million (FY2018) per unit (Galrahn 2009). Just like the USV AMD version, the SUW USV adds additional targets for the adversary to decide from that allows more time for friendly forces to counter target or counter engage. This again is a cost effective alternative for the U.S. Navy’s layered defense and provides a more “strike first mentality” with the given missiles that the SUW USV carries.

Similar to the AMD USV, the SUW USV was outfitted with a payload for the discrete modeling and simulation. For the purposes of this thesis, the following alternative was configured with the specific quantities of missiles based off the author’s operational experience and from a feasibility standpoint of what USVs could potentially hold due to payload capacity. The following table illustrates the design specifications as well as the payloads for the USV SUW platform.

Table 7. USV SUW Specifications

USV SUW	
Class Type:	G
Mission Module Payload:	75 tons
ADL Footprint:	105 sqm
Missile Type:	LRASM - MST
Number of Missiles:	4 - 4
Launch Cells:	8
Centurion System:	1
Countermeasures:	12
Centurion Footprint:	0.0012 sqm

3. USV ISR Alternative

The ISR USV will supplement the existing surface platforms in the IO/INT mission set for the surface domain. The objective is to provide multiple USV platforms, with the ISR mission module, dispersed in the maritime area of operation. They would provide early warning detection, a larger common operating picture, as well as extended firepower reach with targeting solutions for multiple domain assets. The ISR USV will not play any

offensive or defensive role but will be solely the eyes and ears of the surface domain. Just like the USV AMD version, the ISR USV adds additional targets for the adversary to decide from that allows more time for friendly forces to counter target or counter engage. This idea of having multiple ISR surface platforms, at a reduced cost, supplementing the use of manned assets, could play a major role in the future fleet. UAVs are already playing a key role in this matter, therefore, having multiple manned and unmanned systems working cooperatively to display the common operating picture could be a major force multiplier in the DMO concept.

The ISR USV was outfitted with a payload for the discrete modeling and simulation. Since its role is completely different than the first two USV alternatives, the payload mission module does not need an ADL configuration but only the required sensors and equipment for long range sensing, transmitting, and communicating. For the purposes of the discrete simulation, the ISR USV provides an extended range for all missile types when actively conducting its ISR mission and is assumed to have the capability to transmit and receive data link to all platforms in the DMO concept. The following table illustrates the design specifications as well as the payloads for the ISR USV platform.

Table 8. USV ISR Specifications

USV ISR	
Class Type:	E - G
Mission Module Payload:	<20 tons
ADL Footprint:	N/A
Missile Type:	N/A
Number of Missiles:	N/A
Launch Cells:	N/A
Centurion System:	2
Countermeasures:	24
Centurion Footprint:	0.025 sqm

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IV. MODEL DESCRIPTION

This chapter presents the simulation model, consistent with the system architectures presented in Chapter III, to analyze the potential operational utility of USVs. The chapter specifically addresses the concept of operations, the order of battle for the adversary and friendly forces, a summary of the model, the model's limitations and assumptions, and lastly, the author's hypothesis of the implementation of USVs into the DMO concept.

A. CONCEPT OF OPERATIONS

The SEA 27 (2018) capstone project gave a specific setting and scenario to scope the model and simulation. The intention was to provide an underlying operational situation with platforms and technologies equivalent to the 2030–2035 time frame with a near peer competitor. The SEA 27 team wanted to ensure that the DMO concept was analyzed in a realistic scenario and operational environment, so the focus was geared towards a littoral conflict in the South China Sea. For this thesis, the same scenario and setting will be carried forward with minor changes to both the friendly and enemy order of battle. Chapter III in the SEA 27 (2018) capstone report has a detailed description of the concept of operations; however, the following paragraphs are a summary derived from their report, which provides the reader context moving forward.

1. Scenario

The basis of the scenario derives from the narrative described in the “Maritime War of 2030” framework from the Joint Campaign Analysis course (Kline 2018). The narrative can be found in Appendix A. SEA 27 (2018) summarizes the scenario in the following paragraph:

The geopolitical situation in the year 2030 is characterized by continued tension between the United States and the People's Republic of China (PRC) in the South China Sea region, with PRC continuing to construct military basing on contested islands. With the increased threat of PRC expansionism and potential conflict, the United States maintains its routine patrols through the region and maintains its defense treaties with established regional partners. The maritime war at sea in the 2030 to 2035 timeframe progresses from escalating aggression and unlawful PRC activities in the

region, to harassment of neighboring nation's fishing vessels and the massing of PRC maritime forces in the South China Sea. The United States obtains intelligence of the PRC objective to capture the Philippine island nation of Palawan. The U.S. friendly forces anticipate imminent engagement with PRC enemy forces and are consequently conducting preparations for combat at sea, with immediate mobilization of regional friendly assets to the South China Sea (SCS), specifically to the northwestern edge of Palawan. (SEA 27 2018, 15)

2. Operational Environment and Tasking

The primary tasking for the U.S. maritime forces is to establish a defensive perimeter off the western coastline of Palawan. The U.S. will maintain a defensive posture for its allies until the enemy initiates hostile intent towards either friendly forces or allied forces. The execution of a defensive operation in the protection of an island from an imminent attack is primarily the operational scenario; however, friendly forces will have an offensive "strike first" posture when the situation presents itself as prescribed by the DMO doctrine. SEA 27 (2018) states that "U.S. maritime assets must apply the DMO concept through the employment of traditional warfare areas including air and missile defense, surface warfare, and at-sea strike, as well as manned-unmanned tactics, counter-targeting, deception operations, and electromagnetic warfare" (16). All friendly platforms, whether they are manned or unmanned, are integrated into a weapon system network that allows for distribution of friendly intelligence as well as ordnance. A defensive posture will resemble maritime and air superiority in the area of operation by creating a distributed tactical common operating picture that allows all friendly forces, manned and unmanned, situational awareness for the approaching adversary.

3. Area of Operations

The SCS is the primary area of operation, with the western coastline of Palawan and beyond, extending north-west, as the focal point in the scenario. As depicted in Figure 21, the white outline represents the potential operating locations for both friendly and adversary forces, while the yellow outline shows the island of Palawan. This area of operation spans approximately 700,000 square miles of international waters and territorial seas.

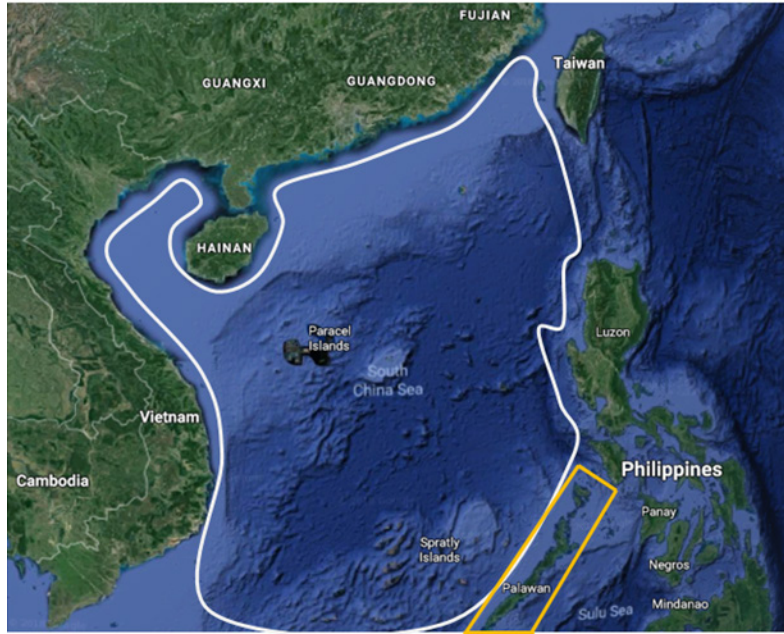


Figure 21. Projected Operating Area. Source: SEA 27 (2018).

B. ORDER OF BATTLE

This thesis' analysis will be bounded by the area and setting of the scenario defined in Section A of this chapter. The order of battle (OOB) was developed for both the friendly and enemy forces based off of historical open source databases for platforms in the specified region. To suit the 2030–2035 timeframe, the author extrapolated some of the current performance characteristics as well as platforms and technologies that are not fully mature or developed. The OOB is comprised of surface ships, aircraft, and unmanned systems (including unmanned aerial vehicles and unmanned surface vehicles), as well as their weapons systems and sensors. For this scenario, only U.S. and the People's Republic of China (PRC) platforms are considered in the OOB. All allied assets for both the U.S. and PRC remain neutral for this thesis' simulation; therefore, allied nations will not be considered in the OOB. A more detailed look at the friendly and enemy OOB can be found in Appendix B and the details and characteristics of each generic sensor for both the enemy and the friendly forces are referenced in Appendix C.

1. Friendly Order of Battle

The area of operations is in the Pacific Commands (PACOM) area of responsibility (AOR); therefore, the OOB considers the current number of platforms that are typically deployed or deployable within this region. The major force concentration bases that provide U.S. platforms are Japan, Guam, Hawaii and San Diego. These platforms are usually deployed in action groups such as Carrier Strike Groups (CSG), Expeditionary Strike Groups (ESG) or Surface Action Groups (SAG). To meet the desired operational objective of providing a defensive perimeter around the Western coastline of Palawan, the following paragraphs address the composition of CSG, ESG, and SAG platforms.

(1) Friendly Surface Platforms

Table 9 shows the different types of friendly surface platforms that will be modeled in the simulation of the thesis scenario. Most of the vessels are currently in the U.S. Navy's inventory; however, the conceptualized unmanned surface vehicles presented in Chapter III are also considered in the OOB. The vessels described in Table 4 may already be deployed in the region, be en-route to the region, or be reassigned to the region due to operational tasking.

Table 9. Friendly Order of Battle – Surface Platforms. Adapted from SEA 27 (2018).

Ship Type	Ship Class	Designator	Manning
Aircraft Carrier	Nimitz/Gerald R. Ford	CVN	Manned
Amphibious Assault	America/Wasp	LHA/LHD	Manned
Amphibious Transport Dock	San Antonio	LPD	Manned
Guided Missile Cruiser	Ticonderoga	CG	Manned
Guided Missile Destroyer	Arleigh Burke	DDG-51	Manned
Guided Missile Destroyer	Zumwalt	DDG-1000	Manned
Littoral Combat Ship	Freedom/Independence	LCS	Manned

Ship Type	Ship Class	Designator	Manning
Unmanned Surface Vehicle Intelligence, Surveillance, & Reconnaissance	E-G Class	USV ISR	Unmanned
Unmanned Surface Vehicle Surface Warfare	G Class	USV SUW	Unmanned
Unmanned Surface Vehicle Anti-Missile Defense	F-G Class	USV AMD	Unmanned

(2) Friendly Air Platforms

Table 10 shows the different types of friendly air platforms that will be modeled in the simulation of the thesis scenario. These aircraft will be either assigned to a Carrier Air Wing (CVW) that will be attached to the CSG, an Aviation Combat Element (ACE) that will be attached to the ESG, a detachment to a smaller surface combatant, or a foreign operating base (FOB) in the region. The aircraft described in Table 10 may already be deployed in the region, be en-route to the region, or be reassigned to the region due to operational tasking.

Table 10. Friendly Order of Battle – Air Platforms. Source: SEA 27 (2018).

Aircraft Role	Aircraft Type	Designator	Nomenclature	Manning
Stealth Multi-role Fighter	Fixed Wing	F-35	Lightning	Manned
Multi-role Combat	Fixed Wing	F/A-18	Super-Hornet	Manned
Electronic Warfare	Fixed Wing	EA-18	Growler	Manned
Airborne Early Warning	Fixed Wing	E-2	Hawkeye	Manned
Maritime Patrol	Fixed Wing	P-8	Poseidon	Manned

Aircraft Role	Aircraft Type	Designator	Nomenclature	Manning
Multi-role Maritime Helicopter	Rotary Wing	MH-60	Seahawk	Manned
Attack Helicopter	Rotary Wing	AH-1	Super Cobra/ Viper	Manned
Autonomous Surveillance	Fixed Wing	MQ-4	Triton	Unmanned
Autonomous Helicopter	Rotary Wing	MQ-8	Fire Scout	Unmanned
Autonomous High Altitude Long Endurance	Fixed Wing	MQ-9	Reaper	Unmanned
Tactical Exploited Reconnaissance Node	Rotary Wing		TERN	Unmanned

(3) Friendly Sensors

Table 11 shows the different types of friendly sensors with their parent platforms that will be modeled in the simulation of the thesis scenario. The sensors' primary roles in the context of DMO and the modeling and simulation on the scenario is to detect, track and target, and engage hostile contacts that pose a threat to the defense of the Island of Palawan. The sensors described in Table 11 are generic in nature and will be modeled as such. For example, there are many variations of Fire Control (FC) radars; however, for this thesis all platforms that have a FC Radar will be modeled with a generic baseline FC radar.

Table 11. Friendly Order of Battle – Sensors. Adapted from SEA 27 (2018).

Sensor	Parent Platforms
Visual	All Surface, All Air, All Unmanned
Infrared	CVN, LHD/LHA, CG, DDG-51, DDG-1000, LCS, LPD, F-35, F/A-18, EA-18, E-2, P-8, MH-60, AH-1, MQ-8 Fire Scout, MQ-4 Triton, TERN

Sensor	Parent Platforms
Electronic Support Measures (ESM)	CVN, LHD/LHA, CG, DDG-51, DDG-1000, LCS, LPD, USV ISR, USV SUW, USV AMD, F-35, F/A-18, EA-18, E-2, P-8, MH-60, AH-1, MQ-8 Fire Scout, MQ-4 Triton
Air Search Radar	CVN, LHA/LHD, CG, DDG-51, DDG-1000, LCS, LPD, USV AMD, MH-60, AH-1, TERN
Surface Search Radar	All Surface Platforms, MH-60, AH-1, TERN
Fire Control Radar	CVN, LHD/LHA, CG, DDG-51, DDG-1000, LCS, LPD, USV SUW, USV AMD, MH-60, AH-1, MQ-8 Fire Scout
Navigation Radar	All Surface Platforms
Phased Array Radar	CVN, CG, DDG-51, DDG-1000
AESA (Active Electronic Scanned Array Radar)	F-35, F/A-18, EA-18, E-2, P-8, MQ-4 Triton
Airborne Early Warning Radar	E-2, P-8
Synthetic Aperture Radar – Maritime	MH-60, MQ-8 Fire Scout, MQ-4 Triton

(4) Friendly Missiles

Table 12 shows the different types of friendly missiles with their parent platforms that will be modeled in the simulation of the thesis scenario. Missiles will be used in both an offensive and defensive role in the context of DMO. A wide range of types of missiles were chosen to be modeled, from air-to-air missiles (AAM) to anti-ship cruise missiles (ASCM). As mentioned in Chapter III, the LRASM and MST are not fully developed, but will be implemented into the missile OOB with the assumption that by the 2030–2035 timeframe they will be technologically mature.

Table 12. Friendly Order of Battle – Missiles. Adapted from SEA 27 (2018).

Missile	Designator	Type	Launching Platform(s)
Standard Missile-2	RIM-66	Medium Range Surface to Air	CG, DDG-51, DDG-1000
Standard Missile-3	RIM-161	Ballistic Missile Defense	CG, DDG-51, DDG-1000
Standard Missile-6	RIM-174	Extended Range Surface to Air, Anti-Ship Cruise Missile (ASCM)	CG, DDG-51, DDG-1000, USV AMD
LRASM	AGM-158C	Long Range Anti-Ship Missile	CG, DDG-51, DDG-1000, USV SUW, F-35, F/A-18
Maritime Strike Tomahawk	MST	Long Range Anti-Ship Cruise Missile	CG, DDG-51, DDG-1000, USV SUW
Harpoon	AGM/RGM-84	Over the Horizon Anti-Ship Missile	CG, DDG-51, LCS, F-35, F/A-18
ESSM	RIM-162	Evolved Sea Sparrow - Medium Range Surface to Air Missile	CVN, LHA/D, LPD, CG, DDG-51, DDG-1000, LCS, USV AMD
Sidewinder	AIM-9	Short Range Air to Air	F-35, F/A-18, EA-18, AH-1
Hellfire	AGM-114	Short Range Air to Surface	F-35, F/A-18, MH-60, AH-1, MQ-8, TERN
AMRAAM	AIM-120	Advanced Medium Range Air to Air	F-35, F/A-18
HARM	AGM-88	High Speed Anti-Radiation	F-35, F/A-18

2. Enemy Order of Battle

The area of operations is in the South China Sea; therefore, the PRC has prime real estate in not only its well-established mainland naval bases, but also throughout its forward operating bases on the contested reefs and island chains. The PRC also has a clear advantage when it comes to employment options. The enemy OOB consists of not only surface and air platforms, but also land-based missiles that can be fired from predesignated

areas. The major force concentration bases that provide enemy platforms are the Spratly Islands, Paracel Islands, and the Southern Naval Theater Head Quarters. These platforms are usually deployed in action groups similar to the friendly forces. According to Cole (2010), the Chinese will use a strategic operational “Clausewitzian measure: how much naval force can be deployed against a given objective at a time of Beijing’s choosing” and also states that it is, “fairly certain that China will be able to seize the initiative when employing its new Navy” (p 113). To meet the enemy’s desired operational objective of establishing a military presence on Palawan, the necessary composition of action groups is addressed in the following paragraphs.

(1) Enemy Surface Platforms

Table 13 shows the different types of enemy surface platforms that will be modeled in the simulation of the thesis scenario. The list encompasses the most technologically advanced platforms currently in the PRC naval forces as well as platforms that are still in development. Of note, no USVs were used in the Enemy’s OOB due to the lack of public information available on characteristics and performance. The vessels described in Table 13 may already be deployed in the region, be en-route to the region, or be reassigned to the region due to operational tasking.

Table 13. Enemy Order of Battle – Surface Vessels. Source: SEA 27 (2018).

Ship Type	Ship Class	Designator	Manning
Aircraft Carrier	Kuznetsov/ <i>Liaoning</i> , CV03	Type 001A/002/ 003	Manned
Guided Missile Cruiser/Destroyer	Renhai	Type 055	Manned
Guided Missile Destroyer	Luyang III	Type 052D	Manned
Multi-role Frigate	Jiangkai II	Type 054	Manned
Multi-role Corvette	Jiangdao	Type 056	Manned
Stealth/Missile Boat	Houbei	Type 022	Manned

Ship Type	Ship Class	Designator	Manning
Amphibious Assault - Landing Helicopter Dock	Not Yet Determined	Type 075	Manned
Amphibious Transport Dock	Yuzhao	Type 071	Manned
Landing Ship – Tank	Yuting II	Type 072A	Manned

(2) Enemy Air Platforms

Table 14 shows the different types of enemy air platforms that will be modeled in the simulation of the thesis scenario. Most of these PRC aircraft will be employed by land bases in the vicinity of the aforementioned force concentration bases, apart from the J-15, which is specifically designed to deploy from the new 001A aircraft carrier. The enemy aircraft OOB has much more variety and quantity than the friendly counterpart's due to ample supply of ground bases and logistical lines. Of note, this thesis chose to model three UAVs similar to the friendly force's UAV OOB. This was done for simplicity's sake due to the multitude of variants and unique UAVs that the PRC has developed. The aircraft described in Table 14 may already be deployed in the region, be en-route to the region, or be reassigned to the region due to operational tasking.

Table 14. Enemy Order of Battle – Air Platforms. Source: SEA 27 (2018).

Aircraft Role	Aircraft Type	Designator	Nomenclature	Manning
Air Superiority Fighter	Fixed Wing	J-11	Flanker B+	Manned
Carrier Based Fighter	Fixed Wing	J-15	Flying Shark	Manned
Multi-role Strike Fighter	Fixed Wing	J-16	Shenyang	Manned
Electronic Warfare Fighter	Fixed Wing	J-16D	Shenyang	Manned
Multi-role Stealth Fighter	Fixed Wing	J-20	Chengdu	Manned
Attack & Close Air Support	Fixed Wing	Q-5	Nanchang – Fantan	Manned

Aircraft Role	Aircraft Type	Designator	Nomenclature	Manning
Strategic Bomber	Fixed Wing	H-6K	Xian	Manned
Airborne Early Warning	Fixed Wing	KJ-3000	Mainring	Manned
Maritime Patrol	Fixed Wing	Y-8FQ	Shaanxi	Manned
Utility/ASW Helicopter	Rotary Wing	Z-18	Changhe	Manned
Airborne Early Warning Helicopter	Rotary Wing	Z-8AEW	Super Frelon	Manned
High Altitude Long Endurance UAV	Fixed Wing		Soaring Dragon	Unmanned
Medium Altitude Long Endurance UAV	Fixed Wing		Pterodactyl	Unmanned
Stealth Supersonic UAV	Fixed Wing	AVIC 601	Dark Sword	Unmanned

(3) Enemy Sensors

Table 15 shows the different types of enemy sensors with their parent platforms that will be modeled in the simulation of the thesis scenario. The sensors are characterized the same as the friendly sensors and are generic in nature. Through operational experience as well as information from open-source literature, the author used different performance parameters for each sensor depending on the parent platform and the contact being sensed.

Table 15. Enemy Order of Battle – Sensors. Source: SEA 27 (2018).

Sensor	Parent Platforms
Visual	All Surface, All Air, All Unmanned
Infrared	Aircraft Carrier, Renhai, Luyang, Jiangkai, Houbei, J-11, J-15, J-16, J-20, Z-18, Z-8AEW
ESM (Electronic Support Measures)	Aircraft Carrier, Renhai, Luyang, Jiangkai, Helicopter Dock, Landing Dock, J-15, J-16, J-16D, J-20, KJ-3000
Air Search Radar	Aircraft Carrier, Renhai, Luyang, Jiangkai, Helicopter Dock, Landing Dock, All Manned Aircraft
	Aircraft Carrier, All Amphibious Assault,

Sensor	Parent Platforms
Surface Search Radar	Renhai, Luyang, Jiangkai, Houbei J-15, J-16, Q-5, H-6K, KJ-3000, Z-18, Z-8AEW
Fire Control Radar	All Surface, J-11, J-15, J-16, J-16D, Q-5, H-6K, Z-18, Z-8AEW
Navigation Radar	All Surface
Phased Array Radar	Aircraft Carrier, Renhai, Luyang, Jiangkai, Jiangdao
AESA (Active Electronic Scanned Array Radar)	Renhai, J-15, J-16, J-16D, J-20, All Unmanned Air
Over the Horizon Radar	Renhai, Luyang, Jiangkai
Synthetic Aperture Radar – Maritime	Aircraft Carrier, Renhai, Luyang, KJ-3000, Y-8FQ, All Land-Based Missiles & Unmanned Air
Synthetic Aperture Radar – Space	Yaogan Satellite

(4) Enemy Missiles

Table 16 shows the different types of enemy missiles with their parent platforms that will be modeled in the simulation of the thesis scenario. Unlike the friendly missiles, the enemy missiles are used solely in an offensive manner due to the nature of the enemy's operational objective of attacking and controlling the Island of Palawan. Similar to the friendly missiles, a wide range of types of missiles were chosen to be modeled. Since the scenario's time horizon is a few decades in the future, one missile that is currently in development – the Very Long Range Air to Air Missile (VLRAAM) – will be considered in the enemy missile OOB as technologically mature.

Table 16. Enemy Order of Battle – Missile. Source: SEA 27 (2018).

Missile	Designator	Type	Launching Platform
Dong-Feng 21	DF-21D	Anti-Ship Ballistic Missile (ASBM)	Land – Mobile Launcher
Dong-Feng 26	DF-26	Anti-Ship Ballistic Missile (ASBM)	Land – Mobile Launcher
Silkworm	HY-2	Anti-Ship Cruise Missile (ASCM)	Land – Mobile Launcher
Eagle Strike-12	YJ-12	Anti-Ship Cruise Missile (ASCM)	Aircraft Carrier, H-6K, Q-5
Eagle Strike-18	YJ-18	Anti-Ship Cruise Missile (ASCM)	Renhai, Luyang, J-15, J-16
Eagle Strike-62	YJ-62	Anti-Ship Cruise Missile (ASCM)	Land – Mobile Launcher, Luyang
Eagle Strike-83	YJ-83	Anti-Ship Cruise Missile (ASCM)	Luyang, Jiangkai, Jiangdao, Houbei, J-15, J-16, Z-18
Eagle Strike-100	YJ-100	Anti-Ship Cruise Missile (ASCM)	Renhai, Luyang, H-6K
Flying Crossbow	FN-16	Man Portable Air Defense (MANPAD) Surface to Air	Jiangdao, Houbei, All Amphibious Assault
Hongqi-16	HQ-10	Surface to Air	Aircraft Carrier, Luyang, Jiangkai, Jiangdao
Hongqi-16	HQ-16	Medium Range Surface to Air	Renhai, Luyang
	CM-102	Anti-Radiation/Anti-Ship	J-16D
Thunderbolt-9	PL-9	Short Range Air to Air Missile	J-11, J-15, J-16, J-16D, J-20
Thunderbolt-12	PL-12	Medium Range Air to Air Missile	J-11, J-15, J-16, J-20
	VLRAAM	Very Long Range Air to Air Missile	J-11, J-15, J-16, J-20

Both the enemy and friendly order of battle have been detailed in the preceding paragraphs. These are all inputs that will be utilized in the modeling and simulation of the DMO scenario, along with the employment of the DMO tactics. The intent in the following

sections is to summarize the model, discuss the assumptions and limitations of the model, and set the stage for the implementation of the unmanned surface vehicles described in Chapter III.

C. MODEL SUMMARY

The purpose of modeling the given scenario is to evaluate the alternative unmanned surface vehicles discussed in Chapter III. By constructing a model, the author is able to examine the appropriate unmanned surface vehicle force structure best suited to the Distributed Maritime Operations concept. ExtendSim, a discrete event simulation (DES) software, was chosen to perform an analysis of USVs in DMO. According to Brailsford (2014), “A DES models queuing systems as they progress through time. In doing so it represents the world as entities that flow through a network of queues and activities” (17). The model used was derived from the original creation of SEA 27’s capstone report (2018) with multiple changes and updates throughout. The model is broken down into four primary phases; the threat generation phase, the finding phase, the targeting phase, and the engagement phase. This is demonstrated by the typical military application of the F2T2EA kill chain, described by Joint Publication 3–60 (JCS 2013). The F2T2EA model is decomposed into the following subtasks: find, fix, track, target, engage, and assess. The SEA 27 report combined these subtasks for simplification and for a more realistic viewpoint, since some of these subtasks are completed near simultaneously as shown in the Figure 22.

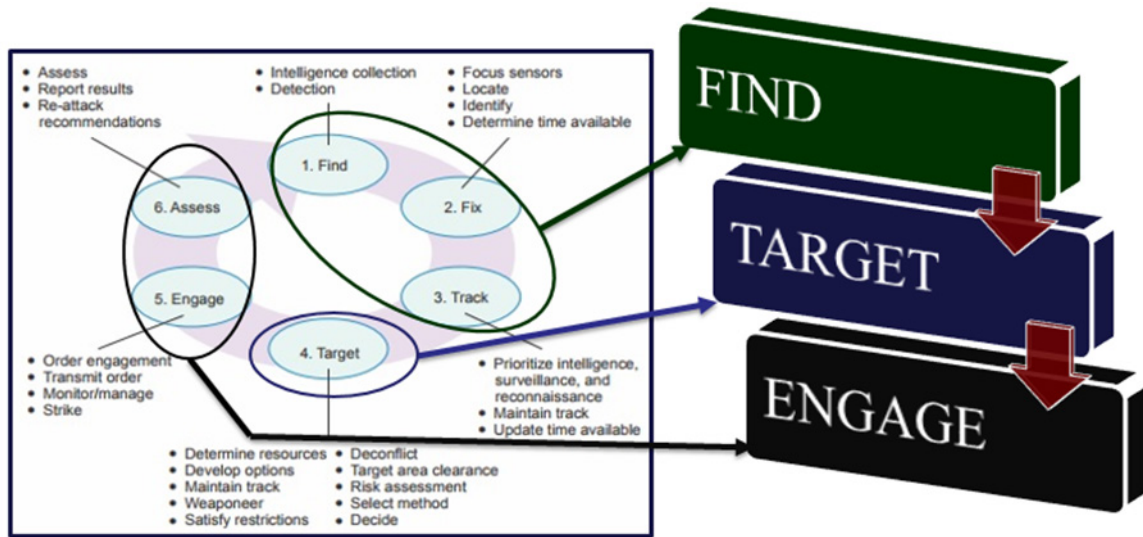


Figure 22. Simplification of the F2Y2EA Kill Chain. Adapted from JCS (2013). Source: SEA 27 (2018).

The Find, Target, Engage (FTE) kill chain is a step-by-step process where the enemy or friendly platform finds a potential contact (which entails fixing and tracking the contact), acquires a targeting solution on the contact (depending on sensor performance), and ultimately engages the contact with a salvo of missiles and assesses the damage inflicted. This kill chain is a systematic process that can be easily disrupted since any one deficiency in the chain will interrupt the entire process.

Phase one of the model introduces the threat generation, which consists of the creation of enemy platforms, the mission assignment and pairing of contacts, the clutter attributed to maritime traffic and potential contacts, as well as environmental effects on the enemy's sensors. Phases two through four of the model illustrate the enemy's FTE kill chain, with friendly forces trying to disrupt, deceive, confuse or destroy the enemy's kill chain before it resolves into a successful engagement. In the pursuit of the operational objective of protecting the Island of Palawan, the intention behind incorporating the DMO concept into the scenario is three-fold: (1) employing tactics, (2) counter-targeting, and lastly (3) counter-engaging the enemy throughout their kill chain.

The employment of tactics, as mentioned briefly in Chapter 2 of this thesis, is addressed in depth in the SEA 27 (2018) capstone report Chapter 4, Section C. The four

primary DMO tactics – emission control, physical and mechanical measures, swarm, and jamming – are implemented throughout all the phases, whereas the counter-targeting and counter-engaging only occur at the targeting phase (phase three) and engagement phase (phase four), respectively.

Each function of the model will be summarized in the following paragraphs and derives from the detailed description in the SEA 27 (2018) capstone report in chapter 4, section 1. Figure 23 depicts a summarized graphic of the model and lists each function as mentioned previously.

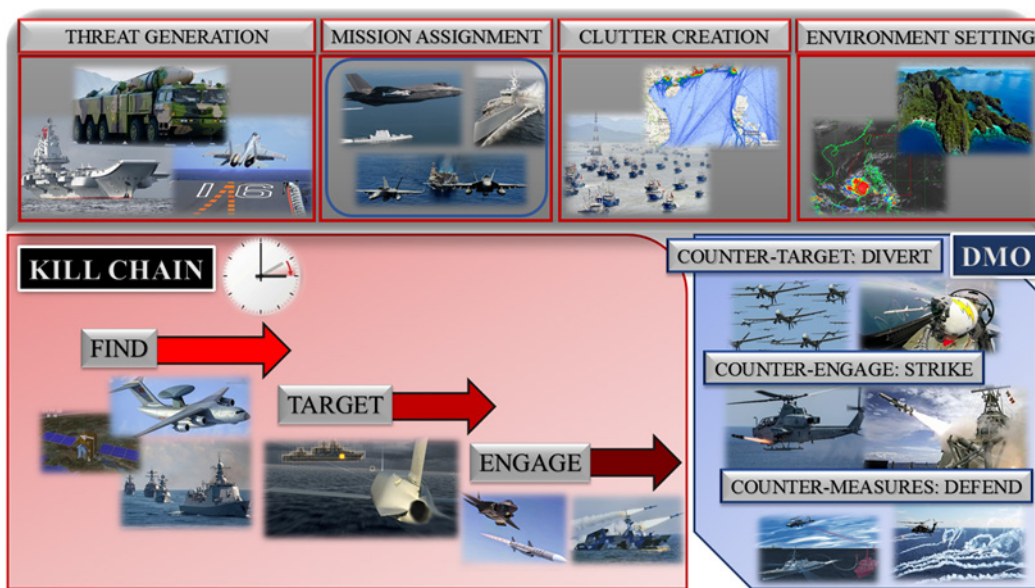


Figure 23. Primary Functions of the DMO Model. Source: SEA 27 (2018).

(1) Threat Generation

The enemy OOB is created at the start of the simulation. The number of surface platforms, air platforms, and land-based missiles add to 149 unique entities, which distributes into approximately 29% surface platforms, 55% air platforms, and 16% land-based missiles. Chapter 5, Table 26 references the specific Enemy OOB numbers. The 149 enemy assets remain constant for every simulation and are given specific attributes that are written in a database labeled “Threat” in the ExtendSim software. This database provides

specific characteristics of each enemy platform, including sensor type, missile type and quantity, and velocity of platform. The enemy platforms also are given an initial range from Palawan, based on platform type and a normal distribution. This gives the model a more realistic scenario where the enemy platforms do not all start from the same location or distance from friendly assets.

(2) Mission Assignment

The enemy platforms are then cycled through a queue to be assigned a friendly platform to find, target and engage. The assignment process is probabilistic in nature and depends on three main factors. (1) Does the enemy have the correct ordnance to destroy the desired target? For example, if the enemy platform has only air-to-air missiles, then it will not target a friendly surface platform. (2) Does the friendly platform actually exist in the given run? This thesis analyzes the operational effectiveness of unmanned surface vehicles; therefore, the design of experiments will focus on changing the USV force structure while all other friendly platforms remain constant. For example, if an enemy platform is assigned a USV SUW and that platform does not exist in that applicable run, then the enemy goes through a reassignment process. Chapter 5 will address the details of the design of experiments. Lastly, (3) how long has the enemy been trying to find the assigned target? If the time lapse in the finding phase is greater than 75% of the allowable time the enemy platform is in the model, then the enemy is reassigned a new friendly platform. To note, once assigned a platform, the enemy will not deviate from its mission assignment even if they “find” other friendly platforms.

A multicriteria scoring model determined the probabilities of assignment. Ragsdale (2015) states that “[t]he multicriteria scoring model is a simple procedure in which we score (or rate) each alternative in a decision problem based on each criterion...Weights are assigned to each criterion indicating its relative importance to the decision maker. For each alternative, we then compute a weighted average score” (783). The scoring model considered the combat power and sensor reach of each of the friendly platforms and gave a representative score for each. These two factors were then weighted, and the average score was calculated for each platform. This approach ensured that each platform was

compared to the same scoring matrix, allowing for a systematic prioritization of the friendly assets available for the enemy to target. The combat power factor considered the ordnance inherent to the platform as well as the organic assets attached to the platform, whereas the sensor reach factor considered the maximum range of sensors, network capability, and operational range of the platform. Combat Power was given a weight of 60%, whereas sensor reach was given a weight of 40%. This was chosen to represent the prioritization of the enemy targeting the more offensively capable platforms. Appendix D details the scoring matrix and the applicable data.

The process of assignment then continues using the applicable scores from the scoring model for each friendly platform. The following is an example of how friendly platforms are given a probability of assignment: if a specific enemy platform is only able to be assigned a surface platform, then the sum of the scores of the friendly surface platforms become the denominator and each individual surface platform score becomes the numerator. It turned out that the friendly CVN and LHA/LHD had the highest weighted score amongst the available friendly platforms. This directly corresponds to reality since these are both considered “high value units” and crippling these assets would leave a devastating impact to our strategic and tactical objectives. Retired U.S. Navy Captain Bernard Cole (2010), in his book *The Great Wall at Sea*, states that “Chinese analysts and strategists consider the aircraft carrier as the center of gravity of the U.S. potential...and have made explicit anti-aircraft carrier doctrine that employ anti-ship ballistic and long-range cruise missiles for carrier mission kills” (148-149). In the mission assignment process most of the enemy platforms have high probabilities to find both the CVN and LHA/LHD, and the land-based enemy missiles, specifically the DF-21 and DF-26, are assigned only to these two friendly platforms.

(3) Clutter Creation

Clutter is defined as “stuff” that the enemy has to filter through during the finding phase of its assigned friendly platform. Clutter is modeled in three different ways, and each factor has variability causing each run to have different input data. First, the model takes into consideration the maritime and commercial airline traffic that typically transits through

the region. This is given by a random variable normally distributed between 55–75 contacts. This range was determined using the annual average of Automatic Identification System (AIS) tracks during a three hour time interval that traveled through the SCS region (Marine Vessel Traffic 2018) and can be referenced in Appendix E. Clutter also considers friendly platforms that the enemy is not assigned to destroy; meaning that if an enemy platform has a E-2D mission assignment, it has to filter through all the “clutter,” including commercial air traffic and friendly platform aircraft. Lastly, one of the DMO tactics contributes to the clutter factor in the model. Passive and active decoys, subfunctions of the Physical and Mechanical countermeasures, play a role in causing more potential targets that the enemy needs to filter through until finding its pre-determined assigned friendly platform.

(4) Environment Setting

Weather can greatly affect sea state as well as radar performance for both enemy and friendly platforms. The climate of Western Palawan and its surrounding seas is relatively calm for six months, while the other six months have torrential rain, and the South China Sea region has seasonal monsoons and typhoons that typically occur during the summer months. The typical visibility ranges from five miles to ten miles off the Northern Coast of Palawan (World Weather 2018). The effects of weather are modeled by randomly attributing a degradation factor to all sensors, ranging from 30% degradation (typical storm and rain effects) to no degradation (negligible cloud cover and rains), which impairs every platform’s ability to find, target and engage for each run in the simulation. The details for the environmental factors can be referenced in Appendix E.

(5) Kill Chain

As previously mentioned, the kill chain series of functions is impersonating the enemy’s FTE Kill Chain. Of note, the enemy has a number of ways of finding its designated target: using multiple radars, using electronic support measures (ESM), and visually acquiring the target either by infrared or the naked eye. Prior to each enemy platform starting their kill chain against their assigned target, a number of degradation factors are calculated that affect the find phase and target phase. The model uses built-in databases to

determine the degradation factors by referencing if any of the friendly platforms on that specific run are in EMCON A (the most restrictive emission control that permits zero promulgating of any electromagnetics) and if any of the jamming tactics are being employed. If any of these DMO tactics are being employed, there could either be a positive or negative impact for the friendly forces. For example, if any of the jamming tactics are employed, which specifically targets the enemy's radar, the electromagnetic signature of the friendly platform dramatically increases, elevating the risk of being found due to ESM used by the enemy. This potentially allows the enemy to have a higher probability of finding or targeting the friendly platform. However, if the jamming is very effective against the enemy's radar, then the radar degradation factor could significantly increase, causing the enemy to have a lower probability of finding or targeting the friendly platform using its radars. These input variables change during each run, allowing the author to determine if any of these tactics are significant in regard to the measures of effectiveness, which will be addressed in Chapter 5.

(a) Find Phase

The find phase consists of each enemy platform running through a sequence of subfunctions to determine if it finds its desired mission assignment. The two main factors that determine if the enemy will find its target are its sensor reach (the range of its sensors) and its radar performance parameter characterized as the probability of find (P_{find}). The P_{find} is referenced in one of the model's databases and is specific per pairing of enemy platform to friendly platform for every unique sensor as depicted in Table 15. The author used open source data and operational experience to determine the P_{find} for the generic sensors modeled. Friendly platform radar cross section (RCS), electromagnetic shielding, and infrared radiation were also considered in this process, as illustrated in the following example: the friendly CVN has a higher probability of being found across all enemy sensors due to its large RCS, whereas the new DDG-1000 has a lower probability of being found due to the technological advancement in reduced RCS as well as the implementation of electromagnetic shielding. An example of the probability of finding a CVN is annotated in Appendix C.

As mentioned previously, the enemy's Pfind can be degraded by either using jamming tactics or emission control tactics. The model also considers a unique factor deemed Area of Uncertainty (AOU). The AOU factor is only applicable in the find phase and demonstrates the friendly platform's speed of advance as the enemy platform reduces its distance between its assigned target. The AOU of a specific target increases as the enemy searches for it and is calculated by multiplying the speed of the friendly platform by the time the enemy takes looking for it. The longer it takes to find, the greater the AOU of the friendly platform. The model has implemented AOU levels that, once reached, will increase the degradation factor and decrease the probability of finding the friendly platform.

Once the enemy runs once through the find phase, it either will find its assigned target and move to the next step in the kill chain or will restart the finding process. Of note, each iteration of the find phase increases the AOU of the assigned target, but also decreases the clutter that the enemy must filter through to find its mission assignment.

(b) Target Phase

The target phase consists of a similar process as the find phase, except instead of using Pfind, the model extracts a probability of target (P_{target}) from a unique enemy sensor performance database per enemy platform. Degradation factors still influence the enemy's sensors; these include the environmental settings factor, the radar degradation factor from jamming tactics, as well as the ESM degradation factor from emission control (a list of degradation factors for jamming can be found in Appendix F). Therefore, the enemy's P_{target} can be significantly reduced from its original value, causing the enemy to take a much longer time acquiring a targeting solution. This phase runs through many iterations until the enemy either successfully targets and moves on to the next step in its kill chain or fails to target and is either counter-targeted or exits the model.

This is the first phase that introduces a counter-offensive posture from the friendly forces. As the enemy is inbound to its designated contact, friendly forces have multiple opportunities to counter-target, especially if the enemy has been delayed in any way. Counter-targeting is the ability to take action prior to an adversary missile launch to prevent

friendly forces from being targets or being engaged. One of the major assumptions of this model and thesis is that friendly forces are all networked within the same common operating picture. This allows for forces to be distributed, yet still share the essential information and resources, such as targeting solutions and ordnance. For example, if the USV ISR is able to find and target an enemy aircraft, it is able to relay the targeting data to a missile carrier, like a destroyer, which is able to fire an assortment of anti-air missiles to intercept the inbound enemy aircraft. Figure 11, in Chapter 2, illustrated a similar scenario.

Modeling the concept of shared resources and information was developed by making a resource pool of friendly missiles available at the start of each run scenario. The model adds the payloads of each friendly platform brought to the fight and creates a dynamic pool of the missiles listed in Table 16. If any of the friendly platforms are in EMCON Alpha, their missiles do not count towards the resource pool and cannot be used throughout the scenario. The missiles are then reduced from the pool as friendly forces counter-target or counter-engage the enemy. The listed missiles have different operational ranges; therefore, the limiting factor for counter-targeting the enemy is not the range of any specific friendly sensor, but the range of the missile being employed. Each friendly missile also has a probability of hit (Phit) and a specified salvo quantity that is fired per engagement. During the targeting phase, the friendly forces determine the current range of the inbound enemy and apply the most effective missiles that are available from the resource pool. Hence, if the resource pool has exhausted all standard missiles, an enemy aircraft will be able to approach undeterred until friendly forces use a missile that can meet the operational range requirement.

(c) Engage Phase

The engagement phase starts once the enemy has successfully targeted its assigned contact. The enemy platform immediately employs a specified salvo and turns outbound to its original point of origin at the start of the scenario. This begins the counter-engagement phase for friendly forces. Whatever friendly missiles were fired during the counter-targeting phase still apply and have an opportunity to hit outbound enemy targets.

However, friendly forces shift to a more defensive posture after the release of enemy missiles. Each enemy missile is a discrete entity that needs to be dealt with accordingly. For example, if the Houbei fires four ASCMs toward a friendly CVN, each ASCM needs to be counter-engaged with friendly missiles.

Each enemy missile, listed in Table 16, has a specific terminal guidance as well as a probability of hit (Phit) that is referenced from one of the model's databases. As the enemy missile approaches the designated target, friendly forces may have multiple opportunities to counter-engage with missiles just like the counter-targeting phase, however, once the enemy missile is within 10 nautical miles of its target, the friendly forces shift to using countermeasures. Countermeasures that are designed in this model are a last resort option when all counter-targeting and counter-engaging efforts fail. Similar to the missile resource pool, friendly forces have a distributed countermeasure pool from which to pull, allowing dissimilar platforms to help defend against inbound missiles. Countermeasures were created to illustrate one of the four DMO tactics. The countermeasures are a design of experiments for this thesis, therefore quantities change run by run. The modeled countermeasures were chaff, flares, active decoys, and infrared smoke and visual smoke. These countermeasures are employed based on the specifications of the enemy's missile terminal guidance and have their own probability of counter-engaging the inbound missile.

Pending on whether the enemy missiles are successful in avoiding any counter-engagement, a one-time Phit is used to determine if the friendly platform is successfully hit. For this model, a successful hit is quantified as a mission kill. A few things take place when this occurs: (1) it counts toward a "killed" friendly platform in the output database, (2) it reduces the missile resource pool by a random factor of what that specific friendly platform brought in terms of friendly missiles (this simulates a real life situation where if a friendly platform is hit by a missile, it does not necessarily mean that they cannot continue fighting), and (3) the enemy missile is removed from the model. If the first of four missiles from the salvo of 4 ASCMs, as described earlier in the Houbei versus CVN scenario, hits the friendly platform, the remaining three missiles will still engage the CVN. However, this doesn't count for multiple "kills" in the output database. Once the CVN is hit, it is

considered “killed” whether or not it is hit multiple times or is assigned by multiple enemy platforms.

D. MODEL LIMITATIONS AND ASSUMPTIONS

The goal of the model was to simulate a balanced fleet-on-fleet engagement between a near-peer adversary in the context of the DMO concept with the implementation of new unmanned surface vehicles. Every model has to be bounded and given direction to receive the desired effects of the simulation; with that comes many assumptions that the author had to consider while reorienting SEA 27’s baseline model. Assumptions had to be made to simplify the complexity of the scenario, but not to the degree of restricting the simulation to a realistic operating condition. This facilitated the gathering of insights as to how operationally effective unmanned surface vehicles could be in the context of a Distributed Maritime Operation.

Table 17 lists the primary assumptions with the justification as well as the incurred limitations of the model. The author also annotates if the assumption is advantageous for either the enemy or friendly forces.

Table 17. Assumptions and Limitations of the Model. Adapted from SEA 27 (2018).

Assumption	Reason	Limitation	Advantage
Each scenario engagement was approximately three hours long.	Determined as a function of the slowest moving platform in the enemy OOB.	The model is effectively examining only the initial round of engagements.	Neutral.
Friendly forces are assumed to have a network established for shared offensive strike capabilities and shared defensive capabilities.	Since this thesis is focused on the DMO concept, it was assumed that all friendly forces would be able to be distributed yet share the common operating picture.	This is not necessarily true in the current fleet. Friendly platforms have different datalink and communication suites that do not have perfect information.	Advantageous to friendly forces since every one-on-one engagement is actually the enemy versus the entire arsenal of friendly forces ordnance.

Assumption	Reason	Limitation	Advantage
Enemy platforms are assumed to operate independently with no shared detection or targeting information	The model was created in such a way that it only simulates discrete one on one engagements and does not allow multiple simultaneous attacks.	In a real life scenario, the enemy would have a common operating picture allowing the decision maker to use common judgment of mission assignment and strategy.	Advantageous for friendly forces since the enemy is not communicating other known targets in the find and targeting phase.
The enemy's best inherent sensor is assumed operational and able to be employed against friendly assets	For simplicity sake, all enemies were modeled with the best available generic sensor that is common for the given platform.	All similar radars were modeled the same way, for example: The phased array radar on the Renhai class destroyer was modeled the same as the phased array radar onboard the Luyang III destroyer. In actuality, the Luyang has a lower performing radar, yet it is modeled with the equivalent of a Renhai.	Advantageous for the enemy since the scenario is assuming that each platform has an operationally perfect radar.
The model does not consider logistical operations.	Since the model is only covering a short time period, the logistical side of the fight is assumed to take place after the initial engagements.	This is a limitation to the model in two ways: (1) it does not consider the military sealift command platforms as potential targets, and (2) It assumes that all platforms in the AOR are	Neutral.

Assumption	Reason	Limitation	Advantage
		initially refueled and rearmed.	
The employment of decoys serves only as additional clutter for enemy forces	The model only considers decoys as additional contacts, which potentially influence the enemy to allocate unnecessary resources to “fake contacts.”	Decoys are not modeled as resources that cause confusion, which does not reflect a real life scenario.	Advantageous to enemy forces since the friendly force’s capabilities are limited.
When jamming tactics are used, the model assumes friendly forces have knowledge of enemy operating frequencies. In addition, jamming tactics impact all enemy threats simultaneously.	For simplicity sake, the model was created to assume that when using jamming that the user’s not all know the frequency to jam but also that it’s effective against all enemy platforms that operate within that specific frequency.	This over simplifies the jamming tactics by not considering the size and power requirements for jamming equipment as well as not considering the anti-jamming techniques that the enemy could use in this given situation.	Advantageous to friendly forces.
Enemy forces do not employ counter targeting, counter engaging, nor countermeasure tactics throughout the model.	The model only considers the initial wave of enemy engagements with the focus on the offensive.	The enemy has the same capabilities as friendly forces when it comes to defensive tactics. This is not considered in the model, which limits the realism of the scenario.	Advantageous to friendly forces.

Assumption	Reason	Limitation	Advantage
Each friendly force countermeasure is considered only effective against one type of enemy missile terminal guidance.	This was modeled for simplification sake. The model considered Chaff, Flares, IR Smoke, Visual smoke, and active/passive decoys. Each impacting only one type of inbound missile.	This impacts the friendly forces by potentially exhausting all available friendly counter-measures as a function of enemy missile quantity and type.	Advantageous to enemy forces.
The model does not include undersea or cyber domains.	The author's expertise is in the areas of surface and air domains. For this reason, domains that were not well understood were excluded from the model.	This limits the diversity of capabilities that both the enemy and friendly platforms bring to the scenario.	Neutral.
The model does not include close-in weapon systems, like CIWS, to defend from inbound enemy missiles.	One of the goals of DMO is to employ specific tactics to deter, distract or destroy the enemy. If an enemy missile comes within 10 nautical miles of any friendly platform the specified countermeasures are used to disrupt the enemy missile.	This limits the realism of an actual engagement. All capable friendly forces would use their close-in weapon systems as well as all other measures to defend themselves.	Advantageous to enemy forces since friendly forces are not using one of their primary means of anti-missile defense.

Assumption	Reason	Limitation	Advantage
When implementing the USV ISR Platform, the model considered it as a binary variable; either on or off.	The binary variable was used for simplification and allowed the author to easily determine if the factor was significant.	This assumption assumes that one USV ISR platform provides perfect information to all friendly forces in the scenario. In actuality, multiple platforms would need to be distributed throughout the AOR to provide this information.	Advantageous to friendly forces due to optimistic nature of only one USV ISR platform providing the ISR capability.

In the following section the author annotates the significant changes that were made to the SEA 27 model as well as a few hypothesis' that were determined before the analysis of the output data discussed in Chapter 5.

E. IMPLEMENTATION OF USVS IN OPERATIONAL SIMULATION

The inherent structure of the SEA 27 model remained the same as described by Figure 23: Primary Functions of the DMO Model. Changes were made throughout the model to improve or fix written code, add different capabilities, and implement USV platforms in the friendly OOB. The biggest change was the four platforms that were added and their applicable capabilities: USV ISR, USV SUW, USV AMD AIR, and USV AMD MISSILE platforms. These represent the three alternative mission package designs described in Chapter III, with the USV AMD split into two unique platforms: AIR and MISSILE; these configurations are meant to defend against air platforms and incoming missiles, respectively.

All alternative USVs brought additional countermeasures to the friendly OOB, including chaff, active and passive decoys, flares, and IR and visual smoke. This allowed for more defensive capability when inbound enemy missiles approached within 10 nautical miles. The missile carrying USVs also brought their specific payloads, as annotated in Chapter III, which provided additional ordnance in the distributed resource pool described

in the model summary. However, the author believes that one of the most significant changes was the implementation of the USV ISR platform. The USV ISR provided a capability unique to the rest of the new platforms. This platform's capability was added during the enemy's targeting and engagement phase and allows every potential friendly missile an extended range to hit incoming enemy platforms or missiles. The USV ISR platform does not replace the already existing E-2D capability of an extended range of networks, communication and common operating picture, but adds additional "eyes and ears" in the maritime arena. The model takes this into consideration when either the E-2D or USV ISR platform are present and adds additional capability when both are present in the model. Appendix G shows the specifics of the extended ranges that both the E-2D and USV ISR platform bring per friendly missile type.

Another significant change was the overly optimistic effectiveness of any jamming technique. Both the SEA 27 team and the author realized that the jamming assumptions were too advantageous to friendly forces, therefore, the model reflects a more conservative jamming tactics approach. The assumptions still remain that jamming is effective against all applicable enemy sensors and that friendly forces have knowledge of what frequency the enemy is operating with, but the degradation factor is significantly decreased, making jamming tactics not as effective when compared to the operational analysis conducted by SEA 27. Other changes throughout the model included the change in mission assignment probabilities for the enemy forces being assigned a friendly platform, the effectiveness of countermeasures in the counter-engagement phase, the effectiveness of enemy missiles and their terminal guidance, and added EMCON capable platforms to include all the new USV platforms as well as the CVN and LHA/LHD.

The author believes that the USV ISR platform as well as the contribution of multiple missile carrying USV platforms will significantly impact the operational effectiveness of friendly forces in the context of the DMO concept, specifically in regard to the survivability of friendly forces, the survivability of enemy forces, as well as the offensive and defensive posture of the U.S. Navy's maritime assets. The following chapter will first address the specific MOEs of this thesis, secondly, the design of experiments for

the input data to the model, and lastly the analysis of the operational effectiveness of the USVs implemented into DMO.

V. DATA ANALYSIS

The arranged sections will develop how the author measured operational effectiveness in the context of unmanned surface vehicles as well as introduce the creation of the design of experiments that the model implements. The data analysis will address each individual MOE and how unmanned surface vehicles performed throughout the simulation. In Chapter 6 a simplified cost analysis versus operational effectiveness is discussed and will conclude with a summary of findings and recommendations for future work.

A. MEASURES OF EFFECTIVENESS

Six principal measures of effectiveness were evaluated using three alternative Unmanned Surface Vehicles implemented into the DMO scenario. The thesis' MOEs serve to measure how operationally effective the USVs are in the context of the DMO concept. The author identified quantifiable measures that could be collected from the model and analyzed to determine the level of success that each alternative brings and what compositions of USV ISR, USV SUW and USV AMD platforms are key enablers in the DMO force structure of the future CSGs, ESGs and SAGs. The subsequent paragraphs develop the specific MOEs and discuss the evaluations of each.

1. MOE #1: Surviving Friendly Forces

One of the key metrics in determining the overall operational success in any engagement is to look at what was brought into the fight, and what came out unscathed. Retired Navy Captain Hughes, in his book *Fleet Tactics and Coastal Combat*, states that “success is measured in ship casualties and a comparison of the numbers put out of action on both sides” (Hughes 1999, 8). The mathematical representation can be shown as the ratio of surviving friendly forces to the initial quantity of friendly forces at the beginning of the engagement. This was easily collected from the model by creating a formula using the Blue Quantity database. Of note, taking the percentage of surviving friendly forces does not necessarily tell the whole story; additional metrics to consider when determining operational success was calculating the percentage of specific platforms that survived, like

high value units, missile carrying platforms, aircraft and USVs. Table 18 shows the formulas that computed this MOE.

Table 18. MOE #1 Metrics. Adapted from SEA 27 (2018).

MOE #1: Surviving Friendly Forces	
Percentage _{Surviving Friendly Forces}	$= \frac{\text{Quantity of Friendly Forces surviving at end of simulation}}{\text{Quantity of initial Friendly Forces}}$
Percentage _{Surviving High Value Units}	$= \frac{\text{Quantity of High Value Units surviving at end of simulation}}{\text{Quantity of initial High Value Units}}$
Percentage _{Surviving Missile Carrying Platforms}	$= \frac{\text{Quantity of Missile Carrying Platforms surviving at end of simulation}}{\text{Quantity of initial Missile Carrying Platforms}}$
Percentage _{Surviving Aircraft}	$= \frac{\text{Quantity of Aircraft surviving at end of simulation}}{\text{Quantity of initial Aircraft}}$
Percentage _{Surviving USVs}	$= \frac{\text{Quantity of USVs surviving at end of simulation}}{\text{Quantity of initial USVs}}$

2. MOE #2: Surviving Enemy Forces

Not only is the percentage of surviving friendly forces key to determining the operational success of the engagement, but so is taking into consideration what the friendly forces destroyed in the context of enemy forces. MOE #2 considers the number of enemy forces remaining at the end of the engagement. The mathematical representation can be shown as the ratio of surviving enemy forces to the initial enemy forces at the beginning of the engagement. Table 19 shows the formula that computed this MOE.

Table 19. MOE #2 Metrics. Adapted from SEA 27 (2018).

MOE #2: Surviving Enemy Forces	
Percentage	$\text{Remaining Enemy Forces} = \frac{\text{Quantity of Enemy Forces remaining at end of simulation}}{\text{Quantity of total Enemy Forces}}$

Since this scenario focused on the defense of the Island of Palawan, the additional metrics, similar to MOE #1, to determine specific enemy platforms' survivability were neglected. When considering operational success, the only metric in regards to percentage of surviving enemy forces is the cumulative aspect, not the specific type of platform. Friendly forces are not actively on the offensive and are not concerned with destroying specific enemy platforms, but rather with defending their national assets and providing support for their allied nation.

3. MOE #3: Percentage of Enemy Missiles Destroyed

One of the primary roles of the USV AMD is to provide a layered defense for friendly forces' high value units by intercepting inbound enemy missiles and platforms. A metric that can easily be determined for operational success is the number of inbound enemy missiles destroyed throughout the engagement. MOE #3 considers the ratio of the number of successful enemy missiles countered to the quantity of total enemy missiles fired. An enemy missile can only be created in the model once the enemy has successfully completed its targeting phase in the kill chain and has engaged its designated target by releasing a salvo of missiles. A countered enemy missile is when a friendly force missile or countermeasure has successfully deterred, distracted, disrupted or destroyed the inbound enemy missile. Table 20 shows the formula that computed this MOE.

Table 20. MOE #3 Metrics. Adapted from SEA 27 (2018).

MOE #3: Percentage of Enemy Missiles Destroyed	
Percentage _{Enemy Missiles Destroyed}	$= \frac{\text{Quantity of Successful Enemy Missiles Countered}}{\text{Quantity of total Enemy Missiles}}$

4. MOE #4: Percentage of Enemy Missiles within 10 Nautical Miles

Another metric that was considered when determining the operational effectiveness of unmanned surface vehicles was the percentage of enemy missiles that made it within 10 nautical miles of friendly forces. MOE #4 is another way of measuring the effectiveness of the friendly forces' anti-missile defense, similar to MOE #3. This MOE provides insight into the ability of the friendly forces to counter-engage enemy missiles with their own missiles before they shift to using only counter measures. If an enemy missile passes the threshold of 10 nautical miles within the friendly forces' layered defense, the friendly forces will then counter only with the applicable countermeasures as described in Chapter 4 in the model assumptions and limitations. The mathematical representation can be shown as the ratio of enemy missiles within 10 nautical miles to the total quantity of enemy missiles fired throughout the engagement. Table 21 shows the formula that computed this MOE.

Table 21. MOE #4 Metrics. Adapted from SEA 27 (2018).

MOE #4: Percentage of Enemy Missiles within 10 Nautical Miles	
Percentage _{Red Missiles in 10 NM Range}	$= \frac{\text{Quantity Enemy Missiles within 10 NM range}}{\text{Quantity of total Enemy Missiles}}$

5. MOE #5: Offensive Strike Success

As previously described in Chapter 4, friendly forces have two distinct opportunities to strike offensively: (1) during the enemy's targeting phase, and (2) during the enemy's engaging phase. For this thesis, offensive strike is described as engaging an enemy platform during the targeting and engaging phases of the enemy's kill chain, whereas defensive measures are engaging an inbound enemy missile after the enemy has successfully completed its kill chain. An offensive strike success is the successful "hit" of an enemy platform with friendly forces' missiles. A "hit" does not necessarily mean a destroyed enemy platform, but for the confines of this thesis it counts as a successful offensive strike. The mathematical representation of this metric is the ratio between the quantity of successful friendly offensive missile "hits" to the quantity of friendly missiles fired at enemy platforms. Table 22 shows the formula that computes this MOE.

Table 22. MOE #5 Metrics. Adapted from SEA 27 (2018).

MOE #5: Offensive Strike Success	
Percentage	$\frac{\text{Quantity of successful Friendly offensive missiles}}{\text{Quantity of Friendly missiles engaging Enemy platforms}}$

6. MOE #6: Defensive Measure Success

The last metric is very similar to MOE #5 except that it is only considering the defensive measure successes. Once an enemy platform has fired a salvo of missiles toward their designated target, friendly forces have two options based on the model design logic: (1) continue attacking the outbound enemy platform, or (2) counter-engage the inbound enemy missiles. For a successful defensive measure, the inbound enemy missile has to be deterred, distracted, or destroyed by either friendly forces' missiles or countermeasures. The mathematical representation of this metric is the ratio of the quantity of successful friendly defensive measures to the quantity of total defensive measures expended (chaff,

flares, smoke, etc.) throughout the scenario. Table 23 shows the formula that computed this MOE.

Table 23. MOE #6 Metrics. Adapted from SEA 27 (2018).

MOE #6: Defensive Measure Success	
Percentage	$\text{Successful Defensive Measures} = \frac{\text{Quantity of successful Defensive Measures}}{\text{Quantity of Total Defensive Measures Expended}}$

B. DESIGN OF EXPERIMENTS

A design of experiments (DOE) was created to facilitate an analysis of the impact that each input variable, in terms of USV and friendly force configuration, had on operational effectiveness, as defined by the aforementioned MOEs. This thesis took all the input variables, whether continuous or discrete, and created a nearly orthogonal balanced (NOB) design for the DOE. The NOB design facilitates a well-balanced DOE that accounts for the full spectrum of potential combinations that the input variables could fill, as well as minimizes the correlation between the input variables. Since simulating every known combination of variables is time consuming, the creation of the DOE allows for a representative sample of the solution space. Vieira (2012) describes that “nearly orthogonal means that the maximum absolute pairwise correlation between any two design columns is minimal,” and “nearly balanced means that for any single factor column, the number of occurrences of each distinct factor level is nearly equal.” Vieira’s 512 datapoint spreadsheet was used to create the DOE, and the model ran 30 replications of the 512 datapoints (totaling 15,360 datapoints), which were used in the data analysis portion of this chapter. Utilizing the 30 replications accounted for the impact of variability throughout the model.

Model output was analyzed to determine the operational effectiveness of the alternative USVs in the construct of the DMO concept. To accomplish this, the author designed a fixed baseline force structure consisting of one CSG, one ESG, and a mixture

of independent friendly force platforms to make up a generic force structure called a SAG, as well as changed input variables (according to the experimental design strategy) that could potentially affect the outcome of the engagement. The baseline composition, shown in Table 24, is the author's opinion of a force structure commonly available within 72 hours of a warning order for the specified region. The summary of input variables, shown in Table 25, is a combination of the alternative USVs addressed in Chapter III, the operational velocity of those USVs, as well as the four primary DMO tactics previously summarized in Chapter 2 and detailed in the SEA 27 Capstone report. The four primary DMO tactics were chosen to remain in the DOE due to the fact that all the alternative USVs contribute to the tactics in some way. For example: all alternative USVs have a number of countermeasures (physical and mechanical measures), have the ability to control electromagnetic emission (EMCON), have the capability of performing Electronic Warfare (Jamming), and are able to conduct military deception, which was the primary objective of the SWARM tactic in the SEA 27 report.

Table 24. Baseline Fixed Force Structure. Adapted from SEA 27 (2018).

Carrier Strike Group (CSG)		Expeditionary Strike Group (ESG)		Independent Units	
1	CVN	1	LHA/LHD	1	DDG-1000
2	CG	2	LPD	2	DDG-51
2	DDG-51	1	DDG-51	2	LCS
1	LCS	2	LCS	3	P-8 MPRA
12	F-35 (Air)	4	F-35 (Air)	2	MH-60 R/S
12	F-35 (Surface)	4	F-35 (Surface)	6	MQ-8
6	F/A-18 (Air)	4	MH-60 R/S	4	MQ-9
6	F/A-18 (Surface)	6	AH-1	2	MQ-4
6	EA-18	2	MQ-8	12	TERN
1	E-2D	2	MQ-9		
4	MH-60 R/S	4	TERN		
2	MQ-8				
2	MQ-9				
4	TERN				

Table 25. Summary of Input Variables. Adapted from SEA 27 (2018).

Alternative USVs and DMO Tactics			
Variable	Minimum	Maximum	Type
USV ISR	0	1	Discrete
USV SUW	0	25	Continuous
USV AMD A	0	25	Continuous
USV AMD M	0	25	Continuous
Velocity	0.005	0.02	Continuous
Swarm	0	1	Discrete
Chaff	0	200	Continuous
Flares	0	50	Continuous
Visual Smoke	0	50	Continuous
IR Smoke	0	50	Continuous
Active Decoys	0	25	Continuous
Passive Decoys	0	300	Continuous
Spot Jamming	0	1	Discrete
Barrage Jamming	0	1	Discrete
Sweep Jamming	0	1	Discrete
DRFM Jamming	0	1	Discrete
GPS Jamming	0	1	Discrete
CG EMCON	0	1	Discrete
DDG-51 EMCON	0	1	Discrete
DDG-1000 EMCON	0	1	Discrete
CVN EMCON	0	1	Discrete
LHA/LHD EMCON	0	1	Discrete
USV ISR EMCON	0	1	Discrete
USV SUW EMCON	0	1	Discrete
USV AMD A EMCON	0	1	Discrete
USV AMD M EMCON	0	1	Discrete

Figure 24 depicts a selection of the DOE input variables; this is called a Scatterplot Matrix and it demonstrates the space-filling properties of the experimental design. Each square presents a two dimensional projection of the design space, where each black dot corresponds to a single system configuration. Note that each projection is nearly completely covered by an even dispersion of dots, suggesting that the design space is well filled. To note, in the example depicted in Figure 24, the USV ISR platform took the

discrete quantity of either 0 or 1; therefore, the space-filling effect looks different from the variables that are continuous in nature.

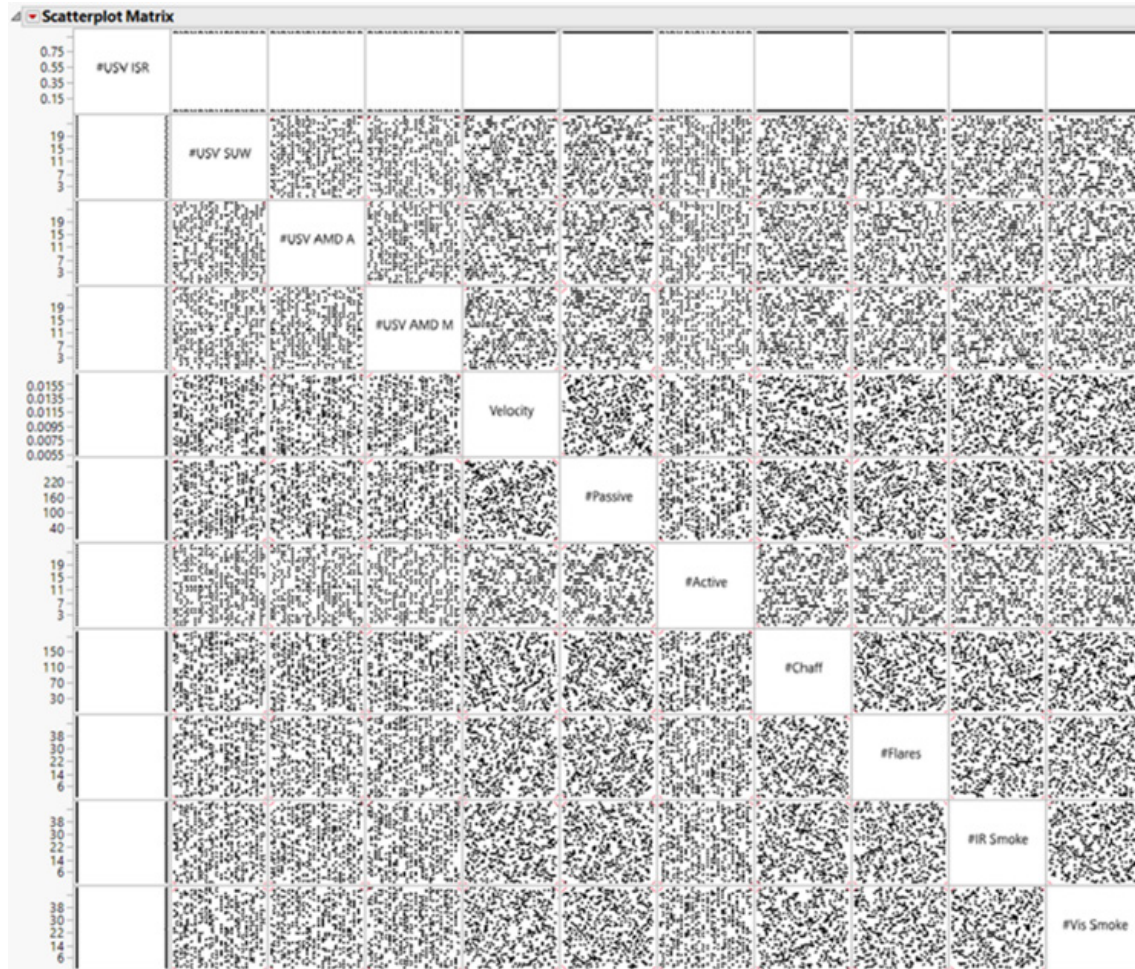


Figure 24. Input Variable Multivariate Scatterplot

Figure 25 shows the correlations between each of the input variables. The correlation of the variables is the quantity measuring the extent of their interdependence amongst each other. The objective is to have every input variable as independent as possible; this thesis had no correlation amongst variables with a quantity greater than .08. This in turn allowed unbiased results in the data collection, since variables were not dependent on one other.

Correlations																													
	#USV ISR	#USV SUW	#USV AMD A	#USV AMD M	Velocity	#Passive	#Active	#Chaff	#Flares	#IR Smoke	#Vis Smoke	CVN	EMCON LHD	EMCON CG	EMCON DOG	EMCON DOG-1000	EMCON USV/ISR	EMCON USV/SUW	EMCON USV/AMD A	EMCON USV/AMD M	EMCON SPOT	JAMMING SWEEP	JAMMING DRFM	JAMMING GPS	JAMMING BARRAGE	JAMMING SWARM			
#USV ISR	1.0000	-0.0195	0.0016	-0.0216	-0.0016	-0.0024	0.0081	0.0018	-0.0089	0.0038	-0.0100	-0.0205	-0.0187	-0.0011	-0.0116	0.0194	-0.0074	0.0235	0.0031	-0.0042	0.0055	0.0102	-0.0310	-0.0012	-0.0126	0.0279			
#USV SUW	-0.0195	1.0000	0.0006	0.0026	-0.0038	-0.0004	0.0032	-0.0052	-0.0073	0.0016	0.0032	0.0061	-0.0119	0.0070	0.0196	0.0043	0.0108	-0.0197	-0.0014	0.0227	-0.0038	0.0165	-0.0070	-0.0175	0.0011	0.1879			
#USV AMD A	0.0016	0.0006	1.0000	-0.0014	0.0071	-0.0032	-0.0007	-0.0012	0.0144	0.0032	-0.0027	-0.0130	-0.0016	0.0076	0.0041	0.0103	0.0173	0.0220	0.0003	-0.0221	-0.0119	0.0165	-0.0070	-0.0008	0.0011	0.0752			
#USV AMD M	-0.0216	0.0026	-0.0014	1.0000	0.0023	-0.0004	-0.0067	0.0020	-0.0023	0.0053	-0.0017	-0.0054	0.0162	-0.0146	-0.0079	0.0005	-0.0082	0.0159	-0.0116	0.0062	0.0062	0.0121	-0.0130	-0.0143	-0.0065	0.0376			
Velocity	-0.0016	-0.0038	0.0071	0.0023	1.0000	-0.0015	-0.0048	-0.0027	0.0107	-0.0081	0.0036	-0.0057	-0.0002	0.0001	-0.0039	0.0044	0.0005	-0.0014	0.0046	0.0049	-0.0045	0.0059	-0.0018	-0.0003	-0.0061	0.0345			
#Passive	-0.0024	-0.0004	-0.0032	-0.0004	-0.0015	1.0000	-0.0038	-0.0011	-0.0008	-0.0036	-0.0077	-0.0033	-0.0039	-0.0010	0.0046	0.0045	0.0012	-0.0024	0.0041	-0.0007	-0.0032	-0.0043	0.0004	0.0032	-0.0038				
#Active	0.0081	0.0032	-0.0007	-0.0067	-0.0048	-0.0038	1.0000	-0.0022	0.0022	0.0011	-0.0061	-0.0081	0.0005	0.0022	-0.0019	-0.0011	0.0027	0.0068	0.0019	0.0062	-0.0057	-0.0005	-0.0077	-0.0005	-0.0077				
#Chaff	0.0018	-0.0052	-0.0012	0.0020	-0.0027	-0.0011	-0.0022	1.0000	-0.0037	-0.0035	0.0005	-0.0038	-0.0003	0.0035	0.0003	-0.0025	0.0009	-0.0021	0.0009	0.0009	0.0029	0.0020	0.0032	0.0007	-0.0001	-0.0458			
#Flares	-0.0089	-0.0073	0.0144	-0.0023	0.0107	-0.0008	0.0022	-0.0037	1.0000	0.0002	-0.0049	0.0143	-0.0070	0.0054	0.0022	0.0078	-0.0052	-0.0119	-0.0038	0.0041	-0.0049	0.0038	-0.0014	0.0084	0.0301				
#IR Smoke	0.0038	0.0016	0.0032	0.0093	-0.0081	-0.0036	0.0011	-0.0035	0.0002	1.0000	-0.0033	-0.0105	0.0043	0.0030	0.0266	-0.0146	0.0038	0.0208	0.0252	0.0038	-0.0168	-0.0024	0.0187	-0.0211	0.0000	-0.0665			
#Vis Smoke	-0.0100	0.0032	-0.0027	-0.0017	0.0026	-0.0077	-0.0081	0.0005	-0.0049	-0.0033	1.0000	0.0054	0.0073	-0.0033	0.0011	-0.0035	-0.0019	0.0032	-0.0000	0.0051	-0.0114	-0.0005	0.0011	0.0276					
CVN EMCON	-0.0205	0.0081	-0.0190	-0.0054	-0.0057	-0.0033	-0.0081	-0.0038	0.0140	-0.0105	0.0054	1.0000	-0.0141	-0.0191	0.0078	-0.0018	-0.0042	0.0216	0.0161	-0.0097	0.0129	-0.0110	0.0057	0.0164	-0.0250	-0.0321			
LHD EMCON	-0.0187	-0.0119	-0.0016	0.0162	-0.0032	-0.0039	0.0005	-0.0033	-0.0070	0.0043	0.0073	-0.0141	1.0000	-0.0045	0.0158	0.0097	-0.0115	-0.0216	0.0153	-0.0216	0.0038	0.0031	0.0042	0.0053	0.0015	-0.0769			
CG EMCON	-0.0011	0.0070	0.0076	-0.0146	0.0001	-0.0010	0.0022	0.0035	0.0054	0.0030	-0.0033	-0.0191	-0.0045	1.0000	-0.0112	0.0195	0.0002	0.0005	-0.0038	0.0195	-0.0139	0.0056	-0.0076	0.0146	-0.0112	-0.0635			
DOG EMCON	-0.0116	0.0196	0.0041	-0.0079	-0.0039	0.0046	-0.0019	0.0053	0.0032	0.0036	0.0011	0.0078	0.0138	-0.0112	1.0000	-0.0150	0.0105	-0.0050	0.0010	0.0164	-0.0123	-0.0019	-0.0123	-0.0001	-0.0472				
DOG-1000 EMCON	0.0194	0.0043	0.0103	0.0005	0.0044	0.0045	-0.0011	-0.0025	0.0070	-0.0146	-0.0033	-0.0018	0.0097	0.0195	-0.0150	1.0000	-0.0113	-0.0172	0.0075	-0.0257	-0.0190	-0.0030	0.0280	-0.0134	0.0138	-0.0312			
USV/ISR EMCON	-0.0074	-0.0108	0.0173	-0.0092	0.0005	0.0012	0.0027	0.0059	-0.0052	0.0038	-0.0019	-0.0042	-0.0115	0.0002	0.0105	-0.0113	1.0000	0.0149	-0.0270	0.0201	-0.0240	0.0099	-0.0010	-0.0006	-0.0120	-0.0467			
USV/SUW EMCON	0.0235	-0.0197	0.0303	0.0159	-0.0014	0.0068	-0.0031	-0.0119	0.0038	0.0032	0.0216	-0.0216	0.0005	-0.0050	-0.0172	0.0149	1.0000	0.0046	-0.0084	-0.0082	0.0068	0.0227	0.0018	0.0216	-0.0419				
USV/AMD A EMCON	0.0031	-0.0014	0.0003	-0.0116	0.0046	0.0041	0.0019	0.0059	-0.0038	0.0252	-0.0030	0.0161	0.0153	-0.0038	0.0010	0.0075	-0.0270	0.0046	0.0018	-0.0112	-0.0032	0.0062	-0.0216	-0.0266					
USV/AMD M EMCON	-0.0042	0.0027	-0.0021	0.0062	0.0049	-0.0027	0.0082	0.0039	-0.0130	0.0030	-0.0005	-0.0097	-0.0216	0.0195	0.0164	-0.0257	0.0204	0.0154	1.0000	0.0124	-0.0106	-0.0270	0.0023	-0.0018	0.0778				
SPOT JAMMING	0.0055	-0.0058	-0.0119	0.0002	-0.0045	0.0038	0.0081	0.0029	0.0041	-0.0168	-0.0000	0.0139	0.0038	-0.0139	-0.0138	-0.0190	-0.0248	-0.0002	0.0054	0.0124	1.0000	-0.0025	-0.0001	-0.0064	-0.0106	0.0077			
SWEEP JAMMING	0.0102	0.0165	0.0165	0.0121	0.0059	-0.0032	-0.0057	0.0020	-0.0049	-0.0024	0.0051	-0.0110	0.0031	0.0056	-0.0019	-0.0030	0.0099	0.0068	0.0018	-0.0108	-0.0025	1.0000	0.0335	0.0065	-0.0031	0.0705			
DRFM JAMMING	-0.0310	-0.0070	0.0070	-0.0130	-0.0018	-0.0043	-0.0022	0.0038	0.0187	0.0174	0.0037	0.0042	-0.0078	0.0184	0.0280	-0.0010	0.0227	-0.0112	-0.0091	0.0335	1.0000	-0.0006	0.0115	0.0262					
GPS JAMMING	-0.0012	-0.0175	-0.0028	-0.0143	-0.0003	0.0004	-0.0057	0.0007	-0.0014	-0.0211	-0.0025	0.0104	0.0053	0.0166	-0.0123	-0.0134	-0.0006	0.0018	-0.0002	0.0085	1.0000	0.0182	0.0098	0.0182	0.0098				
BARRAGE JAMMING	-0.0126	0.0011	0.0011	-0.0065	-0.0001	0.0032	-0.0005	-0.0001	0.0084	0.0000	0.0011	-0.0250	0.0000	-0.0112	-0.0001	0.0138	-0.0120	0.0216	0.0082	-0.0018	-0.0106	0.0031	0.0115	0.0162	1.0000	0.0043			
SWARM	0.0279	0.1879	0.0752	0.0376	0.0345	-0.0038	-0.0877	-0.0458	0.0301	-0.0665	0.0276	-0.0321	-0.0769	-0.0635	-0.0472	-0.0312	-0.0467	-0.0419	-0.0266	0.0778	0.0077	0.0705	0.0262	0.0038	0.0043	1.0000			

Figure 25. Correlations Between Input Variables

The enemy forces had a fixed composition to meet the desired operational objective of invading the Island of Palawan. Table 26 shows the fixed composition, totaling 149 enemy platforms, which are created in the beginning of the simulation. The enemy OOB is composed of the author's opinion of what the PRC would use in the 2030–2035 time horizon. By no means is the composition factual, but for the purposes of this thesis, had to be fixed to run the simulation.

Table 26. Fixed Enemy Force Structure. Adapted from SEA 27 (2018).

Surface Combatants		Aircraft		Land Based Missiles	
1	Type 001/002/003 Carrier	14	J-11 Fighter	8	DF-21D
3	Type 055 Renhai	18	J-15 Fighter	4	DF-26
5	Type 052 Destroyer	18	J-16 Fighter	8	YJ-62
7	Type 054 Frigate	4	J-16D EW	4	HY-2
8	Type 056 Corvette	8	J-20 Fighter		
14	Type 022 Missile Boat	4	Q-5 Surface Attack		
1	Type 075 LHD	3	H-6K Bomber		
2	Type 071 LPD	1	KJ-3000 AEW		
2	Type 072 LST	1	Y-8FQ MPRA		
		6	Z-18 Helo		
		2	Z-8AEW		
		1	Soaring Dragon		
		1	Pterodactyl		
		1	Dark Sword		
Total Enemy Threats in Model = 149					

C. MODEL ANALYSIS

The author used JMP, a statistical analysis program, to conduct model analysis. The JMP software assists in the determination of significant input variables, specifically identifying relationships between variables. The software can process large amounts of

data and create regression models that appropriately fit the input variables against the metrics being considered. The author allowed the JMP program to conduct a stepwise Bayesian Information Criterion (BIC) type regression before creating the best fitting model for each specific MOE. The BIC algorithm has the ability to identify the most significant input variables, allowing factors that are not of particular interest to be left out of the regression analysis.

The author collected the output data, consisting of all 15,360 simulation runs, and organized the input data and output data so that it could be implemented into JMP. Both the output and input data are required for JMP to conduct its regression models; therefore, the output data that was captured by the ExtendSim Model had to be congruent to the MOEs prescribed. Table 27 illustrates each MOE and the detailed output data that was captured and merged with the input variables generated by the DOE. The goal was to determine if any of the unmanned surface vehicle input variables were statistically and operationally significant in regard to the prescribed MOEs. Appendix H illustrates a sample data set of the DOE and the expected MOE outputs.

Table 27. Metrics Captured by the ExtendSim Model. Adapted from SEA 27 (2018).

Surviving Friendly Forces	Percentage of Friendly High Value Surface Assets Killed (CVN/LHD/LHA) Percentage of Friendly Missile Carriers Killed (DDG(s), CG) Percentage of Friendly Force Fighter Aircraft Killed (F-35, F/A-18) Percentage of USVs Killed (USV ISR, USV SUW, USV AMD A, USV AMD M)
Surviving Enemy Forces	Percentage of Enemy Platforms Killed
Percentage of Enemy Missiles Destroyed	Percentage of Enemy Missiles Killed

Percentage of Enemy Missiles within 10 NM	Percentage of Enemy Missiles Reached within 10 NM from Friendly Forces
Offensive Strike Success	Success of Employed Friendly Missiles against Enemy Platforms
Defensive Measure Success	Success of Employed Mechanical and Physical Counter-Measures Success of Employed Defensive Missiles

For this analysis, a statistically significant variable was defined as one that received a p-value of less than 0.0001. This means the relationship between the specified variables and the overall operational effectiveness is likely not caused by random chance. The desired outcome would be that any of the USV variables would be considered statistically significant throughout the analysis. How operationally impactful the specified variable's relationship is in regard to the overall operational effectiveness defines operational significance. The JMP software, during its regression analysis, can identify factors that are statistically significant, yet the same factors could have limited operational impact. A hypothetical example would be if JMP identified the number of USV SUW's as statistically significant in the context of MOE 2: Survivability of Enemy Forces, but the survivability of Enemy Forces only changed from 50% to 49.5% in that specific case. This indicates that while certain factors may be statistically significant, the reduction from 50% survivability to 49.5% survivability is operationally insignificant.

The following sections dissect the six measures of effectiveness using the JMP software. It was discovered that one or more USV variables made a noteworthy impact in three out of the six measures of effectiveness, proving to be not only statistically significant in each given circumstance, but also operationally significant. Each MOE analysis provides an actual versus predicted plot, an analysis summary, and sorted parameter estimates. The actual versus predicted plot provides confirmation that regression is an appropriate analysis technique, the analysis summary provides a condensed summary of the regression results, and the sorted parameter estimates provide additional detail regarding regression results to facilitate identification of results that may be statistically but not operationally significant.

If any unmanned surface vehicle variables turned out to be worth continued investigation, a follow-on partition tree was developed showing the operationally significant results. The author's intent is to show that the success of the six MOEs had some USV variable relationship; however, due to the many factors throughout the model, it was important to distinguish what was actually impactful. It is also interesting to note that the DMO tactics that the SEA 27 developed proved to be very effective throughout the analysis, specifically jamming tactics and emission control. This confirms the importance of the continued effort to utilize and control the EW spectrum.

1. Analysis of MOE #1: Surviving Friendly Forces

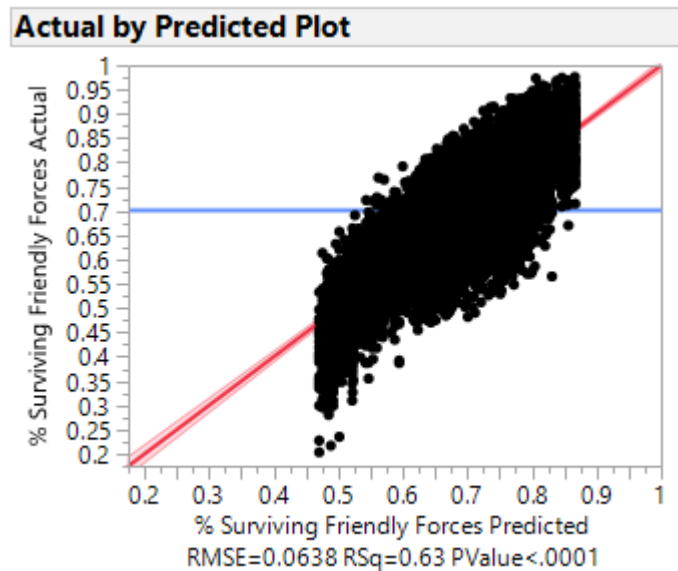


Figure 26. MOE #1 Actual versus Predicted Plot

Figure 26 presents the results of regression analysis for the survivability of friendly forces. The R-squared value of 0.63 indicates an acceptable model fit. Of note, the abrupt cutoffs for the predicted values at 0.45 and 0.85 were due to the complex interactions among EMCON variables and certain terms in the regression model. The statistically significant factors contributing to the friendly force survivability are presented in Table 28 and the sorted estimates are shown in Figure 27. The number of USV AMD A platforms and USV AMD M platforms are listed as statistically significant, yet their operational

impact was negligible. The author chose not to display all the metrics of individual platforms (Survivability of High Value Units, Missile carriers, Aircraft, and USVs) associated with MOE 1 due to the repetition of significant factors in all outputs and the fact that no USV variable proved to be operationally significant.

Table 28. Analysis Summary of MOE#1: Surviving Friendly Forces.
Adapted from SEA 27 (2018).

MOE Calculation	Percentage $\text{Surviving Friendly Forces} = \frac{\text{Quantity of Friendly Forces surviving at end of simulation}}{\text{Quantity of initial Friendly Forces}}$
Significant Contributing Factors	Overall Friendly Force Survivability
	DDG EMCON LHD EMCON CG EMCON DDG-1000 EMCON # Chaff #Active Decoys #USV AMD A #USV AMD M

Sorted Parameter Estimates					
Term	Estimate	Std Error	t Ratio		Prob> t
DDG EMCON	-0.101844	0.001041	-97.87		<.0001*
LHD EMCON	-0.097449	0.001036	-94.06		<.0001*
CG EMCON	-0.06027	0.001045	-57.66		<.0001*
(LHDEMCON-0.48047)*(DDGEMCON-0.45117)	-0.054633	0.002094	-26.09		<.0001*
(#USVAMDA-12.5)*(LHDEMCON-0.48047)	-0.003227	0.000144	-22.40		<.0001*
(#USVAMDM-12.5)*(LHDEMCON-0.48047)	-0.002435	0.000145	-16.80		<.0001*
#Chaff	0.0001421	8.943e-6	15.89		<.0001*
(LHDEMCON-0.48047)*(CGEMCON-0.54297)	-0.031717	0.002098	-15.12		<.0001*
→ #USV AMD A	0.0010695	7.12e-5	15.02		<.0001*
(CGEMCON-0.54297)*(DDGEMCON-0.45117)	-0.031551	0.002114	-14.92		<.0001*
(#Chaff-100)*(LHDEMCON-0.48047)	0.0002579	0.000018	14.34		<.0001*
(#Chaff-100)*(DDGEMCON-0.45117)	0.0002197	1.811e-5	12.13		<.0001*
DDG-1000 EMCON	-0.012503	0.001044	-11.97		<.0001*
(#USV AMD A-12.5)*(#USV AMD A-12.5)	0.0001105	0.000011	10.00		<.0001*
(#USV SUW-12.5)*(#USV SUW-12.5)	9.7134e-5	1.123e-5	8.65		<.0001*
(#USV AMD M-12.5)*(#USV AMD M-12.5)	9.1534e-5	0.000011	8.29		<.0001*
(#USV ISR-0.46094)*(LHDEMCON-0.48047)	-0.01671	0.002106	-7.93		<.0001*
#Active	0.0005094	7.154e-5	7.12		<.0001*
(#Chaff-100)*(CGEMCON-0.54297)	0.0001265	1.827e-5	6.93		<.0001*
→ #USV AMD M	0.0003072	0.000072	4.27		<.0001*

Figure 27. MOE #1: Statistically Significant Factors – Sorted Parameter Estimates

2. Analysis of MOE #2: Surviving Enemy Forces

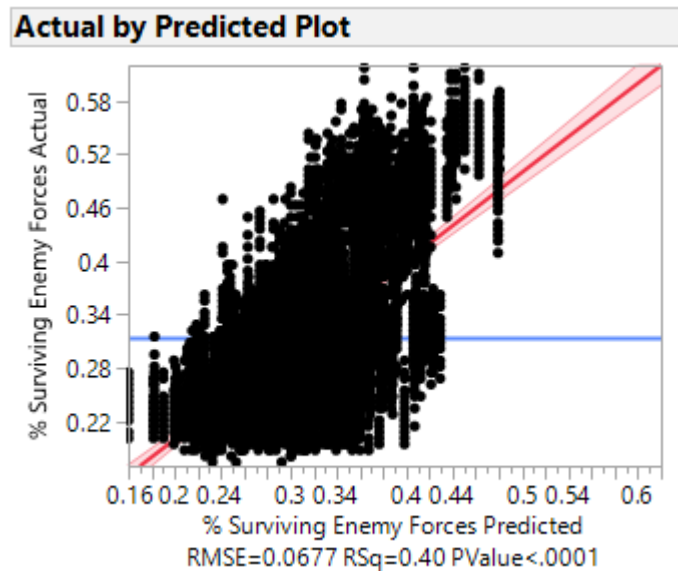


Figure 28. MOE #2 Actual versus Predicted Plot

As with the analysis of friendly force survivability, regression analysis was conducted to identify the factors that had a statistically significant impact on enemy force survivability. Figure 28 presents the results of regression analysis for the survivability of enemy forces. The R-squared value of 0.40 indicates a less desirable model fit and usually would be disregarded as not insightful; however, the following results were of great interest. The statistically significant factors contributing to the enemy force survivability are presented in Table 29 and the sorted estimates are shown in Figure 29. The USV ISR platform and USV AMD A platform were shown to be significant factors, but, the ISR platform proved to be the only operationally significant USV variable. In fact, one variable that did not show up as statistically significant played a key role when combined with the ISR platform; the ISR platform was more operationally impactful in conjunction with the velocity attributed to USVs. As a reminder, Chapter 4, Table 17, discussed that the model took an optimistic approach when considering the USV ISR platform capability. This assumption made it so that the capability of the USV ISR platform was not contingent on the quantity of ISR platforms, but only if one was present in the specific scenario.

Table 29. Analysis Summary of MOE #2: Surviving Enemy Forces.
Adapted from SEA 27 (2018).

MOE Calculation	$\text{Percentage}_{\text{Surviving Enemy Forces}} = \frac{\text{Quantity of Enemy Forces remaining at end of simulation}}{\text{Quantity of total Enemy Forces}}$
Significant Contributing Factors	Overall Enemy Force Survivability
	#USV ISR #USV AMD A DDG EMCON LHD EMCON CG EMCON DDG-1000 EMCON

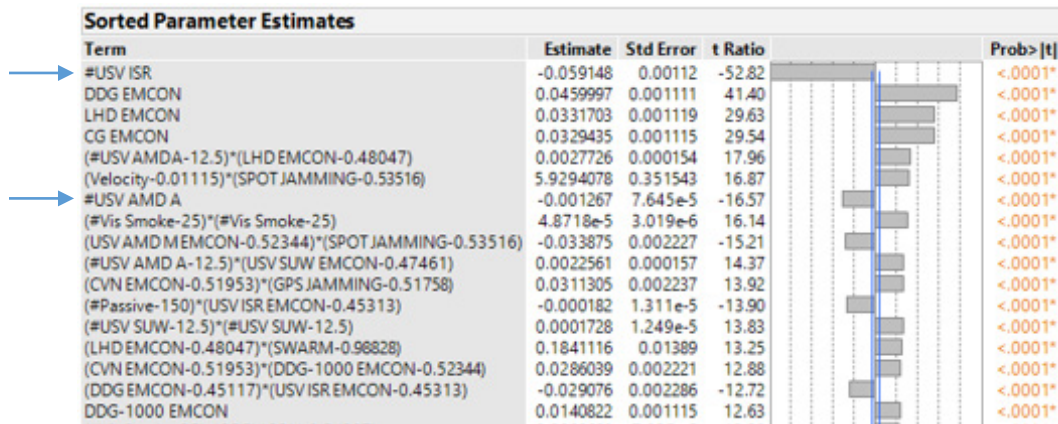


Figure 29. MOE #2: Statistically Significant Factors – Sorted Parameter Estimates

In order to gain additional insight regarding the effectiveness of the ISR platform, a partition tree was created for the ISR platform, shown as Figure 30, as well as a branch associated with the velocity of the USVs. This figure suggests the operational significance of the USV ISR platform. Starting from the top of Figure 30, it is calculated that the average survivability of enemy forces is 31%; interestingly though, if the ISR platform is either present or not present in the model the resulting survivability of enemy forces are 28% and 34%, respectively. Further splitting the partition, one can see that having a velocity of 58 knots or greater for the USV platforms will contribute in decreasing the survivability of

enemy forces to 24%. Therefore, when the ISR platform is present and has a design speed of 58 knots or greater, the survivability of enemy forces will decrease by a cumulative 10%. This happens to be one of the key findings in this thesis and shows that unmanned surface vehicles with ISR capabilities could be key enablers in the DMO concept by supplementing the manned assets that already provide an ISR capability. The author believes that the reason why the USV ISR was so effective was due to the unique capability of providing friendly forces an extended missile range combined with the small likelihood of being targeted due to its lack of firepower as described in the enemy mission assignment in Chapter 4. One only has to look at Figure 30 to see the distribution in data points when the USV ISR platform is greater than or equal to one. The red line indicates that when the USV ISR platform is present, every scenario results in 46% or less of enemy forces surviving.

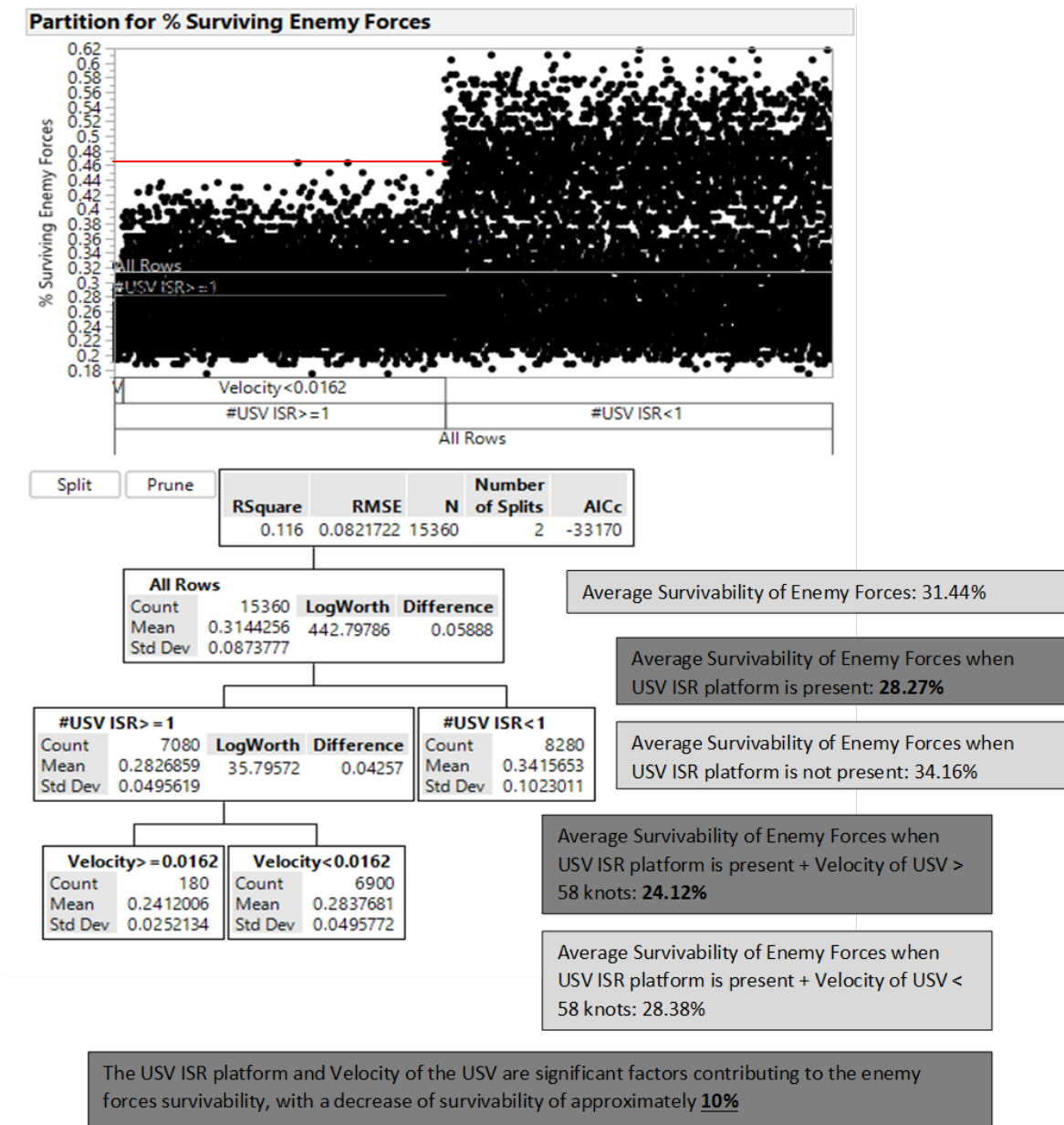


Figure 30. MOE #2 Partition Tree

3. Analysis of MOE #3: Percentage of Enemy Missiles Destroyed

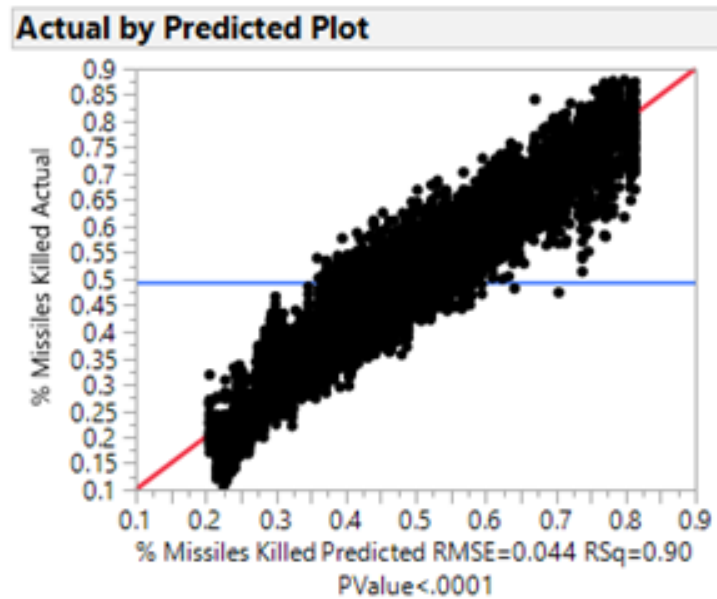


Figure 31. MOE #3 Actual versus Predicted Plot

Figure 31 presents the results of regression analysis for the percentage of enemy missiles destroyed. The R-squared value of 0.90 indicates an acceptable model fit. Of note, the abrupt cutoffs for the predicted values at 0.2 and 0.8 were due to the complex interactions among EMCON variables and certain terms in the regression model. The statistically significant factors contributing to the percentage of enemy missiles destroyed are presented in Table 30 and the sorted estimates are shown in Figure 32. The number of USV AMD A platforms and USV AMD M platforms are listed as statistically significant, yet their operational impact was negligible just like MOE #1.

Table 30. Analysis Summary of MOE #3: Percentage of Enemy Missiles Destroyed. Adapted from SEA 27 (2018).

MOE Calculation	$\text{Percentage}_{\text{Enemy Missiles Destroyed}} = \frac{\text{Quantity of Successful Enemy Missiles Countered}}{\text{Quantity of total Enemy Missiles}}$
Significant Contributing Factors	Percentage of Enemy Missiles Destroyed
	LHD EMCON DDG EMCON CG EMCON #USV AMD A #USV AMD M # Chaff

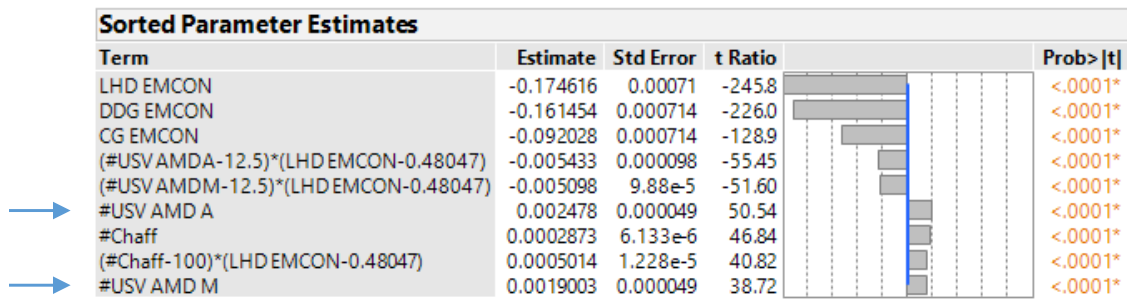


Figure 32. MOE #3: Statistically Significant Factors – Sorted Parameter Estimates

4. **Analysis of MOE #4: Percentage of Enemy Missiles within 10 Nautical Miles**

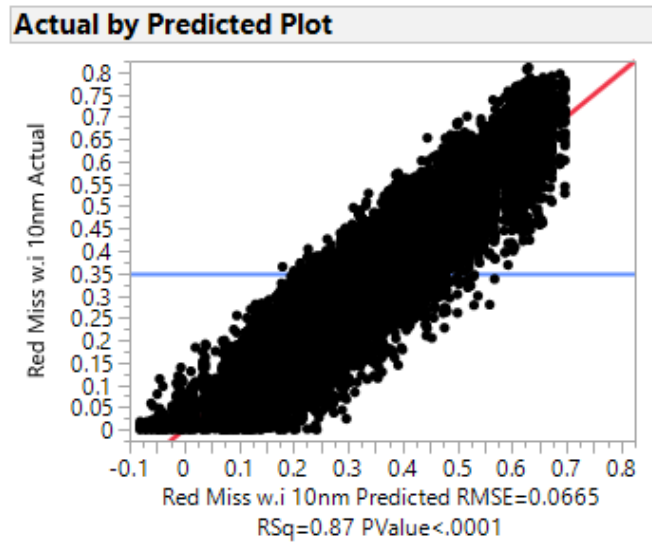


Figure 33. MOE #4 Actual versus Predicted Plot

Figure 33 presents the results of regression analysis for the percentage of enemy missiles within 10 nautical miles of friendly forces. The R-squared value of 0.87 indicates an acceptable model fit. The statistically significant factors contributing to the percentage of enemy missiles within 10 nautical miles are presented in Table 31 and the sorted estimates are shown in Figure 34. Just like MOE #1 and MOE #3, the number of USV AMD A platforms and USV AMD M platforms remain statistically significant, yet the major difference is that these two factors proved to be operationally impactful.

Table 31. Analysis Summary of MOE #4: Percentage of Enemy Missiles within 10 Nautical Miles. Adapted from SEA 27 (2018).

MOE Calculation	Percentage $\frac{\text{Red Missiles in 10 NM Range}}{\text{Quantity of total Enemy Missiles}} = \frac{\text{Quantity Enemy Missiles within 10 NM range}}{\text{Quantity of total Enemy Missiles}}$
Significant Contributing Factors	Percentage of Enemy Missiles within 10 NM
	#USV AMD A #USV AMD M DDG EMCON LHD EMCON CG EMCON SPOT JAMMING BARRAGE JAMMING DFRM JAMMING DDG-1000 EMCON

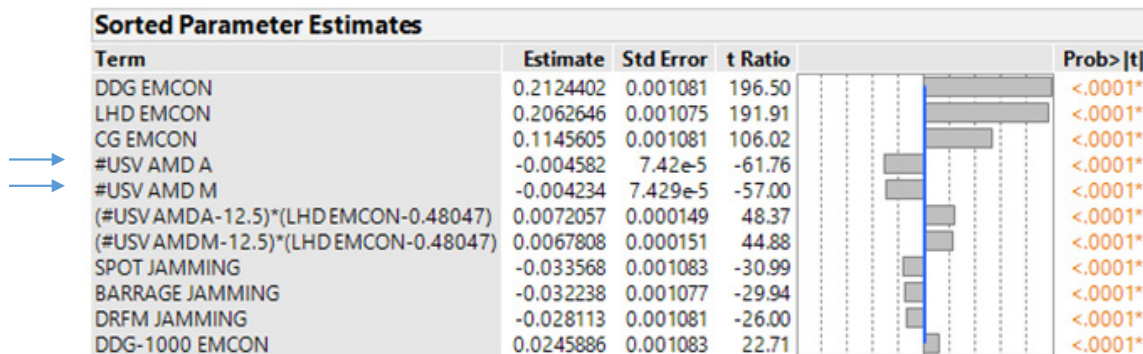


Figure 34. MOE #4: Statistically Significant Factors – Sorted Parameter Estimates

A partition tree, depicted in Figure 35, was created in order to gain additional insight regarding the effectiveness of the USV AMD M and USV AMD A. This figure suggests the operational significance of the two platforms, with the quantity of USV AMD M platforms as the most impactful, and, when combined with a number of USV AMD A platforms, can significantly reduce the percentage of close proximity enemy missiles. This is intuitive since the AMD M shoots down incoming missiles while the AMD A shoots down aircraft that carry missiles. Starting from the top of Figure 35, it is calculated that the

average percentage of enemy missiles within 10 nautical miles is approximately 35%. By the model's standards, this means that about one third of the enemy's missiles get through all the initial friendly layers of defense without being countered. When there is approximately 15 or more USV AMD M platforms, the percentage of enemy missiles crossing the 10 nautical mile line decreases to 31%. Further splitting the partition, one can see that having approximately 8 or more USV AMD A platforms decreases the percentage of enemy missiles to 29%. When considering having less than 15 USV AMD M platforms, the percentage of enemy missiles within 10 nautical miles increases to approximately 38%. Therefore, if the friendly order of battle has the right composition of AMD USVs the swing in the range of percentages of enemy missiles is around 8.5%, which is operationally significant.

To put this into perspective, a hypothetical example was constructed: imagine 149 enemy platforms that originally start off in the model and, according to MOE #2, approximately 68% are killed. Killed does not necessarily mean that the enemy was not able to engage with missiles before being destroyed. So, assume that 90 enemy platforms were able to engage, releasing a salvo of 6 missiles each. This is approximately 540 inbound enemy missiles at different ranges throughout the model, depending on where the enemy started, when it found its assignment, and when it successfully targeted its assignment. On average, without the correct composition of AMD USV platforms, 38% of enemy missiles will reach 10 nautical miles, which is approximately 205 missiles. It is important to note that once the enemy missiles reach 10 nautical miles, friendly forces no longer use missiles to counter engage, but only physical and mechanical countermeasures like chaff, flares, and IR smoke. If the above-mentioned composition of AMD USV platforms is utilized, the 205 missiles will now be reduced to 157 missiles, which is a reduction of 48 missiles. In context, 48 enemy missiles are the equivalent of the number of YJ-100 anti-ship cruise missiles that the Renhai holds within the model parameters. The conclusion drawn from this example is friendly forces' equivalently disable one of the most capable enemy platforms from participating in the engagement. This is operationally significant when breaking down the mechanics of the situation.

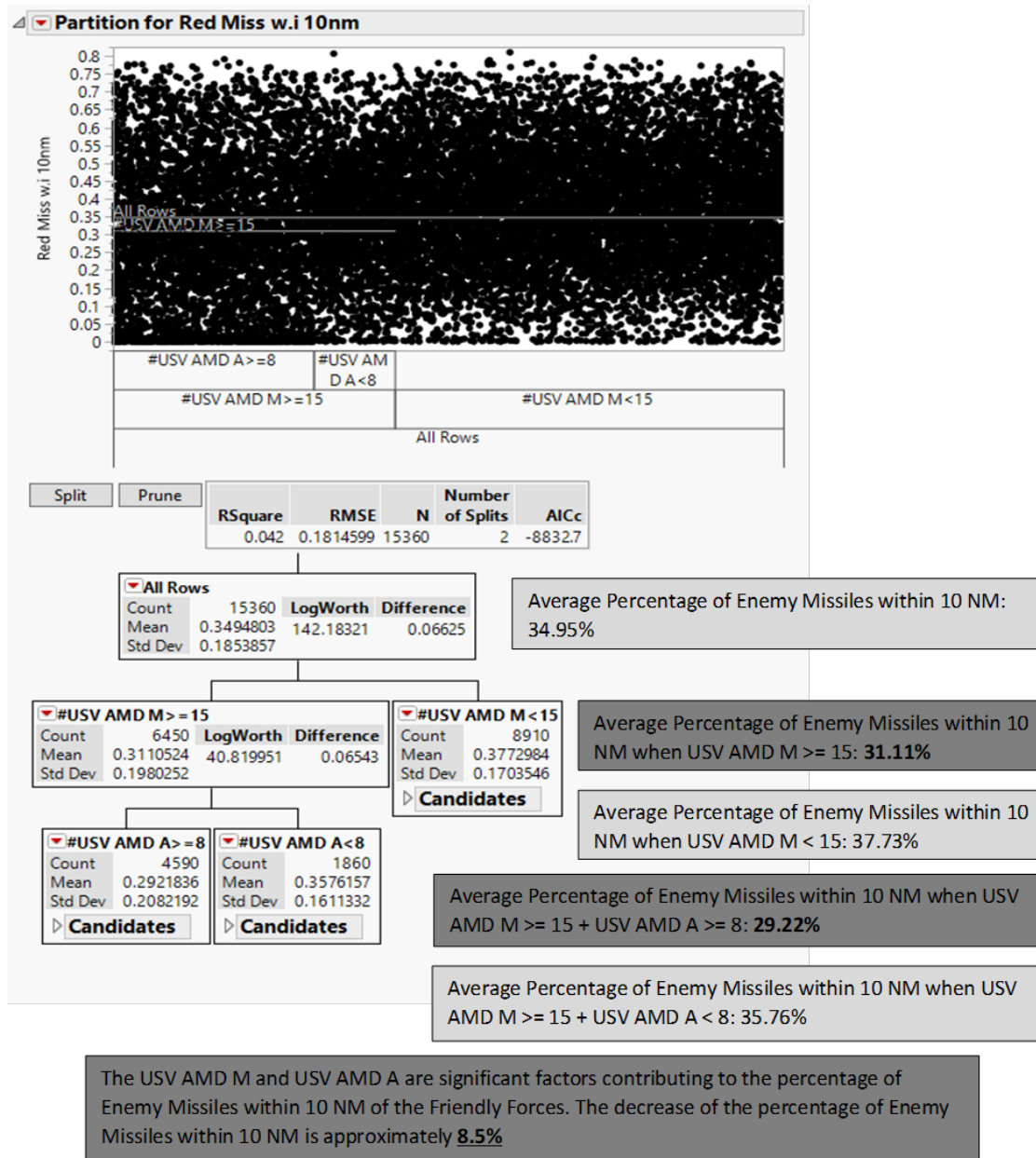


Figure 35. MOE #4 Partition Tree

5. Analysis of MOE #5: Offensive Strike Success

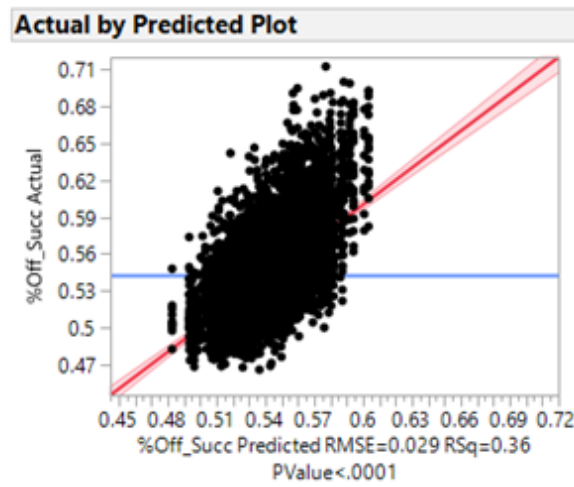


Figure 36. MOE #5 Actual versus Predicted Plot

Figure 36 presents the results of regression analysis for the offensive strike success. The R-squared value of 0.36 indicates a poor model fit; therefore, the information that it provides is less actionable compared to the other MOE's regression analysis models. The statistically significant factors contributing to the offensive strike success are presented in Table 32 and the sorted estimates are shown in Figure 37. The number of USV AMD A platforms, the USV ISR platform, as well as the USV SUW EMCON tactic are listed as statistically significant, yet their operational impact was negligible. Based on how the model was created, the author realized that almost all the input variables, as well as many fixed parameters, affected MOE #5. This, in turn, made it difficult to determine which parameter or variable most significantly impacted the offensive strike success. The conclusion that can be drawn from MOE #5 is that all aspects of the friendly force structure, including their payloads and tactics, contributed somehow to the operational success of friendly missiles hitting their designated target; not one factor stood out as operationally significant.

Table 32. Analysis Summary of MOE #5: Offensive Strike Success.
Adapted from SEA 27 (2018).

MOE Calculation	Percentage $\frac{\text{Success Friendly Missiles - Offensive}}{\text{Quantity of successful Friendly offensive missiles}} = \frac{\text{Quantity of Friendly missiles engaging Enemy platforms}}{\text{Quantity of successful Friendly offensive missiles}}$
Significant Contributing Factors	Offensive Strike Success
	Barrage Jamming Spot Jamming DRFM Jamming Sweep Jamming #USV ISR #USV AMD A USV SUW EMCON LHD EMCON CG EMCON #Visual Smoke

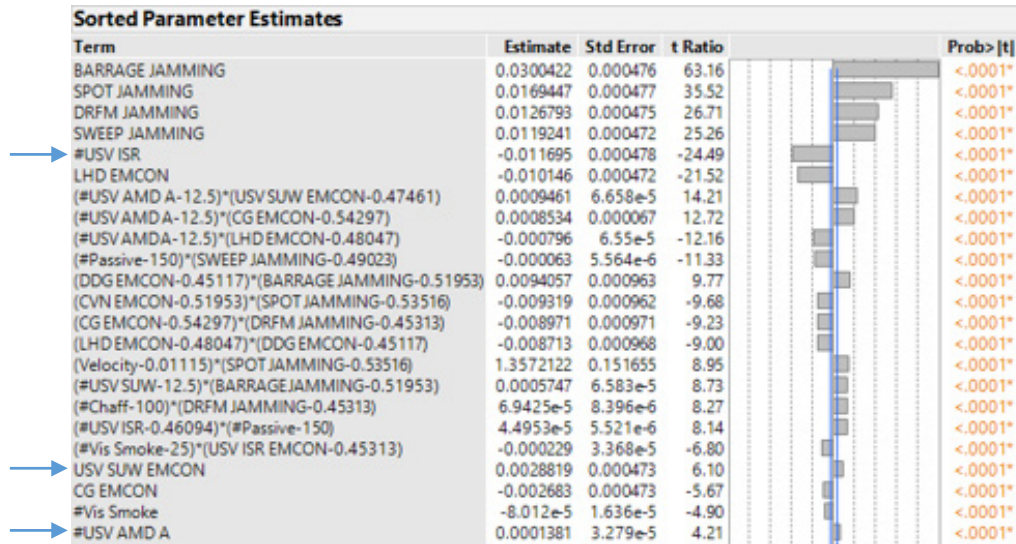


Figure 37. MOE #5: Statistically Significant Factors – Sorted Parameter Estimates

6. Analysis of MOE #6: Defensive Measure Success

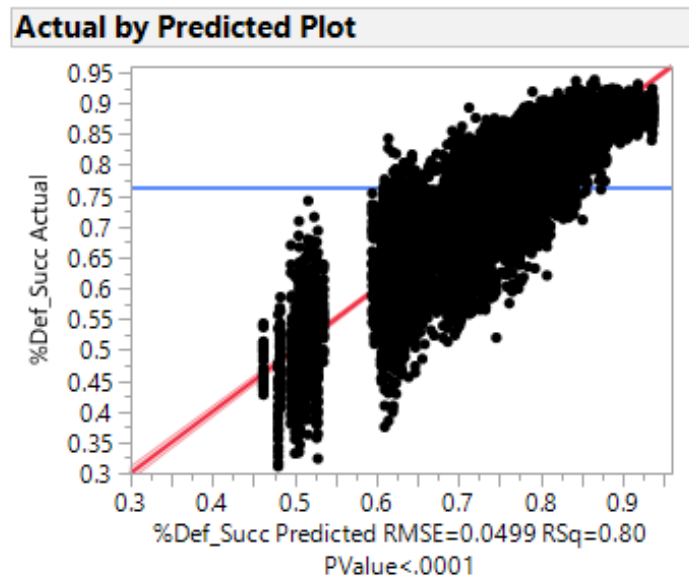


Figure 38. MOE #6 Actual versus Predicted Plot

Figure 38 presents the results of regression analysis for defensive measure success. The R-squared value of 0.80 indicates an acceptable model fit. Of note, the abrupt cutoffs for the predicted values between 0.525 and 0.6 were due to the complex interactions among EMCON variables and GPS Jamming tactics. The statistically significant factors contributing to the defensive measure success are presented in Table 33 and the sorted estimates are shown in Figure 39. Just like MOE #4, the number of USV AMD A platforms and USV AMD M platforms were both statistically and operationally significant.

Table 33. Analysis Summary of MOE #6: Defensive Measure Success. Adapted from SEA 27 (2018).

MOE Calculation	Percentage $\text{Successful Defensive Measures} = \frac{\text{Quantity of successful Defensive Measures}}{\text{Quantity of Total Defensive Measures Expended}}$
Significant Contributing Factors	Defensive Measure Success
	#USV AMD M #USV AMD A LHD EMCON DDG EMCON CG EMCON GPS JAMMING

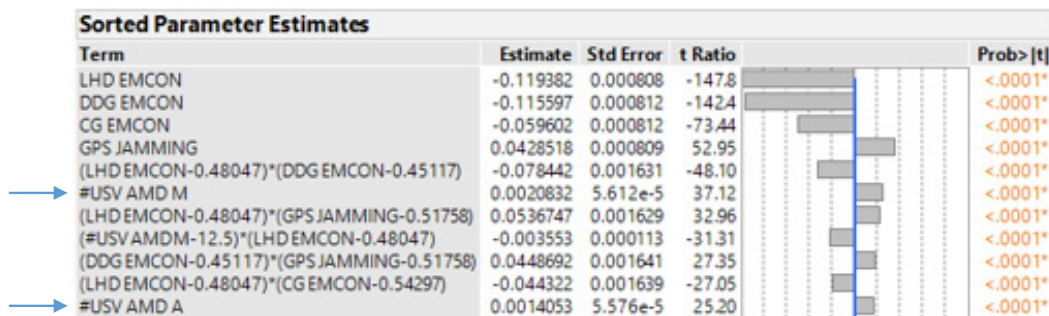


Figure 39. MOE #6: Statistically Significant Factors – Sorted Parameter Estimates

A partition tree, depicted in Figure 40, was created in order to gain additional insight regarding the effectiveness of the USV AMD M and USV AMD A platforms. Just like MOE #4's partition tree, this also suggests the operational significance of the two platforms. The quantity of USV AMD M platforms were the most impactful and when combined with several USV AMD A platforms, can significantly improve the defensive measure success. Interestingly, two other factors stood out when splitting the partition; the velocity of the USV as well as the USV ISR EMCON tactic (if the USV ISR is in EMCON A then all electromagnetic emissions are turned off; this means the unique capability of providing extended ranges for friendly missiles does not exist, however the USV ISR becomes a lot harder to find). When all four factors are combined with the correct

composition, speed, and tactics, the defensive measure success improves even more. Starting from the top of Figure 40, it is calculated that the average defensive measure success is approximately 76%. By the model's standards, this means that about three fourths of friendly force missiles and countermeasure disrupt the enemy's inbound missiles. When there is approximately 15 or more USV AMD M platforms the defensive measure success increases to 78%. Further splitting the partition, one can see that having approximately 18 or more USV AMD A platforms the defensive measure success remains the same. The most interesting results start when the partition is split further into the two remaining factors. If there are less than 18 USV AMD A platforms and the velocity of the USV is less than 21 knots the defensive measure success decreases to 63%, a decrease of 11%. If the velocity of the USV is less than 21 knots and the USV ISR platform is not using emission control tactics the defensive measure success remains relatively the same as before the splitting of the partition, at 78%, but if the USV ISR platform is in EMCON A the defensive measure success drops significantly to 47%. This is an approximately 30% change from the original value.

The conclusions that can be drawn from this particular partition tree is that having 15 or more USV AMD M platforms is essential for the operational success of the friendly forces. If this is not feasible and there is less than 18 USV AMD A platforms present in the scenario, then it is absolutely imperative to have the USV velocity be greater than 21 knots, and or the USV ISR platform not in EMCON A.

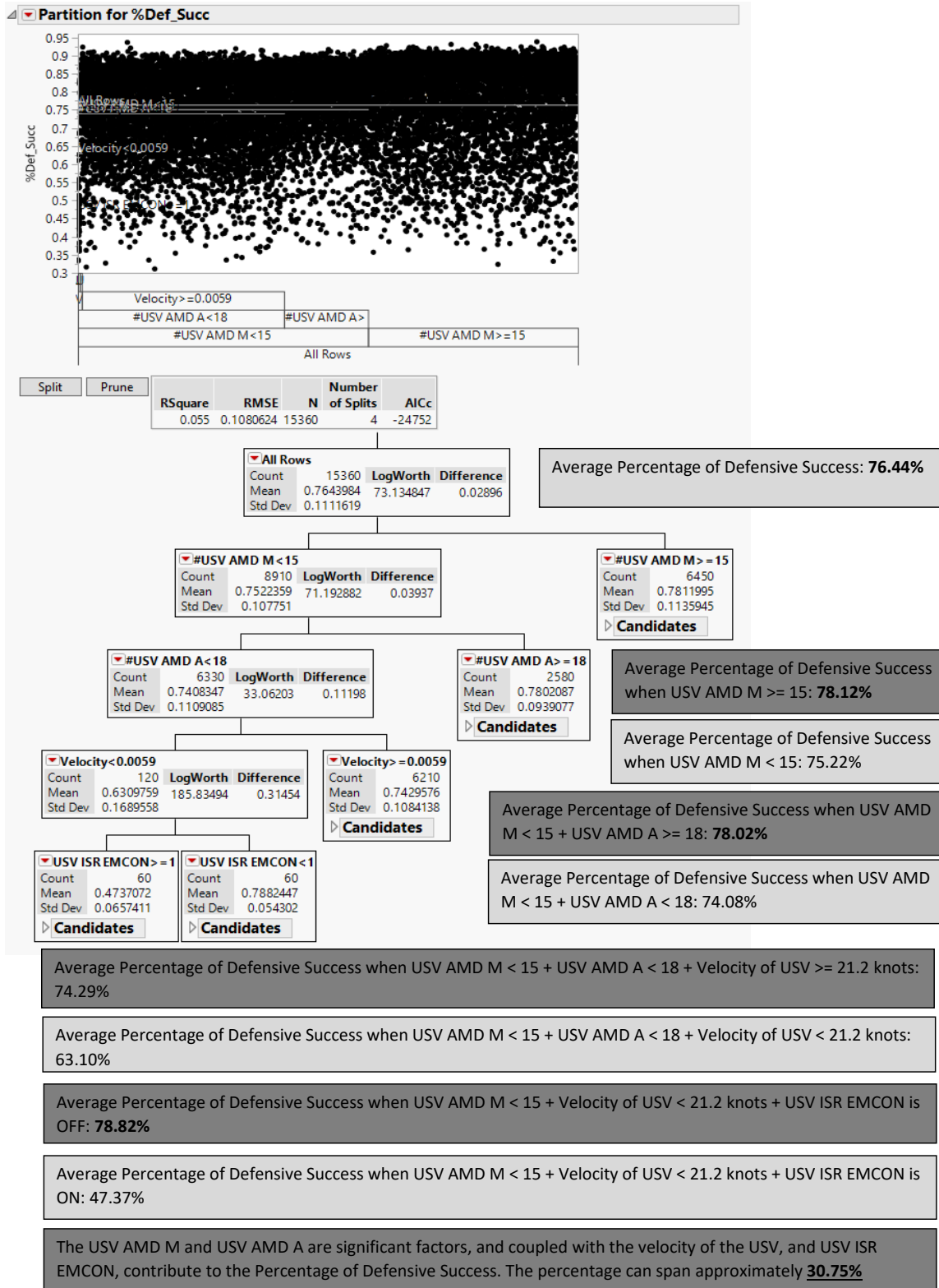


Figure 40. MOE #6 Partition Tree

D. MODEL ANALYSIS SUMMARY

It was shown throughout the data analysis that some of the conceptualized USVs not only were statistically significant, but operationally significant as well. The three measures of effectiveness that were the most interesting when analyzing how USVs contributed to the DMO concept were: (1) MOE #2: Surviving Enemy Forces, (2) MOE #4: Percentage of Enemy Missiles within 10 Nautical Miles, and (3) MOE #6: Defensive Measure Success. The alternative USVs that were the most operationally impactful were the USV ISR platform, USV AMD A platform, and the USV AMD M platform, whereas the USV SUW platform proved to be not operationally significant throughout the entire analysis. To the author's disappointment, this counters the objective of a more offensive strike mentality as proposed in the beginning of this thesis. The results of the analysis are inconclusive: unmanned surface vehicles are most effective by supplementing the manned naval assets in two primary mission sets in the confines of the DMO concept: (1) intelligence, surveillance and reconnaissance mission set, and (2) anti-missile defense mission set (for both anti-air and anti-missile defense). This envisions more of a defensive posture approach for the implementation of USVs, either by counter-engaging enemy platforms or missiles in the defense-in-depth layered strategy. The next chapter uses the three primary MOEs that the USVs excelled in and develops a cost versus operational effectiveness analysis to determine if the proposed alternative USVs, specifically the ISR and AMD platforms, could be a smart investment for the United States Navy in the years to come.

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VI. COST ANALYSIS AND CONCLUSIONS

The purpose of this chapter is to describe the cost estimating approach that the author used to determine the overall cost of each alternative USV and to provide the cost versus operational effectiveness analysis of the specified USVs in the DMO concept. The chapter then summarizes the findings by revisiting the original research questions prescribed in Chapter 1 and completes the thesis by giving conclusions, recommendations and possible future work for the implementation of USVs in DMO.

A. COST ANALYSIS

Cost estimation is a challenging endeavor when developing new systems like the alternative USVs addressed in this thesis. In general, ships consist of many components similar to the physical architecture described in Chapter III, yet the biggest difference between the conceptualized designs and common maritime vessels is the autonomous suite integration. When looking at Table 4, in Chapter 2, of all the current USVs, only a few have available cost data, and only one, the ACTUV, is in the same realm as this thesis' conceptualized USV alternatives in the context of size, tonnage and capability. The current number of platforms that are fully autonomous are limited, which makes it difficult to extrapolate historical cost data when estimating future costs; hence, the following section describes the author's approach in determining the cost of the alternative USVs. Of note, cost estimation is a tool that provides an analytic backing to support decision makers. Cost estimation is never 100% accurate since predicting the future is impossible. However, the objective of this cost analysis is to provide a risk management tool and potential enabler for investment in future development of unmanned surface vehicles for the DMO concept.

1. Parametric Approach

The author chose to use the parametric approach, as referenced by Mun (2016), to derive a cost model that predicts the cost of the alternative USVs described in this thesis. The parametric approach uses historical cost data from publicly available procurement information provided by multiple countries for all different sizes of maritime vessels. This approach is known as the statistical method and generates a cost estimate based on system

performance or design characteristics. The objective of using historical data is to create a multiple non-linear regression model for cost associated with three unique variables: size of the vessel in meters, tonnage of the vessel and speed of the vessel in knots. The author identified 40 platforms that had historical procurement costs and researched their design specifications for the parametric approach. Table 34 organizes the platforms by the three unique variables and displays the cost in fiscal year 2018 money.

Table 34. Historical Cost Data of Maritime Vessels. Adapted from
Historical Cost Data Sources listed in Appendix I.

Vessel Name	Country	Size (m)	Tonnage	Speed (Knots)	FY2018 (\$M)
Amazonas-class corvette	Brazil	90.5	2,000	25	62.421
Hero-Class Patrol Vessel	Canada	42.8	253	25	25.314
Orca-Class Patrol Vessel	Canada	33	210	20	11.873
Type 056 corvette	China	90	1,500	25	53.225
Houbei Type 22 missile boat	China	42.6	220	36	16.798
Iver Huitfeldt-class Frigate	Denmark	138.7	6,645	30	345.963
Gowind-class corvettes	Egypt	102	2,500	25	184.052
Type 23 Frigate	England	133	4,900	28	175.265
Turva Patrol Boat	Finland	95.9	1,800	18	126.115
FTI Medium Size Frigate	France	122	4,200	27	843.036
Braunschweig-Class (corvette)	Germany	89.12	1,840	26	355.617
Holland Class OPV	Holland	108.4	3,750	21.5	163.716
Kamorta-Class (corvette)	India	109	3,300	25	311.833
Saryu-class Patrol Vessel	India	105	2,230	25	157.752
Protector	Israel	11	4	40	3.175
Seagull	Israel	12	5	32	30.843
Comandanti-Class Patrol Vessel	Italy	88.6	1,520	25	153.662
Protector-class Inshore Patrol Vessel	New Zealand	55	340	25	28.208
Protector-class OPV	New Zealand	85	1,900	22	127.126
Khareef-Class (corvette)	Oman	99	2,660	28	263.343
Sigma-class corvette	Romania	90.71	1,692	28	461.1
Karakurt-class corvette	Russia	67	800	30	32.385
Gumdoksuri-class Patrol Vessel	South Korea	63	570	44	46.986

Vessel Name	Country	Size (m)	Tonnage	Speed (Knots)	FY2018 (\$M)
FFX-II Daegu class Frigate	South Korea	122	3,600	30	307.648
Diciotti-Class offshore Patrol Vessel	Spain	53.4	391	23	38.143
BAM	Spain	93.9	2,860	20	238.448
Visby-Class corvette	Sweden	72.7	640	35	245.469
Tyo Chiang-Class (corvette)	Taiwan	60.4	567	40	77.059
Baynunah-Class corvette	UAE	71.3	915	30	187.183
MDUSV	USA	40	145	27	25
CUSV	USA	12	7.7	35	6.3
Hammerhead	USA	5.2	2	35	0.116
USS Oliver Perry Class (frigate)	USA	136	4,100	29	749.834
USS Freedom Class	USA	115	3,500	47	646.2
USS Independence Class	USA	127	3,104	44	646.2
DDG-51 Flight III	USA	155	9,600	30	1800
WMSL-750	USA	127.4	4,500	28	779.079
Sentinel-class cutter	USA	46.8	359	28	58
Heritage-class cutter	USA	110	3,730	22	391
Legend-class cutter	USA	127	4,600	28	682

One of the requisite assumptions for this regression model was that the alternative USVs are similar to the identified platforms listed in Table 34. The author chose mostly warships ranging from patrol craft to large frigates; however, some data was available for current developed USVs. The author assumed adequate justification since the alternative USVs in this thesis require military type systems aboard as shown in Chapter III. The prescribed capabilities of the USV AMD A, USV AMD M, USV ISR and USV SUW platforms require high-performing sensors and systems similar to the SPY radar, VLS, SLQ-32 and countermeasure launchers. This, in turn, allowed a reasonable comparison, even though the conceptualized USVs are not the same as a manned warship. Every platform listed in Table 34 had at least one of the prescribed capabilities or a mixed combination. Therefore, best fitting regression model satisfied the expected costs associated with the alternative USVs, even though it did not consider the specific components described in Chapter III (the ADL, Centurion System, SPY-1K, SLQ-32v(6), and Aegis weapon systems) as a cost per unit. The only unique costs that were considered,

in addition to the predicted cost expression given by the regression model, were the Autonomous Suite integration and an inflation factor for the 2030–2035 time frame. The Autonomous Suite integration cost per platform was a very ambiguous cost estimate, since the author found only one historical cost associated with converting a previously manned platform to an autonomous platform. In 2017, Leidos Inc., the team that led the design and building of DARPA’s Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessels (ACTUV), now named SEA HUNTER, successfully demonstrated autonomous logistics via an LCM-8 autonomous shore resupply mission. According to Rus Cook, from Leidos Inc. (email to author, July 21, 2018), the total cost of the autonomous integration, including materials and labor, was approximately \$1.3 million. Since the LCM-8 is substantially smaller and less complicated than the conceptualized USVs, the author chose a \$2 million estimate for the autonomous suite integration cost for the alternative USVs. The author also added a cumulative inflation rate of 20% to the estimated cost in conjunction with the best fitting regression model.

Using a similar process as the data analysis portion in Chapter V, the author used the JMP software to acquire the best fitting multiple non-linear regression model by adding quadratic terms and using first order interactions using the 40 datapoints from Table 34. Figure 41 depicts the actual versus predicted plot, the summary of fit, the analysis of variance, as well as the predicted mathematical expression for the estimated cost of a maritime vessel given the size, tonnage and speed. The R-squared value of 0.80 indicates an acceptable model fit.

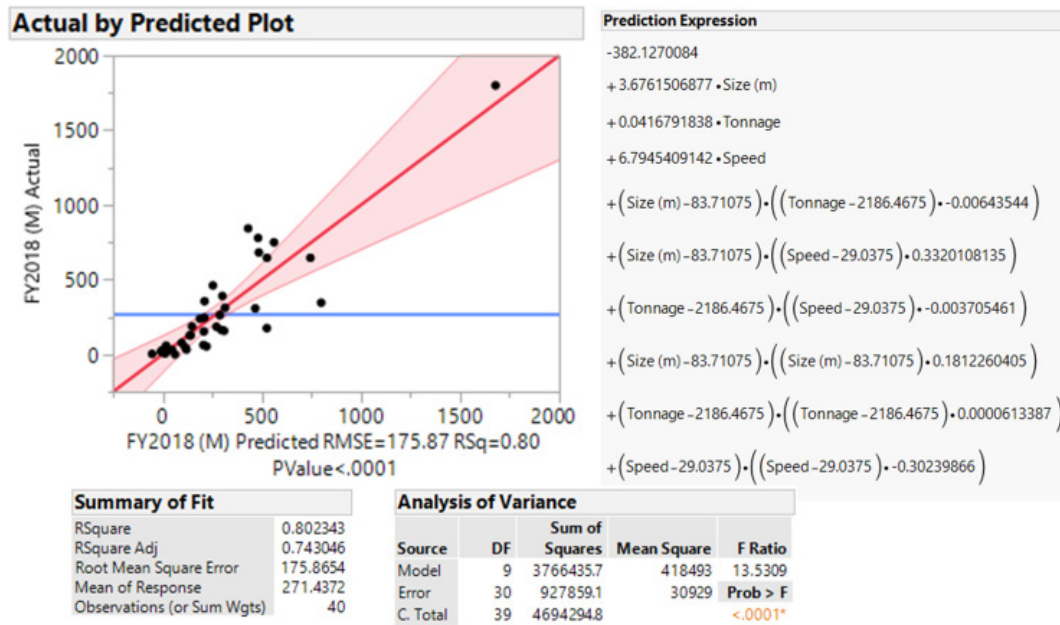


Figure 41. Parametric Cost Model

Using the predicted mathematical expression derived from the regression model, the author was able to estimate the cost of the alternative USVs, shown in Table 35. As Chapter III described, the alternative USVs could potentially fit the design characteristics of either the E, F or G class, depending on the platform. The author designed the USV AMD A and USV SUW platforms to be approximately 51 meters long, which falls into the G class unmanned surface vehicle; whereas, the USV AMD M and USV ISR platforms, having 40-meter and 30-meter lengths, respectively, fall into the F class unmanned surface vehicle. The author's operational experience, supplemented by reasonable expectations of similarly sized platforms, determined each platform's design speed and tonnage. The initial cost was calculated solely based on the model's mathematical expression, then the autonomous suite upgrade as well as the inflation were added to predict the total cost per unit in millions of dollars, displayed in the far-right column in Table 35.

Table 35. Estimated Alternative USV Costs

Platform	Size (m)	Tonnage	Speed (Knots)	Cost (\$M)	Autonomous Suite Upgrade	2030-2035 Time Frame Factor	Total Cost per unit (\$M)
USV AMD A	51	550	33	42.43	2	1.2	53.32
USV AMD M	40	495	27	30.49	2	1.2	38.99
USV SUW	51	550	33	42.43	2	1.2	53.32
USV ISR	30	220	25	25.13	2	1.2	32.56

The next step in the cost analysis process was to take the total cost per unit of each USV platform and implement an equation for each of the 15,360 data runs that the author collected at the end of the model simulation. The equation was simply the number of each type of USV platform multiplied by the cost of that specified platform to give a total cost for USVs in a given scenario. The following section will discuss how the author used this information to analyze cost versus operational effectiveness in the DMO scenario.

2. Cost versus Operational Effectiveness

The author chose to analyze the cost versus operational effectiveness using the top three MOEs identified in Chapter V versus the total cost of the combined USV platforms per scenario. Given the subjectivity of the operational requirements and associated risks, the author chose to present four investment scenarios that describe the trade space associated with each scenario. Those four scenarios are:

- \$0 investment, corresponding to no USV capabilities
- \$500 million investment into the USV program
- \$1000 million investment into the USV program
- \$1500 million investment into the USV program

Note that this analysis is not focused on identification of a single combination of USVs that is “best” or “optimal” for a given investment scenario, rather the goal is to characterize the feasible and infeasible combinations for each scenario and the contour profiler approach suggests realistically appropriate combination for each scenario. To conduct the analysis, the author made some underlining assumptions and offered applicable explanations, depicted in Table 36, to scope the trade-space.

Table 36. Cost versus Operational Effectiveness Assumptions

Assumption	Explanation
The USV ISR platform is always present.	The ISR platform was operationally significant in both MOE #2 and #6. The author considers the ISR platform as a necessity in the future force structure of the fleet. Having at least one ISR platform will add \$32.56 million to the overall cost.
The USV SUW platform are not present.	The SUW platform did not provide any operational impact to any of the MOEs; therefore, it was omitted from the cost vs. operational effectiveness analysis.
Velocity of USV is held constant at 30 knots.	The average design speed of all the USV platforms was approximately 30 knots. 30 knots is a feasible speed specification compared to an optimistic 58 knot design.
USV AMD A and AMD M platforms were varied from 0–25 in quantity.	The anti-missile defense platforms proved operationally impactful in both MOE #4 and #6. The author considers a combination of these platforms as a necessity in the future force structure of the fleet. Each platform brings its own associated cost, as show in Table 35.
All other input variables were held fixed at their mean.	The focus of this analysis is the cost of the USV platform input variables versus their operational impact to the DMO concept. No other input variables were considered for this particular analysis.

The author used the JMP statistical analysis software, previously used for the data analysis, to explore the design space using contour mapping as described in Whitcomb and

Beery (2016). Contour mapping is a dynamic analysis that allows the creator to set low or high limits of the desired measure of effectiveness to determine the necessary quantities of USVs to meet the given objectives. Since the USV ISR platform, the USV SUW platform and the USV velocity were all fixed (as expressed in Table 36), the remaining two USV platforms (AMD A and AMD M) were set as the x and y axis parameters for all cost scenarios. The purpose behind the analysis was to provide the least expensive combination of USVs while still having an operational impact in the DMO scenario. The author would like to specify that the combinations of the required MOE standards and the amount of money associated with the unmanned surface vehicle programs are subjective and have not been verified with actual decision makers. It is ultimately up to the designated stakeholders to set operational requirements and the associated risks and benefits with cost versus the operational impact of the alternative USVs discussed throughout this thesis.

As mentioned, the first scenario of interest is the scenario where no USVS are present in the model, which corresponds to a \$0 investment. This was necessary due to the importance of establishing a baseline comparison before beginning the analysis of different compositions of USVs in the DMO concept. Table 37 depicts the results of the expected performance given a zero-dollar investment from the Navy. For the following baseline and three investment scenarios, a hypothetical example was used from Chapter 5, Section C, for illustration purposes. The example consisted of 90 enemy platforms firing a 6-missile salvo each for a total of 540 inbound missiles. Take into consideration that the model is a DES, therefore, not all 90 enemy platform and their corresponding missiles engaged simultaneously

Table 37. \$0 Cost Constraint

Output Function	Results
Predicted Cost (in millions of dollars)	\$0
MOE #2: Predicted percentage of Enemy killed	62%
MOE #4: Predicted percentage of Enemy missiles within 10 nautical miles of friendly forces	46.5%
MOE #6: Predicted percentage of successful defensive measures	71%

Regarding the example, the minimum quantity of 46.5% of enemy missiles within 10 nautical miles corresponds to roughly 251 enemy missiles. The predicted percentage of successful defensive measures, at 71%, corresponds to approximately 73 out of the 251 enemy missiles unsuccessfully countered. This is the expected number of enemy missiles unsuccessfully countered when the friendly force structure is the conventional CSG, ESG and SAG in the DMO scenario. This information is the baseline for the remaining investment scenarios to compare and contrast expectations for performance when investing in \$500 million increments.

For the first investment scenario (the \$500 million investment), the author adjusted the desired MOE limits to reflect the improvement in operational effectiveness that can be expected as a result of the investment. Table 38 depicts the results of the expected operational effectiveness of all three MOEs given the \$500 million constraint. Note that no formal optimization strategy was employed, rather the author subjectively increased each MOE value by an approximately equal amount. Of note, the white space in the contour mapping figures depict the trade-space available to meet the required MOEs and cost parameters. In every contour map figure, the author chose the combination of USVs that were the closest to the cost constraint while satisfying operational constraints associated with the improved operational effectiveness shown in Tables 38–40.

Table 38. \$500 Million Cost Constraint

Output Function	Results
Predicted Cost (in millions of dollars)	\$494 million
MOE #2: Predicted percentage of Enemy killed	70%
MOE #4: Predicted percentage of Enemy missiles within 10 nautical miles of friendly forces	42%
MOE #6: Predicted percentage of successful defensive measures	73%

Figure 42 provides the contour map for the \$500 million constraint. To meet the feasible percentages of the MOEs while still maintaining a cost of less than \$500 million, the recommended number of USV AMD M and USV AMD A platforms is three and six, respectively. This USV combination is approximately \$494 million. This is the least expensive investment of the three investment scenarios, and when compared to the baseline scenario, provides some improvement for all three MOEs. Using the same hypothetical example as previously discussed, the minimum quantity of 42% of enemy missiles within 10 nautical miles corresponds to roughly 227 enemy missiles instead of 251 enemy missiles from the baseline scenario. The predicted percentage of successful defensive measures, at 73%, corresponds to approximately 61 enemy missiles unsuccessfully countered vice the 73 enemy missiles from the baseline scenario.

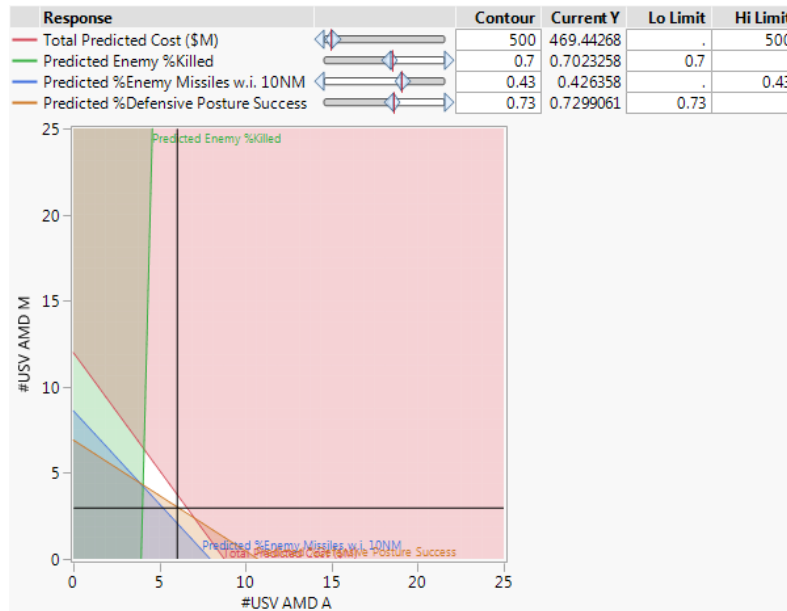


Figure 42. Contour Map of \$500 Million Investment Scenario

For the second investment scenario (the \$1000 million investment), the author adjusted the desired MOE limits to reflect the improvement in operational effectiveness that can be expected as a result of the investment. Table 39 depicts the results of the expected operational effectiveness of all three MOEs given the \$1000 million constraint.

Table 39. \$1000 Million Cost Constraint

Output Function	Results
Predicted Cost (in millions of dollars)	\$1000 million
MOE #2: Predicted percentage of Enemy killed	70%
MOE #4: Predicted percentage of Enemy missiles within 10 nautical miles of friendly forces	37%
MOE #6: Predicted percentage of successful defensive measures	76%

Figure 43 provides the contour map for the \$1000 million constraint. To meet the feasible percentages of the MOEs while still maintaining a cost of less than \$1000 million, the recommended number of USV AMD M and USV AMD A platforms is 18 and five,

respectively. This USV combination is approximately \$1000 million. This is the second least expensive investment of the three investment scenarios and improves MOE #4 and MOE #6. Using the same hypothetical example as before, an MOE #4 of 37% corresponds to approximately 200 enemy missiles reaching within 10 nautical miles versus the 251 enemy missiles from the baseline scenario; and a 76% success rate for MOE #6 reduces the number of unsuccessfully-counteracted enemy missiles from 73 in the baseline scenario to 48.

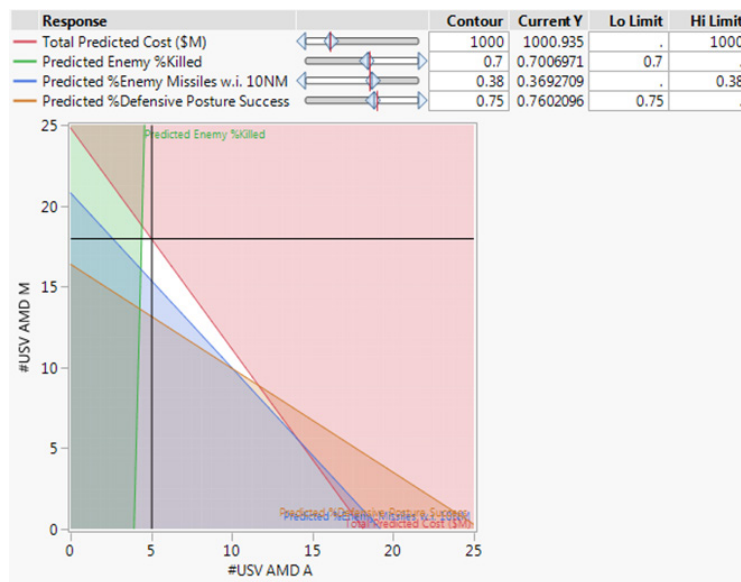


Figure 43. Contour Map of \$1000 Million Investment Scenario

For the last investment scenario (the \$1500 million investment), the author adjusted the desired MOE limits to reflect the improvement in operational effectiveness that can be expected as a result of the investment. Table 40 depicts the results of the expected operational effectiveness of all three MOEs given the \$1500 million constraint.

Table 40. \$1500 Million Cost Constraint

Output Function	Results
Predicted Cost (in millions of dollars)	\$1487 million
MOE #2: Predicted percentage of Enemy killed	70%
MOE #4: Predicted percentage of Enemy missiles within 10 nautical miles of friendly forces	32%
MOE #6: Predicted percentage of successful defensive measures	78%

Figure 44 provides the contour map for the \$1500 million constraint. To meet the feasible percentages of the MOEs while still maintaining a cost of less than \$1500 million, the recommended number of USV AMD M and USV AMD A platforms is 25 and nine, respectively. This USV combination is approximately \$1487 million. This is the most expensive investment of the three investment scenarios and has the best outcome for MOE #4 and MOE #6. Using the same hypothetical example as before, an MOE #4 of 32% corresponds to approximately 173 enemy missiles reaching within 10 nautical miles versus 251 enemy missiles from the baseline scenario, and a success rate of 78% for MOE #6 reduces the number of unsuccessfully-counteracted enemy missiles from 73 in the baseline scenario to 38.

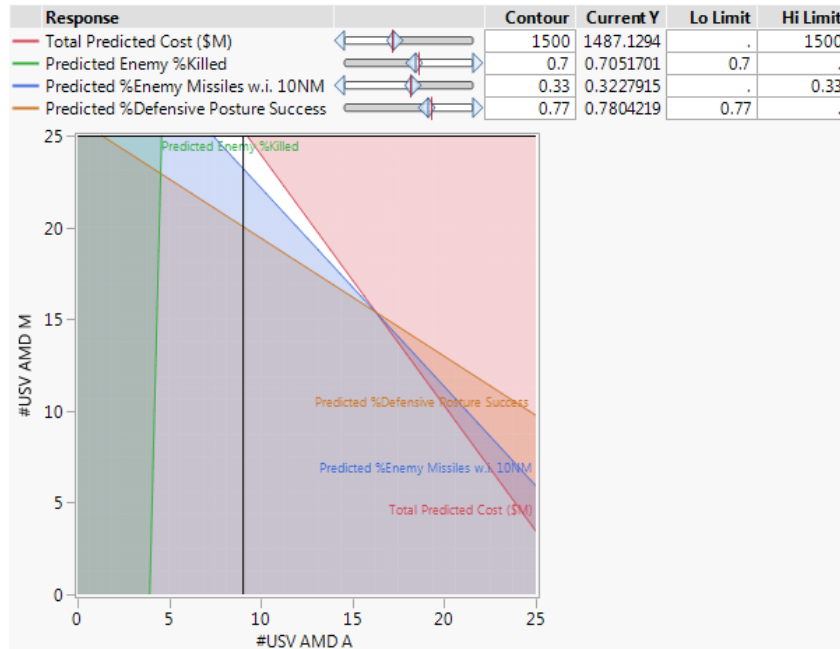


Figure 44. Contour Map of \$1500 Million Investment Scenario

When comparing the three investment scenarios, the common factor that remains constant is the percentage of enemy platforms killed, which is approximately 70%. Therefore, as an illustration, if a decision maker's primary concern is MOE #2 (the maximum destruction of enemy forces), then the \$500 million investment would be the best strategic option since there is no additional operational effectiveness, regarding MOE #2, with increased investment. However, the ideal choice is subjective since money is the limiting factor; therefore, Table 41 illustrates a comparison summary and shows a tangible expectation as the cost of investment increases. The tangible expectation is based on the hypothetical example given in the preceding paragraphs and is quantified as the percentage increase of effectiveness based for MOE #2, MOE #4 and a version of MOE #6 in the given investment scenarios. The baseline performance is also shown for the sake of comparison. Of note, since the actual number of enemy missiles are changing variables, it is more important to focus on the percentage improvements as the investment increases.

Table 41. Cost Scenario Comparison Summary

Investment Scenario	Actual Cost	USV Quantity	Predicted Percentage of Enemy Killed	MOE #2 Comparison	Predicted Percentage of Enemy Missiles within 10 NM	MOE #4 Comparison	Predicted Percentage of Successful Defensive Measures	MOE #6 Comparison
\$0 Million	\$0 Million	0 ISR 0 AMD M 0 AMD A	62%	Baseline- no improvement	46.50%	Baseline-no improvement	71%	Baseline-no improvement
\$500 Million	\$494 Million	1 ISR 3 AMD M 6 AMD A	70%	12.9% improvement from baseline	42%	9.7% improvement from baseline	73%	2.8% improvement from baseline
\$1000 Million	\$1000 Million	1 ISR 18 AMD M 5 AMD A	70%	12.9% improvement from baseline	37%	20.4% improvement from baseline	76%	7% improvement from baseline
\$1500 Million	\$1487 Million	1 ISR 25 AMD M 9 AMD A	70%	12.9% improvement from baseline	32%	31.2% improvement from baseline	78%	9.9% improvement from baseline

Another insight that was important to address was the performance expectations when the USV ISR platform was not present in the analysis. The insight was of particular interest since it illustrated the importance of the USV ISR platform and how beneficial it was compared to its associated costs. Using the \$1500 million investment scenario, when investing in one ISR platform, the impact to MOE #2 (the Enemy's Survivability) changes by a total of five percent. This corresponds to eight additional enemy platforms being destroyed per run. This is shown in Figure 45, which depicts the contour maps of \$1500 million investments with both scenarios side-by-side and the corresponding MOE #2 circled in red. The composition of USV AMD A and AMD M platforms had to be rearranged to maintain MOE #4 and MOE #6 parameters; however, the cost remained the same at roughly \$1487 million per scenario.

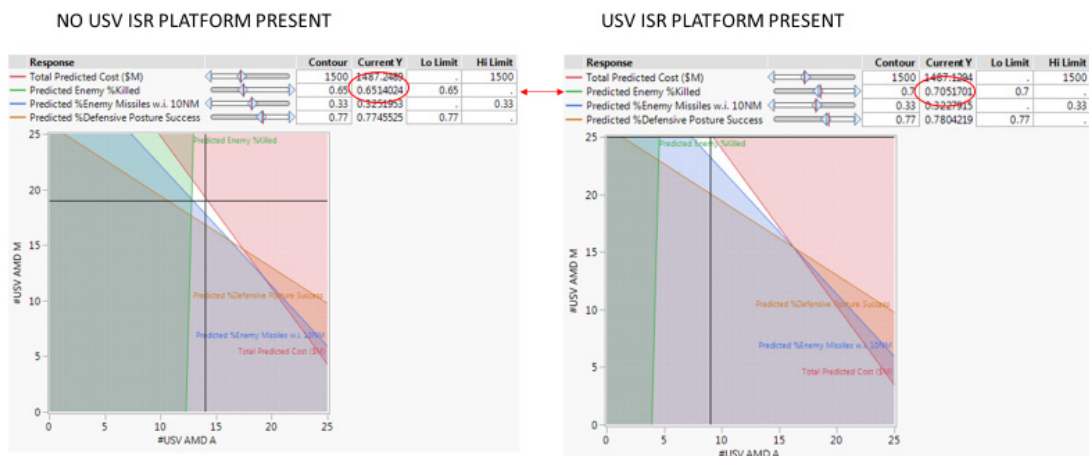


Figure 45. USV ISR Platform Improvement

This is quite interesting since the predicted enemy survivability changes for each scenario, yet the cost is the same. It is imperative for the Navy to invest in the USV ISR platform, since it results in a 5% decrease to enemy survivability with no decrease in performance to any other MOE and without an increase to cost or the total number of platforms required for the operation.

B. CONCLUSIONS

The purpose of this thesis was to investigate the incorporation of unmanned surface vehicles in the context of Distributed Maritime Operations. The goal was to expand on SEA 27 cohort's capstone report by focusing on the implementation of unmanned surface vehicles in DMO, while still utilizing the effective tactics that the report identified, namely, physical and mechanical countermeasures, jamming tactics, emission control, and swarm tactics. Chapter 1 presented two research questions; the following paragraphs will address and comment on each.

- a. ***Does the incorporation of unmanned surface vehicles, in the context of Distributed Maritime Operations, provide a more cost- and operationally- effective order of battle compared to the conventional United States (U.S.) Navy Carrier Strike Group (CSG) configuration, Expeditionary Strike Group (ESG) configuration or the Surface Action Group (SAG) configuration?***

The incorporation of USVs in DMO has both a cost effective and operationally effective order of battle compared to the conventional force structures of the U.S. Navy's CSG, ESG and SAG. The author initially proposed a functional and physical architecture for a generic unmanned surface vehicle in Chapter III, then goes on to develop three alternative designs to be analyzed in the thesis' model as described in Chapter 4. The Intelligence, Surveillance and Reconnaissance mission as well as the Anti-missile Defense mission proved to have the most statistical significance and operational impact regarding the prescribed measures of effectiveness annotated in the beginning of Chapter 5. Three measures of effectiveness stood out as the most interesting among the six that were identified. The following bullet points explain the three most interesting measures in the context of the operational impact from USVs:

* MOE #2: Surviving Enemy Force. This MOE was significantly impacted by whether an USV ISR platform was present or not. A maximum decrease of approximately 5.9% of the enemy force survivability can be expected if the USV ISR platform is present. This seems small, but a 5.9% change is approximately 9 enemy platforms destroyed in the given model scenario.

* MOE #4: Percentage of Enemy Missiles within 10 NM. This MOE was significantly impacted by the number of USV AMD M and USV AMD A platforms present in the model. A maximum decrease in approximately 8.5% of the number of enemy missiles reaching 10 nautical miles is expected when given the correct composition of USV AMD platforms.

* MOE #6: Defensive Measure Success. This MOE was significantly impacted by the number of USV AMD M and USV AMD A platforms present in the model. A maximum increase of approximately 4% of the defensive measure success is expected when given the correct composition of USV AMD platforms.

For the cost effectiveness aspect, Chapter 6 addressed a baseline scenario where no investment was made into the alternative USVs, and additionally three investment scenarios, incremented sequentially by \$500 million. Based off the data analysis, it was shown that the only USVs worth investing in were the USV ISR, USV AMD A and the USV AMD M platforms. For the specified concept of operations and the fixed order of battle, regarding manned assets, the author believes that implementing specific combinations of USVs in the order of battle is a cost-effective approach in achieving the desired measures of effectiveness.

When looking at just the first increment of \$500 million invested compared to the baseline scenario, it was determined that the three pertinent MOE's, #2, #4 and #6, improved when compared to a baseline configuration that does not utilize USVs by 12.9%, 9.7% and 2.8%, respectively. If a decision maker can justify making this investment, which is comprised of at least one USV ISR platform, three USV AMD M platforms and six USV AMD A platforms, the performance benefits seems to outweigh the initial investment. An example is provided to illustrate the cost and risk benefits: suppose the U.S. Navy has the procurement option of either one LCS, which is approximately \$642 million (O'Rourke 2018b), or the procurement of 10 USV platforms, which is approximately \$494 million. The 10 USVs provide a more in-depth distributed layered defense as well as a robust maritime ISR platform (using the \$500 million investment scenario platform recommendation). The risk benefits are also greatly affected since the LCS requires approximately 42 core crew plus up to 35 mission crew, whereas the USVs have no risk to

human life if destroyed. Also, the LCS is only one ship, providing the enemy one radar cross section to find, target, and destroy, whereas 10 USVs provide the enemy more targets to find, target, and destroy, causing the enemy to use additional assets and time. As previously mentioned in Chapter 1, the U.S. Navy's ambition is to have a 355-ship fleet. This objective is very feasible when considering the above conclusions of the cost effectiveness as well as the operational impact that USVs bring to the maritime domain. The author agrees with late Senator John McCain's recommendation of procuring "larger numbers of smaller and relatively cheaper systems...rather than smaller numbers of larger more expensive systems" (McCain 2017, 9) in the future acquisition the U.S. Navy fleet. This thesis' analysis results have shown that a 355-ship fleet (consisting of both manned and unmanned system) is a realistic option in regard to implementing cost effective and operationally impactful USVs into the mix.

b. What are the critical parameters that need to be met in the future designs of unmanned surface vehicles specific to the DMO concept?

This thesis determined through research and analytical tools that the most critical parameters that need to be met in the future designs of unmanned surface vehicles are the following: (1) Have a standardized USV design configuration that can utilize multiple payload mission packages, allowing industry to have specific guidance in terms of U.S. Navy requirements. (2) Construct larger unmanned surface vehicles, either in the F or G class realm, allowing for greater payloads capacities to support systems like: launching systems, missiles, high performance radars, and EW equipment. Lastly, (3) ensuring that the USV's autonomous suite is reliable and functioning and integrated into the command and control network and common operating picture. This allows for manned and unmanned assets to be in a distributed network where humans and machines can work together to accomplish the desired effect, whether that be manned assets acquiring targeting information and launching missiles from USVs or USVs providing early warning detection and communicating enemy locations via link to manned assets.

C. RECOMMENDATIONS AND FUTURE WORK

The author's overall objective in conducting research on unmanned surface vehicles in the DMO concept was to ultimately provide a solid recommendation on whether the Navy should continue to invest in unmanned systems in the maritime domain. The naval community as a whole has accepted and started the transition to utilizing unmanned systems, specifically UASs, however, based off the results of his research and analysis, the author strongly recommends the continual investment into unmanned surface vehicles.

The primary recommendation is to implement a standardized USV design based off of the necessary stakeholder requirements, like Chapter III's physical architecture. Once the design is standardized, the secondary recommendation is to move towards development and construction of multiple USV platforms, specifically having the ISR and AMD based mission modules. The recommended investment would be the first investment scenario of \$500 million, described previously in this Chapter, which would be the procurement of an initial 10 USVs: one ISR platform, three AMD M platforms, and six AMD A platforms. It would then be imperative to integrate the 10 USVs into one of the CSGs, ESGs or SAGs to start the transition and implementation of new tactics, strategy, and naval doctrine. This would be the starting point for lessons learned, focus groups, and an iterative learning process to ensure that the implementation of USVs in the DMO force structure is as smooth transition as any other unmanned system. Baby steps is the key in this process and that is why the author recommends the least expensive investment scenario to initiate the unmanned surface vehicle paradigm.

Some areas of future work that was realized throughout this analysis was the fact that the research and model omitted two primary domains; the undersea and cyber domains. This was due to the author's lack of operational and tactical experience in these realms. The undersea domain, with its corresponding ASW mission, is a definite area that unmanned systems are operating and will continue to be key enablers in the future. Future work could incorporate both friendly and enemy undersea forces in their applicable kill chains, and an analysis of possible USV's with an applicable ASW mission module package. Another idea would be to incorporate the cyber domain by implementing the cyber kill chain and the applicable systems that both the enemy and friendly forces could

exploit. The concept of unmanned systems having the capability of cyber warfare is a unique idea and could be further investigated to see if this is a feasible and effective use for USVs. Lastly, another idea for future research could be to conduct an in-depth cost analysis of the proposed USVs based off of system components and materials, which is a build-up cost approach, the most detailed of all the cost estimating techniques.

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APPENDIX A. MARITIME WAR OF 2030 SCENARIO

The following paragraphs set the tone and scenario for the author's thesis. The narrative is extracted from the Naval Postgraduate School's Joint Campaign Analysis (JCA) course and the SEA 27 (2018) capstone report.

2030 Political, Social, and Economic Narrative:

Although **China's** economic growth began to slow in 2018, she continued her political, fiscal, economic, and military expansionism. In 2030 China is the world's first economy, has a large and growing middle class population and consequently generates a higher demand for oil and natural gas. Relationships between **Russia** and China are thriving, underwritten by a strong energy trade. China depends on the trans-Siberian pipeline developed after negotiations with Russia on oil purchases were signed in 2014. Further economic ties were generated by a series of trade agreements that began in 2019.

Since 2015 the increased economic and social ties between mainland **China and Taiwan**, combined with an economically (yet not necessarily democratically) more liberal Chinese central government, resulted in a 2025 non-aggression treaty between the two states with agreements to begin discussions on unification. By 2030, although not yet under "one government," the Taiwan parliament has Communist party representation and the joint government, military and economic initiatives between China and Taiwan have grown to the point they are a de-facto Chinese economic and military federation. For example, Taiwan has allowed China to build High Frequency Surface Wave radar stations and passive collection systems on Taiwan with joint intelligence sharing responsibilities. Taiwan no longer relies on military sales from the United States.

China has populated several islands terra-formed through dredging in 2015 with military installations. For example, Fiery Cross Reef has a squadron of J-20s (fifth generation plus) with 10 Dark Sword UCAVs, while both Fiery Reef, Gaven Reef, and Hughes Reefs have both surface to air installations (S-500) and anti-surface cruise missile mobile sites (advanced YJ-62s). China is now building facilities on terra-formed islands made from the western end of the Scarborough Shoal reef, protested by the Philippines and the United States.

Tensions remain high on the **Korean Peninsula** with **North Korea** developing greater ballistic missile and cruise missile capabilities. The successful submarine launched ballistic missile in 2017 was followed by a series of failures, then successes of both land launched and sea launched ballistic missiles and well as shore to ship cruise missiles. North Korea retains a nuclear capability.

Japan and the United States have strengthened their social, economic, and military ties in response to China's and Russia's growing influence. The Yokosuka naval facility has

evolved to a joint JMSDF and United States Navy base with GEORGE WASHINGTON and its air wing, three United States DDGs, eight United States LCSs, and the Japanese fleet sharing the installation. In Sasebo, the United States Navy retains LHA-6, LPD-25 and LSD-52 and two LCS for mine clearance and protection.

The United States also established closer ties to **Singapore**, stationing eight LCSs, a squadron of P-8s and their shore support in the city-nation. In addition, the United States now maintains logistic support bases in Diego Garcia and pre-positioned expeditionary supplies in Subic, with joint agreements with the U.K. and Philippines respectively. These bases can act as “rapid build-up” support bases if the host country agrees. Additionally, the Philippines have invited the United States Air Force to use Clark AFB as an expeditionary field. It is currently used in joint training exercises. The United States Air Force has retained Kadena AFB on Okinawa, and III MEF completed its move from Futenma to the newly constructed land-fill air base in Henoko village.

South and East China Sea:

In the spring of 2029, a Vietnamese fisher was rammed and sunk by a Chinese maritime security ship. The Chinese government justified the unfortunate action as an enthusiastic Captain defending China’s EEZ rights, although similar incidents have occurred over the past 20 years. Vietnam did not accept the rationale and vowed their fishing fleet, as well as their at sea drilling rigs, would henceforth be protected. Two weeks later a Chinese deep-sea exploration ship exploded without warning 100 nautical miles north of Natuna Besar.

China claimed either Vietnam, Indonesia or the Philippines were responsible. They mobilized their South China Seas fleet and demanded restoration from all three countries or they would “secure” their sea. One month later the Chinese sank a patrolling Vietnamese ship using a land-based surface to surface missile launched from Woody Island (YJ-83) in the Paracels and moved a squadron of SU-37s to Woody Island. They announced all traffic through the South China Sea would henceforth be subject to inspection and control by Chinese forces. They threatened to assume governorship of the island of Natuna Besar Indonesia to control the South China Sea’s southern approaches and in compensation for the attack on their deep sea exploration ship. The 1st Marine Brigade at Zhanjiang, Guangdong has embarked in the South China fleet’s amphibious flotilla (13 landing ships modernized Type 71 LPDs and Type 72II LSTH). They can be underway in one day’s notice and intelligence indicates their objective is the occupation of Natuna Besar.

During these events a Philippine helicopter fired on a PLAN Type 56 corvette conducting gunnery exercises four miles from Palawan Island. In response, China also threatened invasion of Palawan. Increased activity by the PLA’s 124th Amphibious Mechanized Infantry Division in Guangzhou district indicates they may be readying for this operation. Indonesia, Vietnam, and the Philippines have requested UN support, specifically calling on the United States and Japan to act. In response, China has warned Japan and the United States any interference with their enforcement policy will lead to war, with the threat of nuclear escalation. To show their resolve, China mobilized the East Sea and South Sea fleets and sailed at least 50 submarines from both fleets, including two SSGN on what are

assessed to be strategic deterrence patrols. They have declared a quarantine on all military logistics support (including oil) to Okinawa and have set up ships in blocking positions around the island to conduct MIO.

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APPENDIX B. DETAILED ORDER OF BATTLE

This appendix illustrates the loadouts and speed specifications for both friendly and enemy force platforms and missiles.

Table 42. Friendly Force Missile Loadouts. Adapted from SEA 27 (2018).

	SM-2	SM-3	SM-6	LRASM	MST	HARPOON	ESSM	AIM	HELFIRE	AMRAAM	HARM
<i>CVN</i>							24				
<i>LHA/ LHD</i>							24				
<i>LPD</i>							21				
<i>CG</i>	36	5	25	8	14	8	12				
<i>DDG-51</i>	32	5	10	8	8	8	12				
<i>DDG-1000</i>	10		10	6	30		12				
<i>LCS</i>						4	21				
<i>USV ISR</i>											
<i>USV SUW</i>				4	4						
<i>USV AMD A</i>			8								
<i>USV AMD M</i>							16				
<i>F-35 (A)</i>								2	4	4	
<i>F-35 (S)</i>				4		2			2		2
<i>F/A-18 (A)</i>								2	4	4	
<i>F/A-18 (S)</i>				4		2			2		2
<i>EA-18</i>								4			
<i>E-2</i>											
<i>P-8</i>											
<i>MH-60</i>									4		

<i>AH-1</i>								2	16		
<i>MQ-4</i>											
<i>MQ-8</i>									2		
<i>MQ-9</i>								2	8		
<i>TERN</i>									4		

Table 43. Friendly Force Platform and Missile Speeds. Source: SEA 27 (2018).

Surface Combatants		Aircraft		Missiles	
CVN	34	F-35	1100	SM-2	2300
LHA/LHD	25	F/A-18	1085	SM-3	6620
LPD	25	EA-18	1085	SM-6	2300
CG	32	E-2	400	LRASM	650
DDG-51	32	P-8	550	MST	650
DDG-1000	35	MH-60	120	HARPOON	470
LCS	45	AH-1	120	ESSM	2630
USV ISR	0-60	MQ-4	320	AIM	1650
USV SUW	0-60	MQ-8	150	AMRRAM	2630
USV AMD	0-60	MQ-9	330	HARM	1200
		TERN	70		
<i>Speeds in Knots (Nautical Miles per Hour)</i>					

Table 44. Enemy Force Missile Loadouts. Adapted from SEA 27 (2018).

	YJ-12	YJ-18	YJ-83	YJ-100	FN-16	HQ-10	HQ-16	CM-102	PL-9	PL-12	VLRAAM
<i>Carrier</i>	10					120					
<i>Renhai</i>		20		50			20				

<i>Luyang</i>		30	10				10				
<i>Jiangkai</i>			6				18				
<i>Jiangdao</i>			4								
<i>Houbei</i>			6		2						
<i>LHD</i>					10						
<i>LPD</i>					10						
<i>LST</i>					5						
<i>J-11</i>								2		4	
<i>J-15(A)</i>									2	2	
<i>J-15 (S)</i>		4									
<i>J-16 (A)</i>								2	2	4	
<i>J-16 (S)</i>		4	6								
<i>J-16D (EW)</i>							8				
<i>J-20</i>								2	2	4	
<i>Q-5</i>	4								4		
<i>H-6K</i>	6			6							
<i>KJ-3000</i>											
<i>Y-8FQ</i>											
<i>Z-18</i>			2								
<i>Z-8AEW</i>			2								

Table 45. Enemy Force Platforms and Missiles Speeds. Source: SEA 27 (2018).

Surface Combatants		Aircraft		Missiles	
Type 001/002/003 Carrier	22	J-11 Fighter	660	DF-21D	6620
Type 055 Renhai	25	J-15 Fighter	1130	DF-26	7920
Type 052 Destroyer	22	J-16 Fighter	660	YJ-62	465
Type 054 Frigate	20	J-16D EW	660	HY-2	540
Type 056 Corvette	20	J-20 Fighter	1130	YJ-12	1980
Type 022 Missile Boat	30	Q-5 Surface Attack	370	YJ-18	1980
Type 075 LHD	20	H-6K Bomber	560	YJ-62	465
Type 071 LPD	20	KJ-3000 AEW	220	YJ-83	600

Type 072 LST	20	Y-8FQ MPRA	350	YJ-100	465
		Z-18 Helo	120	FN-16	1110
		Z-8AEW	120	HQ-10	1330
		Soaring Dragon	300	HQ-16	2770
		Pterodactyl	120	CM-102	2380
		Dark Sword	600	PL-9	2300
				PL-12	2625
				VLRAAM	3990
Speeds in Knots (Nautical Miles per Hour)					

APPENDIX C. GENERIC SENSOR AND MISSILE PERFORMANCE AND EXAMPLE PROBABILITIES FOR THE FTE KILL CHAIN

This appendix annotates the capabilities and performance parameters for the generic sensors and missiles onboard enemy platforms. Table 47 explicitly depicts what primary sensors are used for the Find and Target phase for each of the enemy platforms and Tables 49 and 50 give specific examples of the performance expectations when an enemy platform is assigned to find, target and engage a friendly force carrier.

Table 46. Generic Sensor Ranges. Adapted from SEA 27 (2018).

Sensor	Range (Nautical Miles)
Visual	10
Infrared	25
ESM (Electronic Support Measures)	150
Air Search Radar	160
Surface Search Radar	150
Fire Control Radar	40
Navigation Radar	40
Phased Array Radar	180
AESA (Active Electronic Scanned Array Radar)	200
Over the Horizon Radar	1800
Synthetic Aperture Radar – Maritime	530
Synthetic Aperture Radar – Space	4000

Table 47. Primary Sensors used by Enemy Platforms in the Find and Target Phase. Adapted from SEA 27 (2018).

Enemy Platform	Primary Sensor in FIND Phase	Primary Sensor in TARGET Phase
Carrier	Phase Array Radar	Phase Array Radar
Renhai	Phase Array Radar	Phase Array Radar
Luyang	Over the Horizon Radar	Phase Array Radar

Jiangkai	Phase Array Radar	Phase Array Radar
Jiangdao	Phase Array Radar	Phase Array Radar
Houbei	Surface Search Radar	Fire Control Radar
LHD	Air Search Radar	Fire Control Radar
LPD	Air Search Radar	Fire Control Radar
LST	Surface Search Radar	Fire Control Radar
J-11	Air Search Radar	Fire Control Radar
J-15(A)	AESA	AESA
J-15 (S)	AESA	AESA
J-16 (A)	AESA	AESA
J-16 (S)	AESA	AESA
J-16D (EW)	AESA	AESA
J-20	AESA	AESA
Q-5	Air Search Radar	Fire Control Radar
H-6K	Air Search Radar	Fire Control Radar
KJ-3000	Over the Horizon Radar	Over the Horizon Radar
Y-8FQ	Over the Horizon Radar	Over the Horizon Radar
Z-18	AESA	AESA
Z-8AEW	Air Search Radar	Fire Control Radar
DF-21(D)	SAR (Space)	SAR (Space)
DF-26	SAR (Space)	SAR (Space)
YJ-62	Over the Horizon Radar	Over the Horizon Radar
HY-2	Over the Horizon Radar	Over the Horizon Radar

Table 48. Enemy Missile's Terminal Guidance and Range Specifications. Adapted from SEA 27 (2018).

Missile	Terminal Guidance	Range (Nautical Miles)
DF-21D ASBM	Active Radar	800
DF-26 ASBM	Active Radar	1730
HY-2 ASCM	Infrared	125
YJ-12 ASCM	GPS	215

YJ-18 ASCM	GPS	290
YJ-62 ASCM	Active Radar	215
YJ-83 ASCM	Active Radar	100
YJ-100 ASCM	Inertial Navigation System	430
FN-16 MANPAD	Infrared	4
HQ-10 SAM	Infrared	65
HQ-16 SAM	Active Radar	65
CM-102 ARM	Radiation Seeking	65
PL-9 Air to Air	Infrared	12
PL-12 Air to Air	Active Radar	60
VLRAAM Air to Air	Active Radar	180

The tables below depict an example of the probabilities associated with finding and targeting a friendly carrier (CVN) as well as the associated probabilities of successfully engaging the CVN. Each probability is linked to a specific generic sensor, therefore, as an example, if an enemy platform is using a phased array radar to find the CVN, then the applicable probability of finding (given that the sensor is within the specification range) is 90%.

Table 49. Example of Sensor Performance against Friendly Force CVN

Enemy Sensor	Probability of FINDING the CVN	Probability of TARGETING the CVN
Visual	90%	0%
Infrared	80%	0%
ESM (Electronic Support Measures)	100%	0%
Air Search Radar	40%	0%
Surface Search Radar	85%	0%
Fire Control Radar	0%	99%
Navigation Radar	70%	0%

Phased Array Radar	90%	80%
AESA (Active Electronic Scanned Array Radar)	99%	85%
Over the Horizon Radar	80%	50%
Synthetic Aperture Radar – Maritime	70%	0%
Synthetic Aperture Radar – Space	80%	80%

Table 50. Example of Missile Performance against Friendly Force CVN

Enemy Missile	Probability of ENGAGING the CVN
DF-21D ASBM	95%
DF-26 ASBM	92%
HY-2 ASCM	90%
YJ-12 ASCM	90%
YJ-18 ASCM	85%
YJ-62 ASCM	90%
YJ-83 ASCM	92%
YJ-100 ASCM	92%
FN-16 MANPAD	10%
HQ-10 SAM	0%
HQ-16 SAM	0%
CM-102 ARM	80%
PL-9 Air to Air	0%
PL-12 Air to Air	0%
VLRAAM Air to Air	0%

Lastly, the following three tables depict the probability of kill for each of the enemy and friendly force missiles, as well as the friends force countermeasure effectiveness. Table 51 has three columns categorizing the probability of kill for three groups of platforms: High Value Units (CVN, LHD/LHA), Missile Carriers (LPD, LCS, DDG-51, DDG-1000, CG,

USV SUW, USV AMD) and Aircraft (all air platforms). Table 52 has a similar layout, except the probabilities are broken down into: Surface Vessels, Aircraft, and missiles. Table 53 lists the friendly force countermeasures and their applicable effectiveness against enemy missiles.

Table 51. Enemy Missile Performance Probabilities

Enemy Missile	Probability of Kill (High Value Unit)	Probability of Kill (Missile Carrier)	Probability of Kill (Aircraft)
DF-21D ASBM	95%	90%	-
DF-26 ASBM	92%	92%	-
HY-2 ASCM	90%	80%	-
YJ-12 ASCM	90%	85%	-
YJ-18 ASCM	85%	80%	-
YJ-62 ASCM	90%	80%	-
YJ-83 ASCM	92%	90%	25%
YJ-100 ASCM	92%	85%	-
FN-16 MANPAD	10%	20%	70%
HQ-10 SAM	-	-	80%
HQ-16 SAM	-	-	85%
CM-102 ARM	80%	80%	50%
PL-9 Air to Air	-	-	80%
PL-12 Air to Air	-	-	90%
VLRAAM Air to Air	0%	0%	95%

Table 52. Friendly Missile Performance Probabilities

Friendly Missile	Probability of Kill (Surface Vessel)	Probability of Kill (Aircraft)	Probability of Kill (Missile)
Standard Missile-2	-	85%	80%
Standard Missile-3	-	-	95%
Standard Missile-6	92%	90%	85%
Long Range Anti-Ship Missile	92%	-	-

Maritime Strike Tomahawk	90%	-	-
Harpoon	85%	-	-
HARM	85%	-	-
Evolved Sea Sparrow Missiles	-	85%	80%
Sidewinder	-	85%	-
Hellfire	80%	-	-
Advanced Medium Range Air to Air Missile	-	90%	-

Table 53. Friendly Countermeasure Performance Probabilities

Friendly Countermeasure	Probability of Kill (Missile)
Flare	50%
IR Smoke	50%
Chaff	70%
Active Decoy	80%
Visual Smoke	50%

APPENDIX D. MISSION ASSIGNMENT CRITERIA AND SCORING

This appendix details the scoring matrix and applicable scores for each of the friendly platforms. The results were then used to facilitate a systematic method for the enemy forces in their applicable mission assignment to a type of friendly force platform. If a friendly force platform had the highest-ranking score among potential targets, then it would be more probable that the enemy would be assigned to find, target and engage that specific friendly force platform type.

Table 54. Scoring Criteria Definition. Source: SEA 27 (2018).

COMBAT POWER	SCORE	LEVEL OF REACH
Platform & Assets > 300 missiles/bombs	10	Range > 1000 nautical miles
Platform & Assets 250 – 299 missiles/bombs	9	Range 800 – 999 nautical miles
Platform & Assets 200 – 249 missiles/bombs	8	Range 600 – 799 nautical miles
Platform & Assets 100 – 199 missiles/bombs	7	Range 400 – 599 nautical miles
Platform & Assets 80 – 99 missiles/bombs	6	Range 200 – 399 nautical miles
Platform & Assets 50 – 79 missiles/bombs	5	Range 100 – 199 nautical miles
Platform & Assets 25 – 49 missiles/bombs	4	Range 60 – 99 nautical miles
Platform & Assets 10 – 24 missiles/bombs	3	Range 25 – 59 nautical miles
Platform & Assets 5 – 9 missiles/bombs	2	Range 10 – 24 nautical miles
Platform & Assets 3 – 4 missiles/bombs	1	Range 4 – 9.99 nautical miles
Platform & Assets 0 – 2 missiles/bombs	0	Range 0 – 3.99 nautical miles

Table 55. Scoring of Friendly Platforms. Adapted from SEA 27 (2018).

FRIENDLY PLATFORM	COMBAT POWER SCORE	LEVEL OF REACH SCORE	OVERALL SCORE	RANKING
CVN	10	8	9.20	1
LHA/LHD	9	7	8.20	2
LPD	5	5	5.0	6
CG	7	8	7.40	3
DDG-51	6	7	6.40	5
DDG-1000	6	8	6.80	4
LCS	4	5	4.40	8
USV ISR	0	8	3.20	14
USV SUW	2	4	2.80	15
USV AMD-AIR	2	4	2.80	15
USV AMD-MISSILE	3	4	3.40	12
F-35	3	7	4.60	7
F/A-18	3	7	4.60	7
E/A-18	1	7	3.40	11
E-2D	0	10	4.00	9
P-8	0	9	3.60	10
MH-60	1	5	2.60	16
AH-1	3	4	3.40	13
MQ-4	0	8	3.20	14

MQ-8	0	5	2.00	18
MQ-9	3	7	4.60	7
TERN	1	4	2.20	17

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APPENDIX E. ENVIRONMENTAL CONDITIONS

This appendix illustrates the probabilistic weather condition for each run and its associated sensor degradation factor effect. Also Figure 46 shows how the maritime clutter was calculated.

Table 56. Weather Conditions. Source: SEA 27 (2018).

Percentage of Occurrence	Weather Condition	Sensor Degradation Factor
70%	1: Negligible	0%
20%	2: Marginal	10%
10%	3: Poor	30%

Figure 46 depicts the AIS tracks in the SCS. The mean clutter was determined to 65 vessels with a standard deviation of 10 vessels.

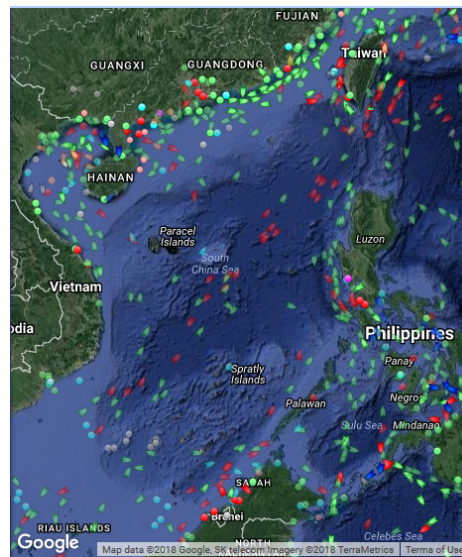


Figure 46. AIS Tracks in the Prescribed Area of Operation. Source: Marine Vessel Traffic (2018).

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APPENDIX F. DEGRADATION FACTORS

Table 57. Degradation Factors. Adapted from SEA 27 (2018).

THREAT SENSOR TYPE	SPOT JAMMING	BARRAGE JAMMING	SWEEP JAMMING	DRFM JAMMING	GPS JAMMING
Visual	1.0	1.0	1.0	1.0	1.0
Infrared	1.0	1.0	1.0	1.0	1.0
ESM (Electronic Support Measures)	1.5	1.5	1.5	1.5	1.5
Air Search Radar	0.75-1.0	0.5-1.0	0.75-1.0	0.75-1.0	1.0
Surface Search Radar	0.75-1.0	0.5-1.0	0.75-1.0	0.75-1.0	1.0
Fire Control Radar	0.75-1.0	0.5-1.0	0.75-1.0	0.75-1.0	1.0
Navigation Radar	0.75-1.0	0.5-1.0	0.75-1.0	0.75-1.0	1.0
Phased Array Radar	0.75-1.0	0.5-1.0	0.75-1.0	0.75-1.0	1.0
AESA (Active Electronic Scanned Array Radar)	0.75-1.0	0.5-1.0	0.75-1.0	0.75-1.0	1.0
Over the Horizon Radar	0.3-1.0	0.75-1.0	0.75-1.0	0.5-1.0	1.0
Synthetic Aperture Radar – Maritime	0.75-1.0	0.5-1.0	0.75-1.0	0.3-1.0	1.0
Synthetic Aperture Radar – Space	1.0	1.0	1.0	1.0	1.0
GPS-Missile Terminal Phase	1.0	1.0	1.0	1.0	0.0-0.8
0 = Maximum/Complete Degradation 1 = No Degradation to Sensor >1 = Adverse Impact (Increased Signature) for Friendly Platforms Ranges follow a uniform distribution between noted minimum and maximum values in table					

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APPENDIX G. E-2D AND USV ISR PLATFORM PERFORMANCE

The following table depicts the generic unclassified ranges of the U.S. Navy's missile arsenal. These ranges are assuming no additional help from friendly assets in extending the missile range coverage.

Table 58. Friendly Force Missile Ranges

Friendly Missile	Range (Nautical Miles)
Standard Missile-2	60
Standard Missile-3	1000
Standard Missile-6	150
Long Range Anti-Ship Missile	300
Maritime Strike Tomahawk	100
Harpoon	65
HARM	80
Evolved Sea Sparrow Missiles	20
Sidewinder	18
Hellfire	4
Advanced Medium Range Air to Air Missile	75

The following matrices depict the effective range of each friendly missile type (in nautical miles) for every E-2D and USV ISR platform combination. The simulation model only considers the two mentioned platforms as either 1 or 0, meaning that it is either present or not present in a given run. Of note, the SM3 is not listed because its effective range is 1000 NM and there is no extended range benefit when either platform is present.

Effective Range (NM) of SM6

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	300	250
<i>E-2D OFF</i>	200	150

Effective Range (NM) of SM2

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	125	100
<i>E-2D OFF</i>	80	60

Effective Range (NM) of ESSM

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	40	30
<i>E-2D OFF</i>	25	20

Effective Range (NM) of LRASM

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	450	400
<i>E-2D OFF</i>	350	300

Effective Range (NM) of MST

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	150	125
<i>E-2D OFF</i>	115	100

Effective Range (NM) of HARM

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	100	90
<i>E-2D OFF</i>	85	80

Effective Range (NM) of HARPOON

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	85	75
<i>E-2D OFF</i>	70	65

Effective Range (NM) of Hellfire

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	10	8
<i>E-2D OFF</i>	6	4

Effective Range (NM) of AMRAAM

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	150	125
<i>E-2D OFF</i>	100	75

Effective Range (NM) of AIM

	USV ISR ON	USV ISR OFF
<i>E-2D ON</i>	25	25
<i>E-2D OFF</i>	24	18

Figure 47. E-2D and USV ISR Platform Performance Matrix

APPENDIX H. SAMPLE DATA EXTRACTED FROM MODEL

Table 59. Sample ExtendSim Model Input and Output Data

Run	#USV ISR	#USV SUW	#USV AMD A	#USV AMD M	Velocit y	% Blue Killed	% Red Killed	% Missiles Killed	%Offens ive Success	%Defensi ve Success	%Red Missiles w.i 10 NM	Total Predicted Cost (\$M)
1	1	5	13	16	0.006	0.284	0.671	0.429	0.571	0.825	0.256	1659.12
2	1	4	19	8	0.011	0.289	0.658	0.536	0.527	0.853	0.101	1413.16
40	1	3	4	10	0.014	0.411	0.738	0.442	0.547	0.810	0.266	881.67
370	1	5	1	23	0.015	0.443	0.698	0.432	0.500	0.629	0.570	1564.51
371	0	19	4	9	0.006	0.308	0.510	0.402	0.585	0.802	0.306	1648.92
372	0	11	21	22	0.016	0.275	0.711	0.362	0.491	0.600	0.475	2578.31
380	0	15	17	17	0.014	0.205	0.698	0.657	0.638	0.907	0.133	2369.04
5000	1	14	17	5	0.016	0.176	0.752	0.625	0.519	0.881	0.227	1708.43
5001	1	23	24	13	0.009	0.111	0.745	0.843	0.521	0.873	0.077	2887.79
5002	0	15	17	16	0.007	0.295	0.745	0.616	0.569	0.874	0.093	2315.72
5004	0	2	19	2	0.009	0.199	0.738	0.645	0.505	0.861	0.186	954.04
5005	1	24	7	23	0.011	0.225	0.718	0.564	0.530	0.851	0.169	2811.52
5010	0	10	0	8	0.009	0.262	0.510	0.352	0.598	0.860	0.249	959.76
15354	0	20	22	3	0.015	0.416	0.691	0.447	0.479	0.697	0.449	2084.09
15357	1	0	0	1	0.011	0.314	0.738	0.320	0.539	0.519	0.560	672.40
15359	0	14	21	14	0.008	0.301	0.564	0.599	0.568	0.697	0.501	2311.70
15360	1	8	25	22	0.010	0.375	0.738	0.364	0.514	0.819	0.317	2608.85
<i>Sample Values for Visualization</i>												

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APPENDIX I. HISTORICAL COST DATA CITATIONS

Table 60. Citations for the Parametric Cost Analysis

Vessel Name	Country	Source
Amazonas-class corvette	Brazil	Fraser, Douglas. 2012 “BAE Systems Sells Patrol Vessels to Brazil - BBC News.” BBC. January 02, 2012. https://www.bbc.co.uk/news/uk-scotland-scotland-business-16383765
Hero-Class Patrol Vessel	Canada	WebCite Query Result. 2009. “Contract for Canadian Coast Guard Mid-Shore Patrol.” September 2009. https://www.webcitation.org/query?url=http://www.casr.ca/doc-ccg-mid-shore-patrol-vessel-2009.htm&date=2009-09-07
Orca-Class Patrol Vessel	Canada	CDN Military. 2006. “New Training Vessels for the Navy: The ORCA Class.” February 2006. https://web.archive.org/web/20110706171833/http://www.cdnmilitary.ca/index.php?p=25
Type 056 Corvette	China	Jr, Richard D Fisher. 2015. “China, Argentina Set for Defence Collaboration, Malvinas-class OPV Deal.” IHS Jane’s Defence Weekly. February 1, 2015. https://web.archive.org/web/20150310030348/http://www.janes.com/article/48512/china-argentina-set-for-defence-collaboration-malvinas-class-opv-deal
Houbei Type 22 missile boat	China	Galrahn. 2018. “Janes Discusses Chinese Streetfighter.” Information Dissemination. August 04, 2009. http://www.informationdissemination.net/2009/08/janes-discusses-chinese-streetfighter.html

Vessel Name	Country	Source
Iver Huitfeldt-class Frigate	Denmark	Cavas, Christopher P. 2014. "Sleek, Modern and Built on a Budget – Denmark's Latest Frigate." Intercepts. November 21, 2014. http://intercepts.defensenews.com/2014/11/sleek-modern-and-built-on-a-budget-denmarks-latest-frigate/
Gowind-class Corvettes	Egypt	Briganti, Giovanni De. 2014. "DCNS Confirms Sale of 10 Gowind Corvettes, Expects More." Defense-Aerospace. October 31, 2014. http://www.defense-aerospace.com/articles-view/feature/5/158485/dcns-confirms-sale-of-10-gowind-corvettes.html
Type 23 Frigate	England	Hansard, Westminster, and House of Commons. "House of Commons Hansard Written Answers for 5 Jul 2001 (pt 5)." House of Commons - Transport, Local Government and the Regions - Appendices to the Minutes of Evidence. https://publications.parliament.uk/pa/cm200102/cmhansrd/vo010705/text/10705w05.htm
Turva Patrol Boat	Finland	Sanomat, Turun. 2011. "Uusi Ulkovartiolaiva on Kallein Vartioalus Koskaan." Ts.fi. November 23, 2011. http://www.ts.fi/uutiset/kotimaa/280788/Uusi+ulkovartiolaiva+on+kallein+vartioalus+koskaan
FTI Medium Size Frigate	France	Tran, Pierre. 2017. "DCNS, Thales Jointly Secure \$4B French Frigate Deal." Defense News. April 24, 2017. https://www.defensenews.com/naval/2017/04/24/dcns-thales-jointly-secure-4b-french-frigate-deal/

Vessel Name	Country	Source
Braunschweig -Class (Corvette)	Germany	Navy Recognition. 2016. "German Navy to Get Five More K130 Braunschweig-class Corvettes." November 14, 2016. http://www.navyrecognition.com/index.php/news/defence-news/2016/november-2016-navy-naval-forces-defense-industry-technology-maritime-security-global-news/4561-german-navy-to-get-five-more-k130-braunschweig-class-corvettes.html
Holland Class OPV	Holland	WebCite Query Result. n.d. "Holland Class Patrol Vessels, Netherlands." Accessed August 16, 2018. https://www.webcitation.org/628y80Q0p?url=http://www.naval-technology.com/projects/hollandclasspatrol/
Kamorta- Class (Corvette)	India	Economic Times. 2018. "INS Kavaratti: Anti-submarine Warfare Class Stealth Corvette Launched." July 14, 2018. https://economictimes.indiatimes.com/news/defence/ins-kavaratti-anti-submarine-warfare-class-stealth-corvette-launched/articleshow/47341938.cms
Saryu-class patrol vessel	India	StratPost News. 2010. "Naval OPV Launched." December 07, 2010. https://www.stratpost.com/naval-opv-launched/
Protector	Israel	Wikipedia. 2018. S.v. "Protector USV." Last modified 24 May 2018. https://en.wikipedia.org/wiki/Protector_USV
Seagull	Israel	Strategy Page. 2017. "Surface Forces: Droids Do The Dirty Work Cheap." August 9, 2017. https://strategypage.com/htmw/htsurf/20170809.aspx
Comandanti- Class Patrol vessel	Italy	Wikipedia. 2018. S.v. "Comandanti-class Patrol Vessel." Last modified 25 February 2018. https://en.wikipedia.org/wiki/Comandanti-class_patrol_vessel

Vessel Name	Country	Source
Protector-class inshore patrol vessel	New Zealand	Wikipedia. 2018. S.v. “Protector-class Inshore Patrol Vessel.” Last modified June 06, 2018. https://en.wikipedia.org/wiki/Protector-class_inshore_patrol_vessel#cite_note-ENZ-2
Protector-class OPV	New Zealand	Radio New Zealand. 2010. “Offshore Patrol Boat Arrives in Home Port.” July 22, 2010. https://www.radionz.co.nz/news/national/54394/offshore-patrol-boat-arrives-in-home-port
Khareef-Class (corvette)	Oman	Naval Technology. n.d. “Khareef Class Corvettes.” Accessed August 16, 2018. https://www.naval-technology.com/projects/khareef-class/ .
Sigma-class corvette	Romania	Butu, Alina Grigoras. 2017. “Defence Ministry to Buy 4 Corvettes by 2024 in a EUR 1.6bn Investment.” <i>The Romania Journal</i> . August 21, 2017. https://www.romaniajournal.ro/defence-ministry-to-buy-4-corvettes-by-2024-in-a-eur-1-6bn-investment/
Karakurt-class corvette	Russia	Kostrinskji, Herman. 2017. “‘Karakurty’ Smear on Shipyards.” <i>Kommersant</i> . July 30, 2017. https://www.kommersant.ru/doc/3371787
Gumdoksuri-class patrol vessel	South Korea	Deagel. 2017. “Gumdoksuri.” Last modified November 27, 2017. http://www.deagel.com/Fighting-Ships/Gumdoksuri_a000091001.aspx
FFX-II Daegu class Frigate	South Korea	Naval Today. 2016. “South Korea Awards Contract for Two More FFX II Frigates.” December 22, 2016. https://navaltoday.com/2016/12/22/south-korea-awards-contract-for-two-more-ffx-ii-frigates/

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Diciotti-Class offshore patrol vessel	Spain	Gaeth, Jonas. n.d. "Diciotti-Class at AFM MARITIME SQUADRON 2nd Regiment." Accessed August 16, 2018. https://web.archive.org/web/20100918060000/http://www.schnellboot.net/mt/diciotti-class/
BAM	Spain	Jane's by IHS Markit. 2018. "Two new Spanish BAM OPVs to be in service by 2019, says Navantia." Aug 15, 2018. https://janes.ihs.com/Janes/Display/jni76406-jdw-2014
Visby-Class Corvette	Sweden	Summers, Chris. "Technology Stealth Ships Steam Ahead." BBC News. June 10, 2004. http://news.bbc.co.uk/2/hi/technology/3724219.stm
Työ Chiang-Class (corvette)	Taiwan	Taipei Times. 2014. "'Carrier-killer' Starts Trials." October 28, 2014. http://www.taipeitimes.com/News/taiwan/archives/2014/10/28/2003603112
Baynunah-Class Corvette	UAE	Jane's by IHS Markit. 2018. "ADSB launches fourth Baynunah-class corvette." Aug 15, 2018. https://janes.ihs.com/Janes/Display/jni74909-jni-2012
MDUSV	USA	Barton, Timothy, and Brintzinghoffer, Dan. 2018. "SEA HUNTER and Maritime Autonomous Behaviors." Presentation at Naval Postgraduate School, Monterey, March 2018.
CUSV	USA	Eckstein, Megan. "Stackley: RMMV, CUSV, Knifefish Will All Play a Role in LCS Minehunting; Not a Competition." April 07, 2016. https://news.usni.org/2016/04/07/stackley-rmmv-cusv-knifefish-will-all-play-a-role-in-lcs-minehunting-not-a-competition
Hammerhead	USA	Naval Drones. n.d. "Hammerhead USV-T." Accessed August 15, 2018. http://www.navaldrones.com/Hammerhead.html

Vessel Name	Country	Source
USS Oliver Perry Class (frigate)	USA	Pike, John. n.d. "FFG-7 Oliver Hazard Perry - class." Accessed August 16, 2018. https://www.globalsecurity.org/military/systems/ship/ffg-7.htm
USS Freedom Class	USA	O'Rourke, Ronald. 2018. <i>Navy Littoral Combat Ship (LCS) Program: Background and Issues for Congress</i> . CRS Report No. RL33741. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/RL33741.pdf
USS Independence Class	USA	O'Rourke, Ronald. 2018. <i>Navy Littoral Combat Ship (LCS) Program: Background and Issues for Congress</i> . CRS Report No. RL33741. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/RL33741.pdf
DDG-51 Flight III	USA	O'Rourke, Ronald. 2018. <i>Navy Force Structure and Shipbuilding Plans: Background and Issues for Congress</i> . CRS Report No. RL32665. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/RL32665.pdf
USCGC Bertholf	USA	Defense Industry Daily. 2007. "USCG National Security Cutters: Bad News, Good News." September 11, 2007. https://www.defenseindustrydaily.com/uscg-national-security-cutters-bad-news-good-news-03776/
Sentinel-class cutter	USA	O'Rourke, Ronald. 2018. <i>Coast Guard Cutter Procurement: Background and Issues for Congress</i> . CRS Report No. R42567. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/R42567.pdf

Vessel Name	Country	Source
Heritage-class cutter	USA	O'Rourke, Ronald. 2018. <i>Coast Guard Cutter Procurement: Background and Issues for Congress</i> . CRS Report No. R42567. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/R42567.pdf
Legend-class cutter	USA	O'Rourke, Ronald. 2018. <i>Coast Guard Cutter Procurement: Background and Issues for Congress</i> . CRS Report No. R42567. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/R42567.pdf

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