2010-09

The Littoral Combat Ship (LCS) Surface Warfare (SUW) module determining the best mix of surface-to-surface and air-to-surface missiles

Jacobson, Kevin Robert

Monterey, California. Naval Postgraduate School

https://hdl.handle.net/10945/5207

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

THE LITTORAL COMBAT SHIP (LCS) SURFACE WARFARE (SUW) MODULE: DETERMINING THE BEST MIX OF SURFACE-TO-SURFACE AND AIR-TO-SURFACE MISSILES

by

Kevin Robert Jacobson

September 2010

Thesis Advisor:	Michael McCauley
Second Reader:	Curtis Blais

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE September 2010	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE The Littoral Combat Ship (LCS) Surface Warfare (SUW) Module: Determining the Surface-To-Surface Missile and Air-To-Surface Missile Mix	5. FUNDING NUMBERS
6. AUTHOR(S) Kevin Robert Jacobson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ___N/A_____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

Asymmetric threats pose increasing challenges to the United States Navy in littoral environments. To address the Navy's need for a new platform to serve in this area, the Littoral Combat Ship (LCS) was designed and put into service. What still has yet to be determined is what surface-to-surface capability the LCS will have as well as what air-to-surface capability the LCS helicopter/unmanned aerial vehicle (UAV) will have.

This study uses freely available data to build a simulation utilizing an agent-based modeling platform known as MANA. The simulation is exercised over a broad range of different weapon systems types with their capabilities ranged across the spectrum of possibilities based on their effectiveness as well as potential difficulties in targeting small boat threats. Using linear regression and partition trees, an analysis is performed on the resulting dataset to address the research question.

The results show that the NLOS system is the best surface-to-surface missile system for the LCS as long as the expected rate of fire is obtained. The best air-to-surface missile system is either APKWS or LOGIR, depending on which can obtain a rate of fire of one missile every nine seconds or faster. Lastly, the rate of fire has been shown to be the most important factor in determining the effectiveness of the different missiles.

14. SUBJECT TERMS Littoral Combat Ship, MH-60R, Fire Scout UAV, Surface Warfare, Air-to-Surface, Surface-to-Surface, Over-the-Horizon, Simulation, MANA	15. NUMBER OF PAGES 77
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

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

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

THE LITTORAL COMBAT SHIP (LCS) SURFACE WARFARE (SUW) MODULE: DETERMINING THE BEST MIX OF SURFACE-TO-SURFACE AND AIR-TO-SURFACE MISSILES

Kevin R. Jacobson
Lieutenant, United States Navy
B.A., University of Florida, 2004

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN
MODELING, VIRTUAL ENVIRONMENTS, AND SIMULATION (MOVES)

from the

NAVAL POSTGRADUATE SCHOOL
September 2010

Author: Kevin Robert Jacobson

Approved by: Michael McCauley
Thesis Advisor

Curtis Blais
Second Reader

Mathias Kolsch
Chair, Moves Academic Committee

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Asymmetric threats pose increasing challenges to the United States Navy in littoral environments. To address the Navy's need for a new platform to serve in this area, the Littoral Combat Ship (LCS) was designed and put into service. What still has yet to be determined is what surface-to-surface capability the LCS will have as well as what air-to-surface capability the LCS helicopter/unmanned aerial vehicle (UAV) will have.

This study uses freely available data to build a simulation utilizing an agent-based modeling platform known as MANA. The simulation is exercised over a broad range of different weapon systems types with their capabilities ranged across the spectrum of possibilities based on their effectiveness as well as potential difficulties in targeting small boat threats. Using linear regression and partition trees, an analysis is performed on the resulting dataset to address the research question.

The results show that the NLOS system is the best surface-to-surface missile system for the LCS as long as the expected rate of fire is obtained. The best air-to-surface missile system is either APKWS or LOGIR, depending on which can obtain a rate of fire of one missile every nine seconds or faster. Lastly, the rate of fire has been shown to be the most important factor in determining the effectiveness of the different missiles.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION 1
- **A. OVERVIEW 1**
- **B. RESEARCH QUESTIONS 2**
- **C. BENEFITS OF THE STUDY 3**
- **D. ORGANIZATION OF THE DOCUMENT 3**

II. LITERATURE REVIEW 5
- **A. INTRODUCTION 5**
- **B. LCS PROGRAM BACKGROUND 5**
  - **1. History 5**
  - **2. What Is the Littoral Combat Ship? 7**
    - ***a. Overview 7***
    - ***b. Seaframe 7***
    - ***c. Capabilities 7***
  - **3. Issues 8**
    - ***a. Combat Survivability 8***
    - ***b. Development of Required Technologies 8***
  - **4. Suitability 8**
- **C. CONCEPT OF OPERATIONS 9**
- **D. ISSUES 10**
  - **1. Options 11**
    - ***a. Current 11***
    - ***b. Future 11***
- **E. AIRBORNE PLATFORMS 11**
  - **1. MH-60R 11**
    - ***a. Overview 11***
    - ***b. Capabilities 12***
  - **2. Northrop Grumman MQ-8 Fire Scout 12**
    - ***a. Overview 12***
    - ***b. Capabilities 12***
- **F. MISSILES 13**
  - **1. Non Line of Sight-Launch System (NLOS-LS) 13**
  - **2. RGM-84 Harpoon 14**
  - **3. AGM-114 Hellfire 15**
  - **4. Low-Cost Guided Imaging Rocket (LOGIR) 15**
  - **5. Advanced Precision Kill Weapon System (APKWS) 16**
  - **6. Directional Attack Guided Rocket (DAGR) 17**
- **G. RELATED STUDIES 17**
- **H. SUMMARY 18**

III. MODEL DEVELOPMENT 19
- **A. INTRODUCTION 19**
- **B. THE MANA COMBAT SIMULATION TOOL 19**

1. Choosing MANA **19**
2. MANA Characteristics **19**
C. CHARACTERISTICS OF THE SIMULATION MODEL **21**
1. Goal of the Simulation **21**
2. Scale and Terrain **22**
3. Friendly Forces **22**
4. Enemy Forces **22**
5. Sources, Abstractions, and Assumptions **23**
D. SUMMARY **23**

IV. EXPERIMENT DESIGN **25**
A. INTRODUCTION **25**
B. VARIABLES OF INTEREST **25**
1. Controllable Factors **26**
a. LCS Probability of Detection (Pd) ***27***
b. MH-60R Pd ***27***
c. UAV Pd ***27***
d. NLOS Probability of Kill (Pk) ***27***
e. NLOS Inter Firing Rate (Ifr) ***27***
f. Harpoon Pk ***27***
g. Harpoon Ifr ***27***
h. Hellfire Pk ***28***
i. Hellfire Ifr ***28***
j. Hellfire Quantity Carried (Qc) ***28***
k. Hellfire Maximum Effective Range (MER) ***28***
l. LOGIR Pk ***28***
m. LOGIR Ifr ***28***
n. LOGIR Qc ***28***
o. LOGIR MER ***29***
p. APKWS Pk ***29***
q. APKWS Ifr ***29***
r. APKWS Qc ***29***
s. APKWS MER ***29***
t. DAGR Pk ***29***
u. DAGR Ifr ***29***
v. DAGR Qc ***29***
w. DAGR MER ***30***
2. Assumptions **30**
C. THE EXPERIMENT **30**
1. The Nearly Orthogonal Latin Hypercube (NOLH) **30**
2. Exploratory Design **31**
3. Preliminary Design **31**
4. Final Design **31**
D. RUNNING THE EXPERIMENT **32**
E. SUMMARY **32**

V. DATA ANALYSIS **33**

A. DATA COLLECTION AND PROCESSING 33
B. INSIGHTS INTO RESEARCH QUESTIONS 33
1. Surface-to-Surface Missile for the SUW Module.....34
a. MH-60R Scenario 34
b. UAV Scenario.....35
c. Overall 36
2. What Type of Air-to-Surface Missile Is Most Effective 36
a. MH-60R Scenario 37
b. UAV Scenario.....39
c. Overall 40
3. Most Important Factors in Missile Selection.....40
a. MH-60R Scenario 40
b. UAV Scenario.....42
c. Overall 44
C. SUMMARY 44

VI. CONCLUSIONS AND FUTURE WORK.....45
A. CONCLUSIONS 45
1. Which Surface-to-Surface Missile Should LCS Deploy With?.....45
2. What Type of Air-to-Surface Missile Should the Aircraft Be Equipped With? 45
3. What Factor Is Most Important in Deciding Which Missile to Select?.....45
B. RECOMMENDATIONS.....45
C. FUTURE WORK.....46

APPENDIX A. PERSONALITIES AND CAPABILITIES OF SQUADS 49

APPENDIX B. EXPERIMENTAL DESIGNS 51
A. MH-60R SCENARIO DESIGN.....51
B. UAV SCENARIO DESIGN 52

LIST OF REFERENCES.....53

INITIAL DISTRIBUTION LIST 57

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1. LCS-1, First ship of the General Dynamics Design (From Jane's, 2010) 1
Figure 2. LCS-2, First ship of the Lockheed Martin Design (From Jane's, 2010) 2
Figure 3. The overlapping threat environment in the littoral region (From Naval Warfare Development Command, 2007) 6
Figure 4. How the U.S. Navy envisions LCS utilizing automated vehicles to complete its missions. (From Naval Warfare Development Command, 2007) 10
Figure 5. NLOS launching from CLU (From Defense Tech, 2010) 13
Figure 6. A four-round DAGR pod plus a Hellfire missile on a M310 launcher (From Jane's 2010) 17
Figure 7. The personality screen used in MANA version 5. 20
Figure 8. Screen shot of MANA start up screen. 21

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1. Harpoon Flight Reliability (From Jane's, Feb 04, 2010).....15
Table 2. Variable factors used in the experiment design. 25
Table 3. The partition tree comparing the Harpoon and NLOS data from the MH-60R summary data based upon the mean number of Red casualties. 35
Table 4. The partition tree comparing the Harpoon and NLOS data from the UAV summary data based upon the mean number of Red casualties.....36
Table 5. The partition tree of the MH-60R summary data in which the number of mean Red casualties based on the missiles equipped are the only categories of data looked at.....37
Table 6. From the MH-60R Summary data. A partition tree of the four air-to-surface missile options and all of their input options. 38
Table 7. A basic partition tree of the UAV summary data showing the breakdown of the four air-to-surface missile options by the mean number of Red casualties.....39
Table 8. From the UAV Summary data. A partition tree of the four air-to-surface missile options and all of their input options based on the mean number of Red casualties.....40
Table 9. The parameter estimates of the regression analysis resulting from effects screening of mean total Red casualties in the MH-60R scenario separated by missile type (Hellfire, LOGIR, APKWS, DAGR, NLOS, and Harpoon respectively).....41
Table 10. The parameter estimates of the regression analysis resulting from effects screening of mean total Red casualties in the UAV scenario separated by missile type (Hellfire, LOGIR, APKWS, DAGR, NLOS, and Harpoon respectively).....43

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

A2	Anti-Access
AD	Area Denial
AOR	Area of Operations
APKWS	Advanced Precision Kill Weapon System
ASW	Anti Submarine Warfare
CCS	Computer and Communications System
CLU	Container Launching Unit
CSV	Comma Separated Value
DAGR	Directional Attack Guided Rocket
DASAL	Distributed Aperture Semi-Active Laser Seeker
DDG	Guided Missile Destroyer
EADS	European Aeronautic Defense and Space Company
FFG	Guided Missile Frigate
FLIR	Forward Looking Infra-Red
FPA	Focal Plane Array
GAO	General Accounting Office
GCS	Guidance and Control System
GPS	Global Positioning System
Hellfire	Heliborne, Laser, Fire and Forget
Ifr	Inter firing rate
IR	Infra-Red
Kg	Kilograms
Km	Kilometers
Lb	Pounds
LCITS	Low Cost Imaging Terminal Seeker
LCS	Littoral Combat Ship
LOAL	Lock-On After Launch
LOBL	Lock-On Before Launch
LOGIR	Low-cost Guided Imaging Rocket
MANA	Map Aware Non-uniform Automata

MIW	Mine Warfare
MMT	Multi-Mission Tomahawk
MOE	Measure of Effectiveness
MTI	Moving Target Indication
NLOS-LS	Non Line of Sight Launch System
NM	Nautical Miles
NPS	Naval Postgraduate School
NSM	Naval Strike Missile
ONR	Office of Naval Research
PAM	Precision Attack Missile
Ph	Probability of hit
Pk	Probability of kill
Qc	Quantity carried
RAM	Rolling Airframe Missile
SAL	Semi-active Laser
SAM	Surface-to-Air Missile
SAR	Search and Rescue
SAR	Synthetic Aperture Radar
SEED	Simulation Experiments and Efficient Designs
SOUTHCOM	Southern Command
SUW	Surface Warfare
TRS-3D	Track Reporting System – Three Dimensional
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vehicle
UV	Unmanned Vehicles
XML	Extensible Markup Language

ACKNOWLEDGMENTS

I would first like to thank my advisors, Professor Mike McCauley and Curtis Blais for their superhuman patience and efforts in helping me get this thesis done. They both provided critical insights into agent-based modeling as well as sending me to talk with the right people to provide critical insights into the Littoral Combat Ship (LCS) as well as experimental design, data processing, and data analysis.

I want to thank CAPT Jeff Kline, USN (Ret), for his assistance in sanity checking my assumptions with his vast operational experience as a retired surface warfare officer and for steering me in the right direction with some of my LCS research. I would also like to thank LCDR Stacey Prescott, USN, for helping to sanity check my missile data and assumptions based on her experience as an operational SH-60 pilot.

I would also like to thank Professor Susan Sanchez and Mary McDonald for their help in designing my experiment and simulation. Professor Sanchez's expert knowledge of experimental design and data analysis was crucial in this thesis and Mary McDonald was instrumental in troubleshooting my model and getting it into its final form. I would also like to thank Mary McDonald and the SEED center for their assistance in running the experiment, especially since they were able to cut down to one hundredth the amount of time it would have taken me to run all of the data.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. OVERVIEW

With the ending of the Cold War, the United States Navy is seeing its mission change. Gone are the days of the threat of an engagement with a large blue water navy as represented by the Soviet Navy. Today's challenge is from smaller nations that employ diesel submarines, fast missile armed patrol boats, and shore-based cruise missiles in an attempt to deny access to U.S. forces. Another new threat is the development of more capable unmanned remote control aircraft, boats, and submersibles. The Navy realized that to counter these threats would require a ship capable of operating in the littoral environment and able to incorporate these newer unmanned technologies. This resulted in the design of the modular, focused, mission platform known as the Littoral Combat Ship (LCS); see Figure 1 and Figure 2.

Figure 1. LCS-1, First ship of the Lockheed Martin Design (From Jane's, 2010)

Figure 2. LCS-2, First ship of the General Dynamics Design (From Jane's, 2010)

The LCS has several different mission modules that give it the ability to be utilized in a specific warfare area. These modules are the Anti-Submarine Warfare (ASW), Mine Warfare (MIW), and Surface Warfare (SUW).

B. RESEARCH QUESTIONS

This thesis looks at a LCS equipped with the SUW module and with an embarked aircraft and attempts to see how the LCS handles itself in an over-the-horizon surface engagement against missile-armed patrol boats. The following questions guide this research:

- What surface-to-surface missile should LCS equip?
- What type of air-to-surface missiles should the aircraft be equipped with to be the most effective?
- What factor is more important in determining the type of missile to select?

This thesis uses simulation models, data analysis, and other analytical tools to investigate these questions and determine which combination of missiles and aircraft provides for the best overall SUW package. The simulation model utilizes a given littoral region and threats that may exist in that area.

C. BENEFITS OF THE STUDY

This thesis provides the U.S. Navy analytical support for the customization of the SUW module package for the LCS. Additionally, this study provides insight into the comparative capabilities of different air-to-surface missiles as well as an insight into which missiles will offer more 'bang for the buck.'

D. ORGANIZATION OF THE DOCUMENT

Chapter II consists of the literature review, exploring the background and capabilities of the platforms and missiles used in this thesis. Chapter III describes the modeling tool used in this thesis and the reasoning for selecting it. Chapter IV describes the design of the experiment with respect to behaviors of simulated entities and creation of the scenarios. Chapter V contains analysis and conclusions as well as recommendations for future work.

THIS PAGE INTENTIONALLY LEFT BLANK

II. LITERATURE REVIEW

A. INTRODUCTION

This chapter covers the current threats and deficiencies within the U.S. Navy that have necessitated the launching of the LCS class.

> Operating in the littoral presents a complex collection of challenges. As …From the Sea put it, the "mastery of the littoral should not be presumed." …From the Sea recognized that "Some littoral threats–specifically mines, sea-skimming cruise missiles, and tactical ballistic missiles–tax the capabilities of our current systems and force structure." In the past decade, swarming small boats (armed with short range missiles or a payload of explosives) and diesel submarines have also been cited by the Navy as obstructing U.S. access to the littoral. These systems enable even relatively unsophisticated adversaries to adopt a strategy of anti-access and area denial (A2/AD), whereby the defender seeks to prevent the attacker from bringing strike power to bear with a layered, but not symmetric force-on-force, defense of the approaches (Long/Johnson 2007).

B. LCS PROGRAM BACKGROUND

1. History

Faced with new threats in the littoral region, pictured below in Figure 3, the Navy strategy initially focused on avoiding the littoral and projecting power over the littorals using gunfire, missiles, and air power delivered by platforms already in service in the fleet. This would minimize exposure to mines and land-based anti-ship missiles. This strategy of avoiding the littoral resulted in the DD-21 Land Attack Destroyer program which the primary mission foreseen to be to support ground forces. Over time, however, elements within the Navy begin to recognize the difficulty of supporting ground forces without a more persistent presence within the littoral environment and proposed filling this gap with new, small surface combatants. Recognition of this difficulty was furthered by a 1997 General Accounting Office (GAO) report which indicated that the Navy's shipbuilding program was facing a significant fiscal challenge and that if the Navy was to meet its force structure goal then it would have to either buy less expensive ships or spend more. The suggestion from GAO to the Navy was to consider cheaper ships that

would be tailored to perform only one or two missions. This cause was furthered by the Chief of Naval Operations' Strategic Studies Group (SSG), which recommended that the two most important attributes for the future fleet were for distributed combat power, achievable through use of unmanned vehicles and offboard sensors, and modularity to provide mission flexibility (Long/Johnson 2007). What finally caused the Navy to act on this need was the release of a report by the GAO in 2001 citing the need for improved war-fighting capabilities in the littoral region (GAO 2001). The Navy launched a study in 2001 to find the ship that would address all of its needs for a littoral capable warship. The Navy decided upon the Littoral Combat Ship, a smaller and less expensive ship, when compared to destroyers and cruisers, that depending on which module it is equipped with, could handle the mine, diesel submarine, and small boat threats in the littoral environment. The LCS design does not, however, have an anti-air capability outside of limited self-defense.

Figure 3. The overlapping threat environment in the littoral region (From Naval Warfare Development Command, 2007)

2. What Is the Littoral Combat Ship?

a. Overview

The LCS is planned to fill the need for a combatant in the littoral regions of the world and to replace several classes of ships that are being retired, most notably frigates and minesweepers. Flexibility is the defining characteristic of LCS as it is expected to operate in a littoral region in the SUW, MIW, and ASW missions.

> The LCS is a relatively inexpensive Navy surface combatant that is to be equipped with modular "plug-and-fight" mission packages, including unmanned vehicles (UVs). Rather than being a multimission ship like the Navy's larger surface combatants, the LCS is to be a focused-mission ship equipped to perform one primary mission at any one time. The ship's mission orientation can be changed by changing its mission packages. The basic version of the LCS, without any mission packages, is referred to as the LCS sea frame. (Navy Littoral Combat Ship (LCS) Program: Background, Issues, and Options for Congress, April 8, 2010)

b. Seaframe

As the core of LCS, the seaframe provides for basic self-defense capability through organic sensors, weapons, and speed. There are two seaframe designs that are being considered with one of each already in service. There are differences between the two seaframes but those are not the focus of this thesis. The two seaframes are capable of 40+ knots and are similarly equipped regarding organic sensors and weaponry. The only organic capabilities that this thesis looks at are the speed of 40+ knots and the radar system. The radar is the European Aeronautic Defense and Space Company (EADS) Three-Dimensional Track Reporting System (TRS-3D), which is a naval multimode three-dimensional air/surface search radar with periscope detection capability.

c. Capabilities

The focus of this thesis is on the SUW module equipped LCS. The SUW module is designed to detect and engage multiple surface contacts in a littoral environment. It strengthens the core seaframe capability by adding an air-to-surface missile armed aircraft and a surface-to-surface missile capability. According to the Naval Sea System Command:

> These components include electro-optical/infrared sensors mounted on a vertical takeoff unmanned air vehicle to provide over-the-horizon detection; 30mm guns to kill close-in targets; four non-line-of-sight launching system (NLOS-LS) container launch units or "missile-in-a-box" systems, with each system containing 15 offensive missiles; and the MH-60R armed helicopter for surveillance and attack missions(U.S. Navy, 2007).

3. Issues

There are some concerns about the LCS program. Some concerns stem from the rising costs of the ships, some from the slow development of the required technologies for the warfare modules, and some from the combat survivability of the seaframes.

a. Combat Survivability

There are concerns about the survivability of the LCS in a combat situation due to its small crew size, which limits damage control operations, and the limited shock hardened design of both seaframes.

> The LCS is not expected to be survivable in a hostile combat environment as evidenced by the limited shock hardened design and results of full scale testing of representative hull structures completed in December 2006 (O'Rourke 2010, p. 17).

b. Development of Required Technologies

Of the 19 critical technologies required for the two different seaframe options, only 15 can be said to be fully mature and of the 25 critical technologies required for the MIW, SUW, and ASW modules only 17 are currently mature (GAO March 2009). Not only has the development been behind what was expected, but the development cost of the modules and the seaframes have been much higher than expected.

4. Suitability

Some that feel that the LCS is not, in fact, the right ship for the littoral environment. One such person is Milan Vego, who in an article in the Armed Forces Journal writes, "The best weapon to counter enemy small surface combatants is a force of small surface combatants" (Vego 2008). He goes on to state that the LCS is not a real

littoral combat vessel but is an ocean-going vessel due to its draft of 20 feet. He feels this will limit the maneuverability of the LCS in the confined waters of a littoral environment and that no matter how well equipped it might be that it would not be able to defend against a large number of hostile small boats. He is mistaken in his talk of the draft of the LCS. The Freedom class has a draft of 13.5 feet and the Independence class has a draft of 14.8 feet. Martin Murphy, of the Center for Strategic and Budgetary Assessment came out in favor of the LCS. He makes the point that the LCS with its high speed and shallow draft of 15 feet is a kind of "light cavalry" for the Navy. He also points out that the real value of the LCS comes from its large flight deck and its ability to operate two MH-60R helicopters or an assortment of drones; moreover, a MH-60R is faster and more maneuverable than any small boat and when armed with Hellfire Missiles it is a very lethal aircraft (Murphy 2010).

C. CONCEPT OF OPERATIONS

Figure 4 is an excellent illustration of how the U.S. Navy envisions LCS being used. The Navy refers to this as a distributed force in the littoral, not platform-centric (Global Security 2003). The Navy sees Littoral Combat Ships, each with appropriate network of off board sensors and systems, being able to operate independently or interdependently as part of a littoral operations force or a multi-mission fleet force. The point is for the LCS to be networked with its autonomous vehicles, whether for SUW, MIW, or ASW and to use those vehicles to allow LCS to investigate contacts or shipping without exposing the ship or any of its crew to harm. Looking at it from the SUW point of view, these networked UAVs or MH-60R will be able to detect, identify, classify and track a threat and with the Non Line-of-Sight Launch System (NLOS-LS) that the LCS is equipped with, it will be able to engage surface threats as far out as 40 kilometers. This means that the SUW LCS will have the capability to handle most threats outside of their engagement envelope thereby limiting the loss of equipment and life to that of the UAV or the MH-60R. This also means that the UAV or MH-60R can limit their risk by remaining just close enough to laser-designate the target for the ship without getting within the range of any hand-held Surface-to-Air Missiles (SAMs) that might be onboard the threat boat.

Figure 4. How the U.S. Navy envisions LCS utilizing automated vehicles to complete its missions. (From Naval Warfare Development Command, 2007)

D. ISSUES

There is a major issue with the current plan for the SUW module equipped LCS and that is the development of the NLOS-LS. Originally an Army program it was discovered earlier this year that the NLOS-LS's Precision Attack Missile (PAM) is not very precise, missing four out of six targets in tests conducted in at White Sands Missile Range, New Mexico, between January 26, 2010 and February 5, 2010.

> Test missiles failed to hit a moving tank 20 kilometers away, a moving infantry vehicle 10 kilometers away, a stationary tank 30 kilometers away, and a stationary truck 35 kilometers away. It missed the infantry vehicle by 20 meters, and the truck by 25 kilometers. (Brannen February 22, 2010)

It is note-worthy that the two hits came when the missile used its laser designator instead of its infrared seeker, so there is still potential. The results of the test were alarming enough that earlier this year the Army canceled the NLOS-LS program and the

funding for continued research and development switched to the Navy (Brannen May 12, 2010). Another cause for concern is the price tag; each PAM costs an astounding $466,000.

1. Options

These issues with the NLOS-LS program have some in the Navy wondering if the NLOS-LS program is the right fit for the LCS SUW module. Other options are available to provide the LCS with an over-the-horizon anti-surface capability.

a. Current

The RGM-84 Harpoon missile is the current U.S. Navy surface-to-surface anti-ship missile. It is an existing technology and is still in production. The main downside is that where the talk for NLOS was for putting 45 or 60 PAMs on the LCS, with Harpoons it would probably be limited to eight missiles.

b. Future

The Navy is looking ahead for a next-generation ship-launched surface-to-surface missile (Peterson 2010), but as of April 2010, the Navy was still drafting an initial capabilities document, which means that any next-generation program is still quite a few years down the road. Some of the programs that have potential are the Naval Strike Missile (NSM) of the Royal Norwegian Navy, the Multi-Mission Tomahawk (MMT), or a more advanced Harpoon missile (Peterson 2010).

E. AIRBORNE PLATFORMS

This section provides a brief overview and capabilities description of the aircraft used in the scenarios for this thesis.

1. MH-60R

a. Overview

The MH-60R is one of the latest versions of the Sikorsky S-70B helicopter that has been in use in the U.S. Navy for years. Much like the LCS, the MH-60R is a

multi-mission platform. It is equipped to conduct both ASW and SUW as its primary missions and is able to employ Link 16 to further incorporate it into a strike group's network. The avionics have been designed to be non-mission specific so that the pilot can shift from a search and rescue (SAR) mission to a SUW mission to an ASW mission and be looking at the same cockpit.

b. Capabilities

The MH-60R combines the capabilities of the SH-60B with the dipping sonar of the SH-60F. Most of these capabilities are for ASW and are of no interest to this thesis. The capabilities that are relevant to this thesis are that the MH-60R is outfitted to carry and use eight Hellfire missiles and is equipped with the Telephonics AN/APS-147 search radar and the Raytheon AN/AAS-44 FLIR/laser ranger. The AN/APS-147 has the ability to auto detect and track up to 255 contacts simultaneously.

2. Northrop Grumman MQ-8 Fire Scout

a. Overview

Based on a modified Schweizer 333 light helicopter, the MQ-8B has a four-blade rotor, a streamlined fuselage pod in place of the cabin, and increased fuel capacity. Due to delays in the LCS program, a ship of the FFG-7 class, the USS McInerney, was selected to conduct a technical evaluation of the Fire Scout. Between December 2008 and November 2009 110 ship take-offs and landings were conducted. During this time period the Fire Scout completed a successful deployment in the US Southern Command (SOUTHCOM) area of responsibility (AOR) (Jane's April 21, 2010).

b. Capabilities

The Fire Scout is capable of 125 knots in level flight and has a mission radius of 110 nautical miles (NM). With a maximum payload of 272 kg (600 lb) it has an endurance of three hours. It is also equipped with FLIR, a laser designator, and the General Atomics AN/APY-8 Lynx Synthetic Aperture Radar (SAR)/Moving Target Indication (MTI) radar.

F. MISSILES

This section provides a brief introduction to the different missile systems and missiles relevant to this thesis.

1. Non Line of Sight-Launch System (NLOS-LS)

The NLOS began as an Army project being developed by Lockheed Martin. Since then it has become a Joint Army-Navy project and is now just a Navy project. The plan was to integrate the NLOS-LS into the LCS but the future of the program is currently in question due to some subpar test results in which the missile missed four out of six targets (Defense Tech, 2010). The design concept is for the target to be detected, identified, classified, and tracked by an off-board surveillance platform and then for the LCS to set aim points for the Precision Attack Missile (PAM). LCS will send continuous target updates to the missile until it is about eight km from the target at which time each PAM begins to zero-in on its specified target using its MTI and its automatic target acquisition capabilities. The missiles are contained in Container Launching Units (CLUs); each CLU is a self-contained 16 cell launching system that has 15 missiles and a Computer and Communications System (CCS). The plan is for four CLUs to be carried in each LCS SUW module.

Figure 5. NLOS launching from CLU (From Defense Tech, 2010)

The PAM is subsonic and has a range of 40 km. The PAM has three seeker options available: it can use its IR seeker to search for and lock onto its target, it can use

its laser-guided seeker to search for reflected laser energy from a third party designator, or it can use GPS to fly to a specified GPS location and detonate on impact. The PAMs can be fired at five-second intervals and each is equipped with a 13.2 kg multi-mission warhead. Current estimates put the cost of each NLOS missile at $466,000 apiece (Defense Tech, 2010).

2. RGM-84 Harpoon

The Harpoon is the most widely used, western made, ship-launched, anti-ship missile. It has been in use in the U.S. Navy since 1977. Although it has not seen much use of late in the U.S. Navy, having not been included on the flight II DDGs; the U.S. continues to fund research into upgrades and is continuing to upgrade its current stock of Harpoon Missiles.

The latest version of Harpoon is sea-skimming capable with an active radar seeker and datalink, meaning it can be updated while in flight. It carries a 222 kg warhead and has proven flight reliability, which has increased over the years, has can be seen in the Table 1.

Table 1. Harpoon Flight Reliability (From Jane's, Feb 04, 2010)

Fiscal Year	Missiles launched	Successes	Success percentage
1975-76	98	87	88.77
1977-78	73	68	93.15
1979-81	114	106	92.98
1982-89	136	134	98.5
Total	421	395	93.35

3. AGM-114 Hellfire

The Hellfire (an acronym for Heliborne, Laser, Fire and Forget) Modular Missile System was designed as an anti-armor and precision attack weapon in the 1970s with the requirement that it could attack both stationary and moving targets. The Hellfire has been cleared for use with several helicopter and UAV platforms in the U.S. inventory, including the MH-60R, the MQ-1 Predator UAV, and AH-64 Apache. The Air Force is even looking at integrating it with the next generation of AC-130 gunships.

The missiles can be carried on two or four-rail launcher assemblies. The variant this thesis is looking at is the AGM-114M, which has a 12.5 kg warhead, a maximum range of nine kilometers, and uses semi-active laser guidance.

4. Low-Cost Guided Imaging Rocket (LOGIR)

There have been several efforts by the U.S. Navy to design and build an affordable precision guidance system for the standard Hydra 70 rocket. The LOGIR is unlike most other guided rocket programs, in that it relies on infrared guidance rather than semi-active laser homing technique. As of 2007, LOGIR was being co-operatively developed by the United States and South Korea.

The LOGIR modification is designed to turn an existing Hydra 70 rocket or CRV7 rocket into a guided rocket with the addition of a new guidance and control system (GCS). This system incorporates an imaging infrared seeker for terminal homing and an

inertial navigation platform. This seeker uses an uncooled staring focal plane array (FPA) that uses imaging matching to locate and identify its target. The target is then designated using the FLIR sensor on the launching helicopter or UAV and the LOGIR then uses that data to track and acquire the target itself. LOGIR is intended to be used as a fire-and-forget weapon, allowing for a greater rate of fire than a semi-active laser homing guided rocket. The effective range is expected to be about five kilometers and since it is using existing Hydra 70 rockets, the warhead should be the standard 7.7 kg (Jane's). Since this program will be using the existing Hydra 70 rockets, there is a possibility that the Office of Naval Research (ONR) will attempt to utilize the existing Hydra 70 rocket launchers.

5. Advanced Precision Kill Weapon System (APKWS)

The APKWS program is another initiative by the United States military to develop the standard Hydra 70 rocket and the CRV7 rocket into low-cost precision-guided weapons. This program was initiated by the U.S. Army and was taken over by the Navy in 2008 with the intention to equip Marine Corps combat helicopters. APKWS has a range from between 0.91 miles to 3.1 miles and also has the standard 7.7 kg warhead found in the Hydra 70 rocket. The big difference between APKWS and LOGIR is that APKWS uses semi-active laser guidance. There is a big difference between APKWS and other laser guided rockets in that it uses four distributed aperture semi-active laser seekers (DASALs), similar to those found in the Army's precision guided mortar munitions program. With these four seekers, the APKWS has demonstrated an accuracy of 0.5 meters in tests (Jane's 2010). Eight operational assessment test firings were conducted by the U.S. Marines in January 2010 and in April 2010, low rate initial production was approved. As with the LOGIR, there is a good chance that ONR will attempt to utilize the existing Hydra 70 rocket launchers, which come in seven packs and 19 packs of rockets. The APKWS is very similar to the LOGIR in capability but appears to be slightly more accurate but with a slower rate of fire due to its required lasing of the target.

6. Directional Attack Guided Rocket (DAGR)

The DAGR is another attempt to convert the conventional Hydra 70 and the standard CRV7 rockets into precision-guidance weapons. Like the APKWS, the DAGR uses a semi-active laser (SAL) seeker. The DAGR is so similar to the Hellfire that it is often called the Hellfire II. A feature about the DAGR that stands out is that Lockheed Martin has designed a smart launcher for the DAGR that can be clipped into place on a M299 or M310 Hellfire launcher. This launcher allows for a four-pack of DAGRs to be placed in each Hellfire slot. Lockheed Martin is also working on a six-pack DAGR launcher design. The DAGR is highly capable precision rocket, having both Lock On Before Launch (LOBL) or Lock On After Launch (LOAL) modes. If launched from an altitude of 20,000 feet, it is designed to be accurate to within one meter at a 12,000 meter range. If launched from near-ground level it is accurate to within one meter at 7,000 meters. The DAGR is currently being looked at by all branches of the U.S. armed forces.

Figure 6. A four-round DAGR pod plus a Hellfire missile on a M310 launcher (From Jane's 2010)

G. RELATED STUDIES

Several theses have been conducted at the Naval Postgraduate School concerning LCS and/or allied ships conducting operations against large numbers of small boats. Andre Tiwari's thesis (2008) showed that a gap in capability exists in the surface force to defend itself against small threat craft. Benjamin Abbot's thesis (2008) explored the best mix of LCS mission packages and determined that LCS should operate in squadrons of between six to ten ships for the best results, with five LCS equipped for the primary threat and two LCS for the secondary threat. Another thesis dealing with LCS was done by Michael Milliken in September 2008 in which he conducted an impact analysis of a mixed squadron, containing LCS and multi-mission surface platforms, on blue force

casualties and mission effectiveness. Milliken's conclusion was that a squadron with five to eleven LCSs with one to two DDGs is the most effective in an SUW scenario. Omur Ozdemir's thesis (2009) did a comparison of the Freedom class LCS and other frigates/corvettes against small boat, fast patrol boat, and submarine threats in confined waters. His conclusion was that the LCS was the most combat effective, but that its high cost meant that it was not the best candidate.

H. SUMMARY

The LCS is the Navy's answer to the challenge of projecting power "from the sea" in the littoral environment and in supporting ground forces ashore. The concept of operations calls for the LCS to operate distributed sensor platforms, both manned and unmanned to find and engage threats, keeping the LCS out of direct combat and utilizing missiles from the LCS matched with the sensor platforms to provide over-the-horizon capability.

III. MODEL DEVELOPMENT

A. INTRODUCTION

In order to accurately capture how these different missiles will work in a wartime environment, a robust scenario that contains a realistic and capable threat is required. In this chapter, a brief description of the MANA simulation tool is provided as is a description of the behavior of the simulation model.

B. THE MANA COMBAT SIMULATION TOOL

1. Choosing MANA

MANA is combat model developed and provided to NPS by New Zealand's Defense Technology Agency (DTA). "MANA is an agent-based distillation model developed by DTA for use in military operations analysis studies" (McIntosh 2009). One of the best qualities of MANA and one of the main reasons it was used in this thesis is that it is event driven, and as a result, it gives a remarkable depiction of simulated combat. In using MANA, one can more accurately depict the attributes of the individual agents and MANA gives one the ability to vary these attributes which allows the simulator to have the ability to observe and quantify the effects of these varying attributes on the battlefield outcomes. Another point in MANA's favor is how easy it is to use. It has a very simple interface that allows the simulator to vary all of the attributes of the agents involved. "The simple nature of the model allows both rapid parameter space exploration and experimentation with co-evolving tactics, yet it has enough sophistication to produce realistic looking behaviors and tactics (Lauren 2002)."

2. MANA Characteristics

In this thesis, version 5.00.89 of MANA is being used. Released in June 2010, this is the latest version of MANA. One of the biggest advantages of MANA version 5 over older versions is that battlefield distances, agent speeds, and weapons characteristics can be defined in real world units (for example, meters, km/hr, nautical miles). This is possible because the cell-based movement scheme of previous MANA versions has been

replaced by a vector-based scheme. Not only does this allow for real world units to be used, but it also allows for much larger battlefields to be utilized as well. One of the other advantages of MANA in general, is that it leaves out detailed physical attributes of the entities being analyzed, such as the effects of the sea state upon the ships involved, allowing for the model to run relatively fast on a PC or laptop. This also means that a large number of runs of the scenario with varying attributes can be explored in a reasonable amount of time. In MANA the user develops squads, one for each type of platform being used in the simulation. Each squad is assigned weapons and sensors and personalities based on the user's needs. These personalities give the squads simple rules about how they are to move based upon the location of other squads and conditions on the battlefield. The user sets this up by weighing different aspects of the squad in the Personalities tab of the squad properties, shown below in Figure 7. In this example the squad would be focused only on going to the next waypoint, but would fire upon enemies if they are within range and its weapons are activated, but would not pursue any action other than following its pre-designed path.

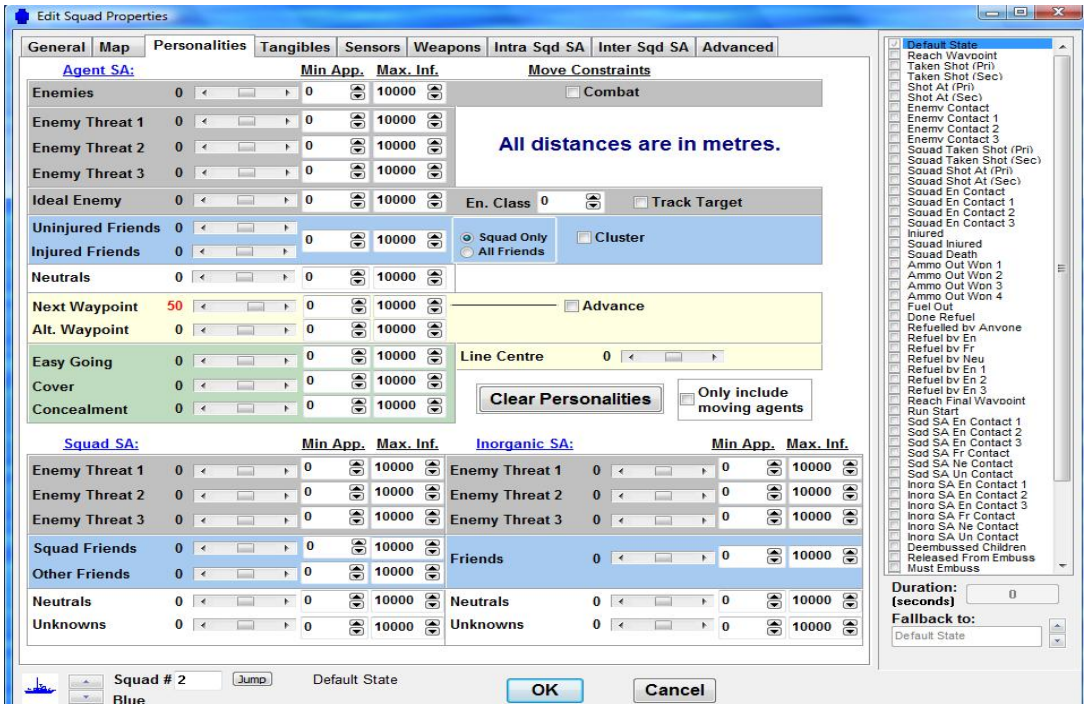


Figure 7. The personality screen used in MANA version 5.

Figure 8. Screen shot of MANA start up screen.

C. CHARACTERISTICS OF THE SIMULATION MODEL

The focus of this section is to provide the characteristics of the MANA model that was created for this research. The goal of the simulation is discussed as is the scale, the friendly forces, the enemy forces, and issues regarding sources of data, abstractions, and assumptions. A more detailed breakdown of the personalities and capabilities of the friendly and enemy forces can be found in Appendix A.

1. Goal of the Simulation

The scenario used in this thesis is designed to stress the capabilities and potential capabilities of each missile type in order to gain insight into which missiles would be best for use with the SUW module equipped LCS. The factors that play an important role in this simulation are all concerned with the missile capabilities. These factors are the maximum range, the rate of fire, the probability of hit, and the number of missiles being carried. Using design of experiment techniques, these capabilities are explored over large

ranges to determine which were the most important and to what extent and which missile, based on its potential capabilities, is the best for use. Chapter IV describes the experimental design in detail.

2. Scale and Terrain

MANA is a time step model. For this study, the model was set so that each time step was equal to 10 seconds of real world time. Each run of the simulation lasts no longer than 500 time steps; which is equivalent to about an hour and 23 minutes in real world time. The simulation map is 40 kilometers by 40 kilometers. MANA does provide for one to be able to model different types of terrain. Since the effect of the sea state on the ships was not one of the aspects being measured, no terrain was used in this simulation as it would be introduce unnecessary detail.

3. Friendly Forces

The friendly forces are assigned a home position as well as waypoints. The LCS transits from its home position due north and engages enemies when it is capable. The helicopter/UAV is 25 kilometers northeast by east of the LCS and is transiting towards the suspected location of enemy guided missile patrol boats. The helicopter/UAV transits according to its speed and will pursue and engage enemies detected.

4. Enemy Forces

Just like the friendly forces, the enemy forces are also assigned a home position. Their home position is a box in which they can start at any point in that box, which MANA decides randomly. They know there is an American LCS to the west and are headed to get good contact on it and attack. The enemy threat consists of 20 missile boats. They transit and attack as a group for safety and cumulative strength. Once the LCS is detected the missile boats will pursue.

5. Sources, Abstractions, and Assumptions

As with every simulation, the source of input data and assumptions are important. In this scenario, communications and logistics are assumed to work perfectly, and fuel is unlimited. Maintenance and equipment failure are not considered.

Enemy force sensor and weapon information, number of weapons per enemy agent, and the capabilities of some of the friendly sensors and weapons were taken from Jane's Fighting Ships 2010. The probabilities associated with the sensors and weapons were generalized and reviewed by Jeff Kline, retired Navy Captain and Chair of Warfare Innovation at NPS, and LCDR Stacey Prescott, a SH-60B pilot with Hellfire experience. These probabilities are explored through design of experiment techniques that are discussed in the next chapter.

It is a rare occurrence in which a simulation tool perfectly fits the problem being modeled. Oftentimes, issues are discovered during the model development process that are either fixed by the developers or addressed via other modeling work-arounds. In this thesis, one such modeling issue was discovered. The issue had to do with MANA's ability to simulate one squad's ability to spoof a missile using electronic warfare or chaff, or to be able to shoot it down. Since the enemy missile boats that were simulated are not equipped with an anti-missile defense system, it was not necessary to worry about this issue with them. With the focus solely on the LCS it was easy to ignore the problem by making the goal of the friendly forces to be to ensure that none of the missile boats even got to where they could fire their missiles at the LCS.

D. SUMMARY

MANA was used for this thesis to simulate a scenario in which a SUW module equipped LCS and its accompanying aircraft are faced with 20 inbound missile boats. The scenario is designed to test the potential capabilities of different surface-to-surface and air-to-surface missiles that the SUW module may be equipped with and to determine which capabilities are the most important.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. EXPERIMENT DESIGN

A. INTRODUCTION

This chapter covers the assumptions used for the setup of the simulation as well as a description of how the simulation was designed. Special attention is paid to the parameters used to direct the abilities and actions of the squads.

B. VARIABLES OF INTEREST

There are two types of variables that are used in simulation: controllable and uncontrollable. Controllable variables are those that can be altered by the decision maker and uncontrollable variables are the ones that a decision maker cannot control. Controllable variables are often known as decision factors, whereas uncontrollable variables are often referred to as noise factors. This thesis focuses on the decision factors in order to provide greater insight into which weapons systems provide the best option in Surface Warfare. Since the enemy sensor and weapon ranges, their probabilities of detection and kill, and the number of enemy patrol craft are fixed, there are no noise factors in this thesis. Table 2 defines the variables used in this study.

Table 2. Variable factors used in the experiment design.

Factor	Value Range	Explanation
LCS Probability of Detection (PD)	0.5…1	Probability of Detection associated with the LCS seaframe
MH-60R PD	0.5…1	Probability of Detection associated with the MH-60 sensor
UAV PD	0.4…1	Probability of Detection associated with the UAV sensor
NLOS Probability of Kill (PK)	0.13…0.585	Probability of kill associated with the NLOS Missile System
NLOS Inter-firing rate (Ifr)	5…25	Time between subsequent firings of the NLOS Missile System
Harpoon PK	0.8075…0.9405	Probability of kill associated with the Harpoon missile system

Factor	Value Range	Explanation
Harpoon Ifr	10…25	Time between subsequent firings of the Harpoon Missile System
Hellfire Pk	0.6375…0.7125	Probability of kill associated with the Hellfire missile
Hellfire Ifr	8…18	Time between subsequent firings of the Hellfire missile
Hellfire Quantity Carried (QC)	8 MH60 2…6 UAV	Number of Hellfires carried in a given run
Hellfire Maximum Effective Range (MER)	5000…8000	Maximum effective range of the Hellfire missle in a given run
LOGIR Pk	0.4225…0.585	Probability of kill associated with the LOGIR
LOGIR Ifr	6…16	Time between subsequent firings of the LOGIR
LOGIR Qc	14…38 MH-60 7…19 UAV	Number of LOGIR carried in a given run
LOGIR MER	4000…5800	Maximum effective range of LOGIR in a given run
APKWS Pk	0.4875…0.6175	Probability of kill associated with the APKWS
APKWS Ifr	8…20	Time between subsequent firings of the APKWS
APKWS Qc	14…38 MH-60 7…19 UAV	Number of APKWS carried in a given run
APKWS MER	4000…5000	Maximum effective range of APKWS in a given run
DAGR Pk	0.4875…0.6175	Probability of kill associated with the DAGR
DAGR Ifr	8…20	Time between subsequent firings of the DAGR
DAGR Qc	8…12 MH60 2…8 UAV	Number of DAGR carried in a given run
DAGR MER	4500…7000	Maximum effective range of DAGR in a given run

1. Controllable Factors

The following variables are chosen in order to explore the effectiveness of different surface-to-surface and air-to-surface weapon systems.

a. LCS Probability of Detection (Pd)

The probability of detection associated with the sensor used by the LCS. The sensor being modeled is the 3D surface search radar that will be used by LCS.

b. MH-60R Pd

The probability of detection associated with the sensor used by the MH-60R. The sensor being modeled is the AN/APS-147 surface search radar.

c. UAV Pd

The probability of detection associated with the sensor used by the MQ-8 Fire Scout. The sensor being modeled is the Tactical Synthetic Aperture Radar (TSAR).

d. NLOS Probability of Kill (Pk)

The probability of kill associated with the NLOS missile system when employed in the SUW mission package. The Pk is the product of the probability of hit and the probability of kill given a hit.

e. NLOS Inter Firing Rate (Ifr)

The inter-firing rate associated with the NLOS system. This is the amount of time between subsequent firings of the NLOS.

f. Harpoon Pk

The probability of kill associated with the Harpoon missile system when employed in the SUW mission package. The Pk is the product of the probability of hit and the probability of kill given a hit.

g. Harpoon Ifr

The inter-firing rate associated with the Harpoon missile. This is the amount of time between subsequent firings of the Harpoon missile.

h. Hellfire Pk

The probability of kill associated with the Hellfire missile when employed by the MH-60R or the Fire Scout UAV. The Pk is the product of the probability of hit and the probability of kill given a hit.

i. Hellfire Ifr

The inter-firing rate associated with the Hellfire missile. This is the amount of time between subsequent firings of the Hellfire missile.

j. Hellfire Quantity Carried (Qc)

The number of Hellfire missiles being carried by the MH-60R or the Fire Scout UAV. This is based off of it being known that the MH-60R is capable of carrying eight Hellfire Missiles (Jane's) and that the Fire Scout is capable of carrying two based on its weight limitations.

k. Hellfire Maximum Effective Range (MER)

The maximum effective range of the Hellfire missile when employed by the MH-60R or the Fire Scout UAV.

l. LOGIR Pk

The probability of kill associated with the LOGIR when employed by the MH-60R or the Fire Scout UAV. The Pk is the product of the probability of hit and the probability of kill given a hit.

m. LOGIR Ifr

The inter-firing rate associated with the LOGIR. This is the amount of time between subsequent firings of the LOGIR.

n. LOGIR Qc

The number of LOGIR being carried by the MH-60R or Fire Scout UAV.

o. LOGIR MER

The maximum effective range of the LOGIR when employed by the MH-60R or the Fire Scout UAV.

p. APKWS Pk

The probability of kill associated with the APKWS when equipped by the MH-60R or the Fire Scout UAV. The Pk is the product of the probability of hit and the probability of kill given a hit.

q. APKWS Ifr

The-inter firing rate associated with the APKWS. This is the amount of time between subsequent firings of the APKWS.

r. APKWS Qc

The number of APKWS being carried by the MH-60R or Fire Scout UAV.

s. APKWS MER

The maximum effective range of the APKWS when employed by the MH-60R or the Fire Scout UAV.

t. DAGR Pk

The probability of kill associated with the DAGR when employed by the MH-60R or the Fire Scout UAV. The Pk is the product of the probability of hit and the probability of kill given a hit.

u. DAGR Ifr

The inter-firing rate associated with the DAGR. This is the amount of time between subsequent firings of the DAGR.

v. DAGR Qc

The number of DAGR being carried by the MH-60R or Fire Scout UAV.

w. DAGR MER

The maximum effective range of the DAGR when employed by the MH-60R or the Fire Scout UAV.

2. Assumptions

- The DAGR, APKWS, and LOGIR will be based on the Hydra 70 rocket with its 7.7 kg warhead and not the CRV7 rocket with 4.5 kg warhead.
- The Fire Scout UAV can carry two Hellfire Missiles
- The Fire Scout UAV can laser designate targets for the LCS
- LOGIR and DAGR have the same minimum rage as APKWS, which is reported as 0.93 miles in Jane's
- The LCS can fire its missiles off of MH-60R or Fire Scout sensor data
- The MH-60R detect range of a 50 foot missile patrol boat is 30,000 meters and the classify range is 8,500 meters
- The Fire Scout detect range of a 50 foot missile patrol boat is 28,000 meters and the classify range is 8,000 meters

C. THE EXPERIMENT

1. The Nearly Orthogonal Latin Hypercube (NOLH)

The NOLH experimental design technique was developed at NPS by Lt. Col. Thomas Cioppa, United States Army, in 2002. This technique was designed to efficiently explore simulations that have a large input space, requiring minimum a priori assumptions (Cioppa, 2002). The space filling property of the NOLH allows the analyst to explore more of the input space than the traditional factorial design, in which only high and low values are considered. The NOLH does not allow the analyst to see all of the response surface, but does enable the analyst to see a broader section of the response

surface. A NOLH generation tool created by Professor Susan Sanchez at NPS was used to generate the designs for this thesis. Detailed tables of the experimental designs used are provided in Appendix B.

2. Exploratory Design

To explore MANA's suitability to address the question posed by this thesis, an exploratory design of the scenario was created. This scenario is very abstract, includes a smaller number of threat vessels, and is intended to provide insight into the modeling of the different personalities, sensor capabilities, and communications capabilities for each squad in the scenario. This scenario verifies that the aircraft are not able to be shot down by the surface-to-surface missiles on the red forces, that the LCS can use the aircraft's sensor data, and that the sensors and weapons are working properly. Sensor verification was, in part, accomplished by having MANA track the detection of each squad by the other squads and using this data to tweak the personalities of the squads.

3. Preliminary Design

With the exploratory design working bug free, it was time to expand upon it. The aircraft was copied and made into two squads with the adjustments made to differentiate between the Fire Scout UAV and the MH-60R. The simulation was then run several times with the aircraft variously turned on or off to ensure that the switch was working smoothly. Turning the aircraft on and off was done by marking the corresponding aircraft squad as either active or inactive in that particular scenario. The same procedure was done with the aircrafts' weapons. Then, the number of enemy missile patrol boats was slowly worked up in increments of two until reaching the maximum of 20.

4. Final Design

After several dozen runs of the preliminary design, during which the design was validated with the assistance of Mary McDonald of the SEED center, the final design was implemented. The 512 runs created by the NOLH were used with each run being replicated 40 times for both versions of the scenario, one with the Fire Scout UAV active and one with the MH-60R active. These 40 replications of each run resulted in there

being 20,480 runs for each scenario, which resulted in 532,480 data points for each scenario and 1,064,960 total data points. The analysis of these data points is the basis for this thesis and is covered in the next chapter.

D. RUNNING THE EXPERIMENT

The base case MANA scenario, in Extensible Markup Language (XML) format, and the DOE file, in comma-separated value (CSV) format, were entered into a software program called XStudy, written by SEED Center Research Associate Steve Upton. The XStudy program enables the user to map each column in the design file to a specific parameter in MANA using XPath expressions. Other details about the study design, such as the version of MANA and number of replications per design point, are also entered into this tool, yielding a single Study.xml file. This file is used by another program called oldmcdata, also written by Steve Upton, which automatically updates the MANA XML file, producing a separate XML scenario file for each of the different factor combinations. This program then launches MANA runs on the SEED Center's high-performance computing cluster for each of the separate files. This is done to automate the parallel implementation of the MANA simulated runs and subsequently collect the output data into a single CSV file.

E. SUMMARY

The NOLH design provided by Professor Susan Sanchez of NPS was used to vary the 23 variables across the full range of values into a total of 1,028 rows of data. These rows of data, in two sets of 512 each, were each executed 40 times to provide 1,064,960 total data points.

V. DATA ANALYSIS

The experiment described in the Chapter IV generated a large amount of data. This chapter begins by discussing how the data was collected and processed for analysis. The purpose of this analysis is to provide insight into the research questions, which are restated in this chapter.

A. DATA COLLECTION AND PROCESSING

The output provided by MANA is in the form of a CSV file that allows for simple processing, as it is a file that can be read by a multitude of statistical software programs without the need to adjust the data. These output files provide the number of casualties to each squad, as well as the input variables that are used with each run. For each scenario there were 512 different sets of input data that were run 40 times each, resulting in 20,480 rows of data for each scenario, or 40,960 rows of data total. In order to compile the output data into a more manageable number, summaries of the output files were needed. Each of the scenario output files was imported into a statistical software packaged called JMP version 8.0, a program created by SAS Institute Incorporated. The means and standard deviations were generated for each input combination, bringing the rows of data from 20,480 down to 512 for the summaries of the two scenarios. The measure of effectiveness (MOE) used in this research is the mean total Red casualties.

B. INSIGHTS INTO RESEARCH QUESTIONS

In Chapter I, three questions were offered as the basis of this research. Each of these questions has been addressed through data analysis. The research questions for this thesis are:

- What surface-to-surface missile should LCS deploy with?
- What type of air-to-surface missiles should the aircraft be equipped with to be the most effective?
- What factors are more important in determining the type of missile to select?

This analysis includes the use of several analytical tools, including partition trees and bivariate analysis.

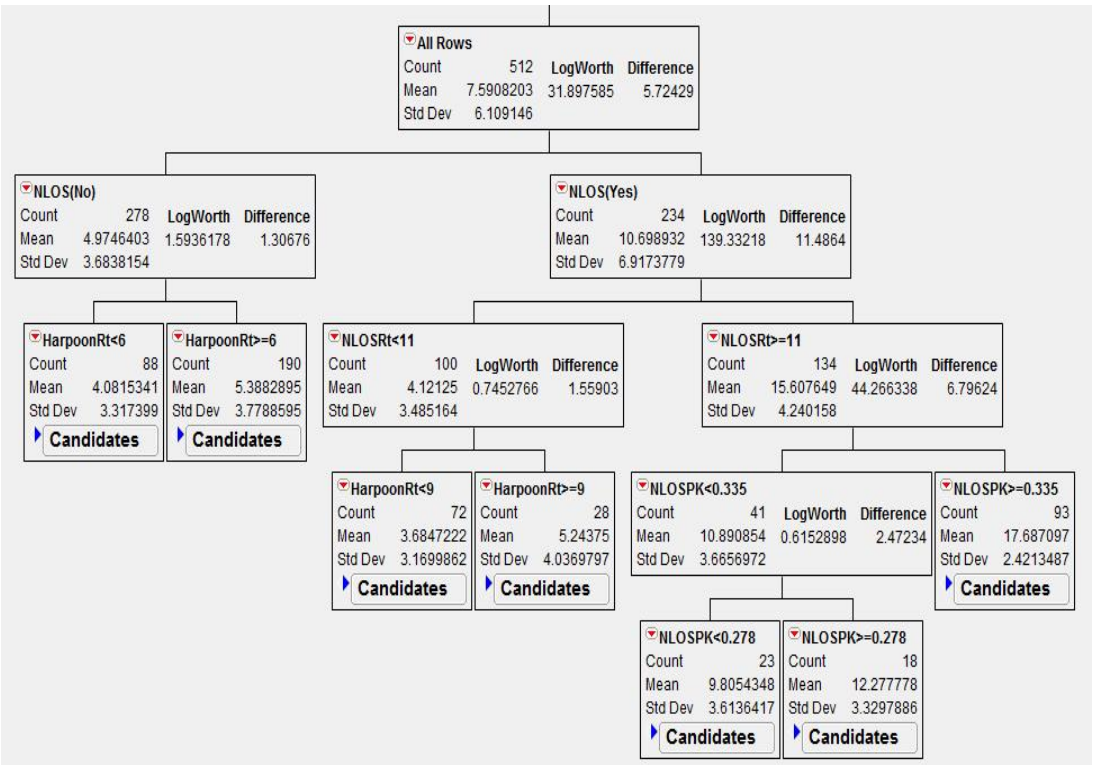
1. Surface-to-Surface Missile for the SUW Module

The question regarding the LCS surface-to-surface missile is the same in both versions of the scenario and so data from both output summaries will be viewed.

a. MH-60R Scenario

As shown in Table 3, the first split is determined by whether or not the ship is equipped with NLOS or Harpoon. With NLOS the mean number of Red casualties is 10.70 while the mean with Harpoon is only 4.98. This result can be interpreted to mean that the NLOS missile system is superior, but if one splits the data further, one can see that, when the rate of fire of the NLOS is less than 11 (or greater than 9.1 seconds between shots), that the mean number of Red casualties drops to 4.12 making it less capable than Harpoon. As one can see from Table 3, the Pk of the NLOS is less important as long as the rate of fire is 11 or better (9.1 seconds or less between shots). If the NLOS rate is below 11, then the Harpoon appears to be a better choice based on the split as long as the Harpoon rate of fire is greater or equal to 6 (16.7 seconds between shots of less).

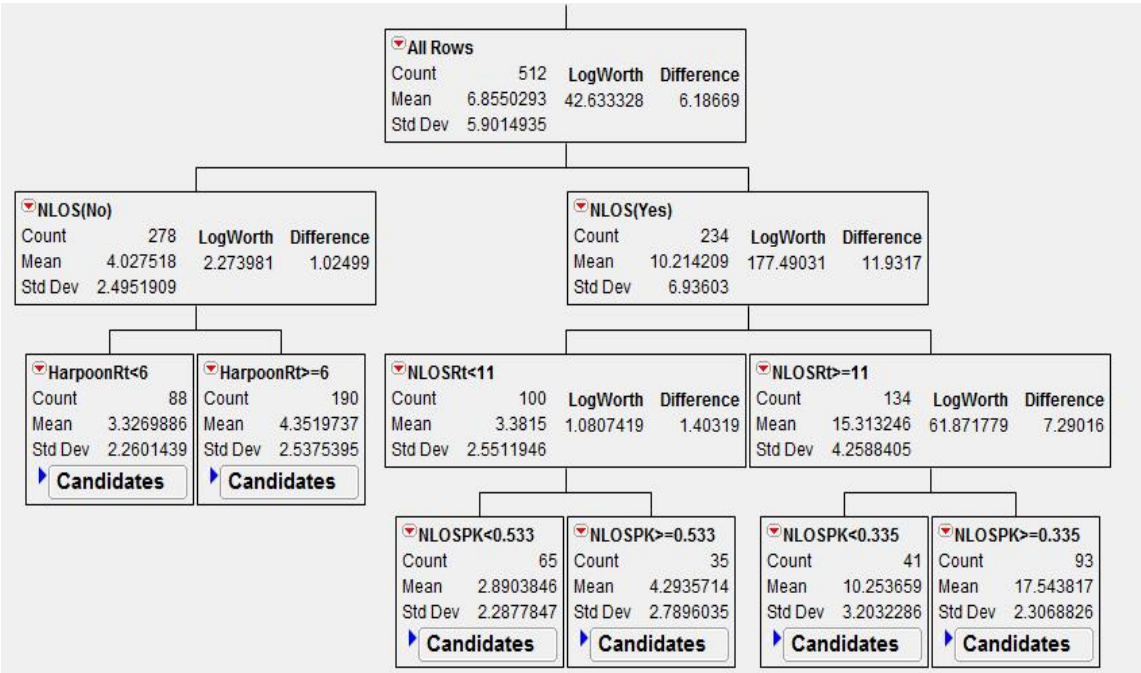
Table 3. The partition tree comparing the Harpoon and NLOS data from the MH-60R summary data, based upon the mean number of Red casualties.



b. UAV Scenario

As shown in Table 4, the data from the UAV runs shows nearly identical results as the MH-60R data. The NLOS is superior to the Harpoon as long as the rate is greater than or equal to 11 (9.1 seconds or less between shots), with there being a vast difference between the means (10.21 vs 4.02). If the NLOS rate is greater than 11, then it does not appear to matter much what the Pk is. As before, the Harpoon at a rate greater than or equal to 6 (16.7 seconds between shots of less) is superior to the NLOS with a rate less than 11 (greater than 9.1 seconds between shots), but only if the NLOS Pk is below 0.533.

Table 4. The partition tree comparing the Harpoon and NLOS data from the UAV summary data, based upon the mean number of Red casualties.



c. Overall

The partition trees for both summaries look very similar and both agree that the NLOS is superior to the Harpoon as long as the rate of fire is 9.1 seconds between shots or less. If the NLOS rate of fire is less than 9.1 seconds, then a Harpoon with a rate of 16.7 seconds or less between shots is slightly superior.

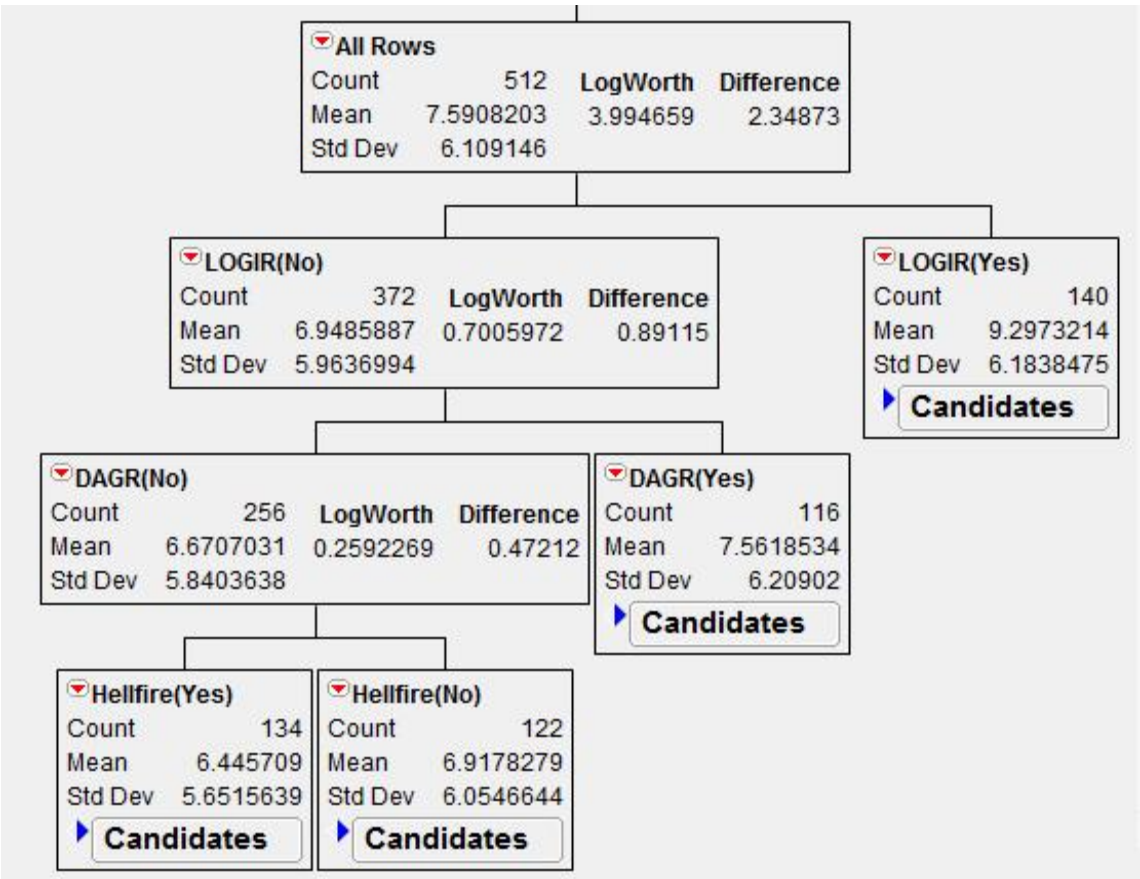
2. What Type of Air-to-Surface Missile Is Most Effective

The question regarding which air-to-surface missile would be best to equip the aircraft with is the same in both versions of the scenario and so data from both output summaries will be viewed.

a. MH-60R Scenario

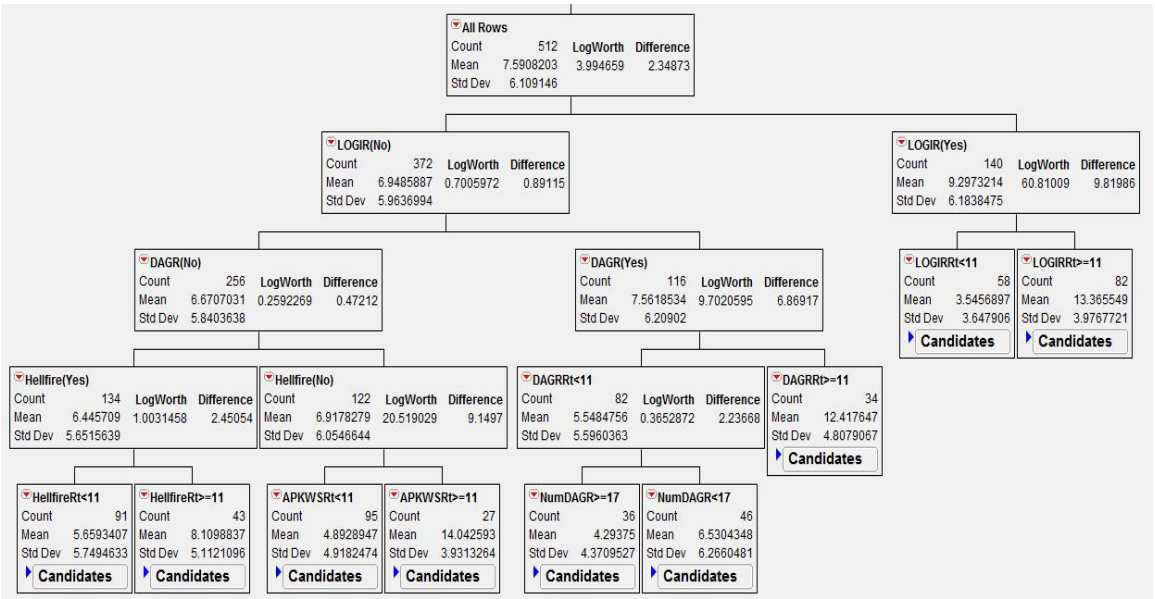
Table 5 shows that the LOGIR is the most effective missile system. The LOGIR had a mean of 9.30, DAGR had a mean of 7.56, APKWS had a mean of 6.92, and Hellfire had a mean of 6.45. Unfortunately, this interpretation does not provide a complete picture since the Standard Deviations are approximately six in each category.

Table 5. The partition tree of the MH-60R summary data in which the number of mean Red casualties based on the missiles equipped are the only categories of data studied.



As is evidenced by Table 6, the first split still takes place with the aircraft being equipped with LOGIR having a mean of 9.30 compared to a mean of 6.95 for all other missile types. But, if the rate of fire of the LOGIR is less than 11 (or greater than 9.1 seconds between shots), then it is no longer the best option. The next missile that meets the criterion for a split is the DAGR. If the DAGR is equipped and its rate is greater than 11 (9.1 seconds or less between shots) then it is the third best option, with a mean of 12.418, compared to the LOGIR with a rate greater than 11 having a mean of 13.366. The APKWS comes out ahead after the breakdown when it has a rate greater than 11, beating out LOGIR with a mean of 14.043. Of the two, however, LOGIR is more likely to have a higher rate of fire, being a fire-and-forget type of missile. The next section will feature a more in-depth look at what features affect the missiles the most.

Table 6. From the MH-60R Summary data. A partition tree of the four air-to-surface missile options and all of their input options.



b. UAV Scenario

The results from the UAV summary are quite similar to those from the MH-60R summary. Looking at Table 7, which shows the overall split between each missile, LOGIR is once again leading the way with a mean of 8.07, followed by DAGR, then APKWS, then Hellfire. Looking to Table 8 for a more in-depth breakdown, one can see that LOGIR splits off first again, but while LOGIR with a rate of 11 or greater appears to lead the way, further splits show that APKWS with a rate of fire of 11 or greater has a slightly higher mean; 11.97 versus 11.24. However, as stated in the previous section, it is more likely that the LOGIR will have a greater rate of fire, with it being a fire-and-forget type of missile.

Table 7. A basic partition tree of the UAV summary data showing the breakdown of the four air-to-surface missile options by the mean number of Red casualties

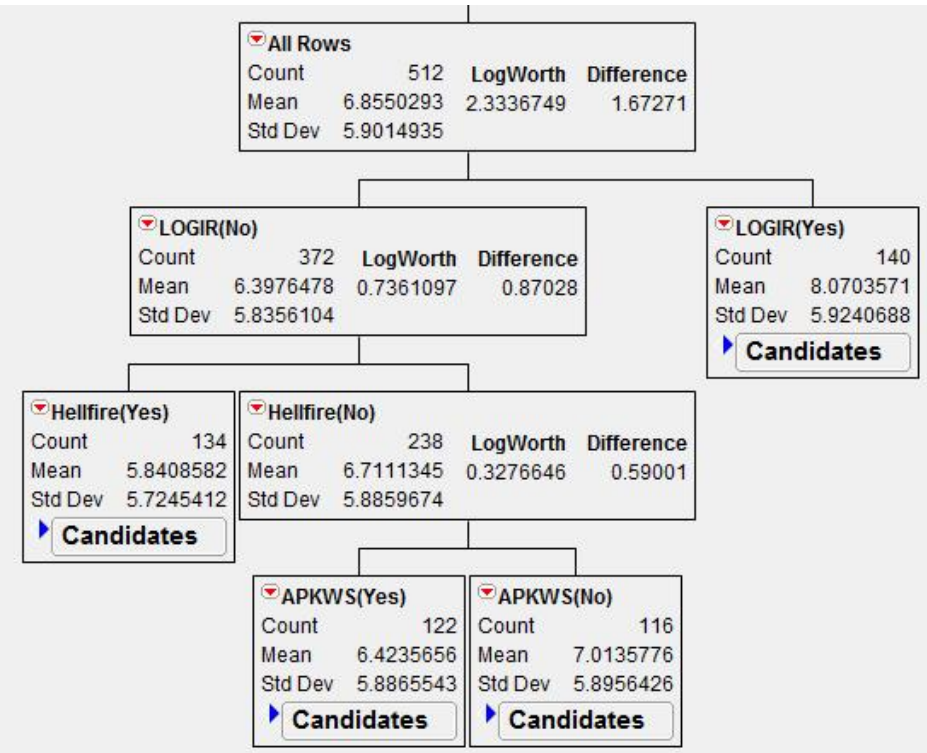
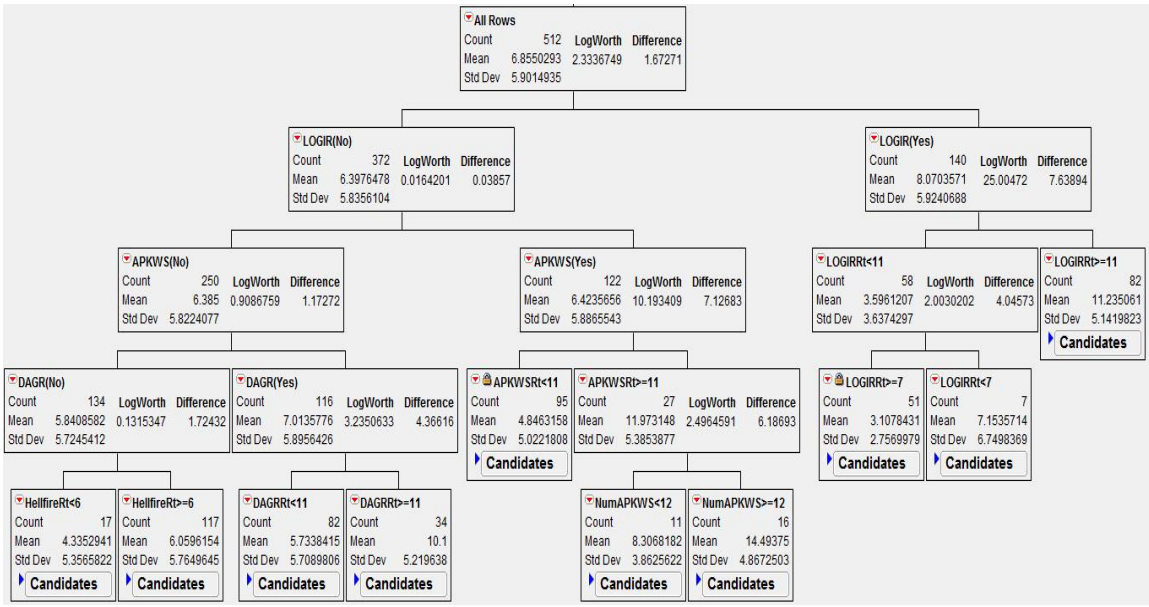


Table 8. From the UAV Summary data. A partition tree of the four air-to-surface missile options and all of their input options based on the mean number of Red casualties



c. Overall

The summary data for both versions of the scenario seem to agree that the APWKS is the air-to-surface missile of choice. This holds true only as long as the rate of fire of the APKWS is 9.1 seconds or faster. If the rate is slower than 9.1 seconds, then the LOGIR with a rate of 9.1 seconds or faster is the best missile option. Since the LOGIR is a fire-and-forget type of missile, it is more likely to have this higher rate of fire.

3. Most Important Factors in Missile Selection

The question regarding which factors most impact the MOE of a selected missile is the same in both versions of the scenario and so data from both output summaries will be viewed.

a. MH-60R Scenario

When analyzing mean total Red casualties as broken down per missile type, effects screening identifies the rate of fire of each missile as the only statistically

significant, or close to statistically significant, factor. This result is shown in Table 9. The only exception to this result is the NLOS system, in which effects screening identifies both the rate of fire and the Pk as being statistically significant ($p < .05$). The reason behind this potentially lies in the fact that the NLOS Pk was varied over a much broader range than the other missiles' Pks. Of note is that when the NLOS data is put into a partition tree, it splits first based on rate of fire, which implies that rate of fire is more significant than the Pk. This is also evident in the overall MH-60R summary partition tree in which the rate of fire of the NLOS is the second split in the data, coming only after the split between whether the LCS is equipped with NLOS or Harpoon. This was seen previously in Table 3.

Table 9. The parameter estimates of the regression analysis resulting from effects screening of mean total Red casualties in the MH-60R scenario separated by missile type (Hellfire, LOGIR, APKWS, DAGR, NLOS, and Harpoon, respectively)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	28.447506	17.09077	1.66	0.0984
NumHellfire	-0.43597	0.345671	-1.26	0.2095
HellfirePK	-35.47884	22.71844	-1.56	0.1208
HellfireRt	0.349551	0.181176	1.93	0.0559
HellfireRng	0.0001994	0.000793	0.25	0.8019

Rate of fire is most statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-6.878955	6.997866	-0.98	0.3274
NumLOGIR	0.0337985	0.059705	0.57	0.5723
LOGIRPK	-2.945522	8.613624	-0.34	0.7329
LOGIRRt	1.2319363	0.127247	9.68	<.0001*
LOGIRRng	0.0005192	0.000959	0.54	0.5890

Rate of fire is most statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-10.79361	13.2737	-0.81	0.4178
NumAPKWS	0.0276469	0.072218	0.38	0.7025
APKWSPK	-20.28933	12.44339	-1.63	0.1057
APKWSRt	1.1960358	0.197015	6.07	<.0001*
APKWSRng	0.0038893	0.002514	1.55	0.1245

Rate of Fire is by far the most statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.166745	11.34594	-0.28	0.7807
NumDAGR	0.1460278	0.122586	1.19	0.2361
DAGRPK	-2.108077	15.24337	-0.14	0.8903
DAGRRt	0.8391069	0.216147	3.88	0.0002*
DAGRRng	0.0003805	0.001069	0.36	0.7227

Rate of fire is most statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-7.557176	1.121909	-6.74	<.0001*
NLOSPK	12.940663	1.774032	7.29	<.0001*
NLOSRt	1.0539823	0.062665	16.82	<.0001*

Pk and rate of fire are statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.097265	5.085149	-0.61	0.5430
HarpoonPK	6.478016	5.764441	1.12	0.2621
HarpoonRt	0.3524386	0.110232	3.20	0.0015*

Rate of fire is statistically significant

b. UAV Scenario

When analyzing mean Red casualties as broken down per missile type, effects screening identifies the rate of fire of the missile as the most common statistically significant factor. These effects screenings can be seen in Table 10. In the LOGIR, APKWS, DAGR, and Harpoon analyses, the rate of fire is the only statistically significant factor. The NLOS data shows both the rate of fire and the Pk as both being statistically significant, but once again, this is most likely due to the large range of the Pk that was used for the NLOS. Similar to the MH-60 data, when the NLOS data is put into a partition tree, the first split is on the rate of fire, identifying it as more significant than the Pk. The only oddity is the Hellfire missile, in which effects screening identifies no statistically significant factors.

Table 10. The parameter estimates of the regression analysis resulting from effects screening of mean total Red casualties in the UAV scenario separated by missile type (Hellfire, LOGIR, APKWS, DAGR, NLOS, and Harpoon respectively)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	23.961973	17.34564	1.38	0.1695
NumHellfire	0.3221869	0.611094	0.53	0.5989
HellfirePK	-33.57364	23.35904	-1.44	0.1531
HellfireRt	0.0870608	0.187037	0.47	0.6424
HellfireRng	0.0004026	0.000817	0.49	0.6232

Nothing is statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2.097096	7.427855	-0.28	0.7781
NumLOGIR	0.2100166	0.124793	1.68	0.0947
LOGIRPK	-5.373745	9.139264	-0.59	0.5575
LOGIRRt	0.9505791	0.135083	7.04	<.0001*
LOGIRRng	-0.000157	0.001017	-0.15	0.8776

Rate of fire is statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-4.452351	13.50048	-0.33	0.7421
NumAPKWS	0.1695402	0.146024	1.16	0.2480
APKWSPK	-24.27671	12.7033	-1.91	0.0584
APKWSRt	0.9555766	0.200609	4.76	<.0001*
APKWSRng	0.0030006	0.002562	1.17	0.2439

Rate of fire is statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.7875214	12.1466	0.15	0.8833
NumDAGR	0.1068216	0.374792	0.29	0.7762
DAGRPK	-0.421228	15.30179	-0.03	0.9781
DAGRRt	0.4539336	0.215983	2.10	0.0378*
DAGRRng	7.6766e-5	0.001071	0.07	0.9430

Rate of Fire is statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-8.937351	1.055838	-8.46	<.0001*
NLOSPK	13.919951	1.669556	8.34	<.0001*
NLOSRt	1.093062	0.058975	18.53	<.0001*

PK and rate of fire are statistically significant

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.321198	3.419782	-0.39	0.6995
HarpoonPK	3.9027353	3.876608	1.01	0.3149
HarpoonRt	0.2832501	0.074132	3.82	0.0002*

Rate of fire is statistically significant

c. Overall

Analysis of both sets of data shows that the rate of fire is statistically significant for the LOGIR, APKWS, DAGR, NLOS, and Harpoon missile systems. This supports the conclusion that the rate of fire is the most important factor in missile selection.

C. SUMMARY

Analysis of the data points shows that the NLOS is the preferred surface-to-surface missile as long as it is able to maintain a rate of fire of 9.1 seconds or faster. The analysis of the data on the air-to-surface missiles shows that the LOGIR is superior overall, but that the APKWS is slightly better if its rate of fire is 9.1 seconds or faster. When analyzing how the different factors contribute to the effectiveness of the missiles, it is evident that the rate of fire of the missiles is the most important factor.

VI. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

1. Which Surface-to-Surface Missile Should LCS Deploy With?

Based on the data analysis the NLOS-LS is superior to the Harpoon as long as a firing rate of 9.1 seconds or faster is maintainable. The data also shows that the Pk of the NLOS does not matter for the most part as long as the high firing rate is maintained.

2. What Type of Air-to-Surface Missile Should the Aircraft Be Equipped With?

Based on the analysis of the summary data, the LOGIR is best Air-to-Surface missile option overall, especially if a rate of fire of 9.1 seconds or faster can be maintained. Further analysis shows that the APKWS is slightly superior to the LOGIR if its rate of fire is 9.1 seconds or faster, but because the LOGIR is a fire-and-forget missile that does not require lasing of the target, it is much more likely that the LOGIR will be able to maintain a higher rate of fire.

3. What Factor Is Most Important in Deciding Which Missile to Select?

The regression analysis of each missile and its factors show that that most statistically significant factor is the rate of fire. The Pk of the NLOS is statistically significant but that is most likely due to the broad range of Pk that was used for NLOS in the experiment.

B. RECOMMENDATIONS

The results of this thesis support the following recommendations:

- The Navy should continue the development of the LOGIR and APKWS
- The DAGR is a viable alternative if the costs rise for LOGIR and APKWS
- The Navy should continue with the development of the NLOS-LS and PAM.

- When looking at future missile systems, the rate of fire should be the most important deciding factor, within reason. A missile system that has a high rate of fire but only four missiles would not be very beneficial and neither would a missile system that has a high rate of fire but a very poor hit probability.
- Tactics should allow for the LCS to use its speed and maneuverability, when conditions permit, to keep the distance between it and the enemy combatants beyond the enemy's detection and/or weapons' range and use LCS's aircraft and over-the-horizon capabilities to defeat the enemy without exposing the LCS to direct harm.

C. FUTURE WORK

While working on this thesis the following items were identified as warranting further research.

- Work the missile defense capability of LCS into the simulation.
- Include aircraft and subsurface threats into the simulation.
- Rework the scenario in SimKit and compare the results.
- Conduct a cost benefits analysis on which options provide the best combination of combat effectiveness and low cost.
- Investigate effects of communications failures between the LCS and the aircraft on their combat effectiveness.
- Rework the scenario to include the frontrunners of the Navy's next generation long-range anti-ship missile program.
- Look into the implications of this research and what it might mean for LCS tactics in the SUW environment.

- Test the different LCS and aircraft missile combinations in situations involving different tactics on the part of Blue and Red forces to further test the effectiveness of the different missile systems.
- Analyze the impact of using different UAVs in place of the Fire Scout.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. PERSONALITIES AND CAPABILITIES OF SQUADS

NAVAL POSTGRADUATE SCHOOL

Modeling Summary – Missile Boats

Weapon	Effective Range	Pk	Rounds
C-802	120 km	0.45	4

Sensors and Speed: Basic surface search with a detection range of 29 km and a classification range of 24 km. Missile boats transit and attack at a speed of 45 knots.

Personality Summary: The missile boats are headed west at full speed based on intelligence of an LCS in the area. They commence attack as soon as their sensors are within range to provide sufficient data to their missiles.

WWW.NPS.EDU

NAVAL POSTGRADUATE SCHOOL

Modeling Summary – LCS

Weapon	Effective Range	Pk	Rounds
NLOS	40 km	0.16 – 0.72	60
Harpoon	85 km	0.8075 – 0.9405	8

Sensors and Speed: Basic surface search with a detection range of 32 km and a classification range of 26 km. LCS transits and attacks at a speed of 35 knots.

Personality Summary: The LCS are transiting north at 35 knots. They commence attack as soon as their sensors or the helicopter/UAV's are within range to provide sufficient data to their missiles.

WWW.NPS.EDU

NAVAL POSTGRADUATE SCHOOL

Modeling Summary – MH-60R

Weapon	Effective Range	Pk	Firing Rate	Rounds
Hellfire	6000 – 8000 m	0.6375 – 0.7125	8 – 18 seconds	4 – 8
LOGIR	4350 – 5800 m	0.4225 – 0.585	6 – 16 seconds	14 – 38
APKWS	4350 – 5000 m	0.4875 – 0.6175	8 – 20 seconds	14 – 38
DAGR	5250 – 7000 m	0.4875 – 0.6175	8 – 20 seconds	8 - 24

Sensors and Speed: Basic surface search with a detection range of 30 km and a classification range of 6.5 km. The MH-60 transits and attacks at a speed of 125 knots.

Personality Summary: The MH-60 is headed east to conduct surface search based on intelligence of Enemy missile boats in the area. They commence attack as soon as their sensors are within range to provide sufficient data to their missiles. If out of missiles, the MH-60 stays within sensor range to provide targeting data for the LCS.

WWW.NPS.EDU

NAVAL POSTGRADUATE SCHOOL

Modeling Summary – UAV

Weapon	Effective Range	Pk	Firing Rate	Rounds
Hellfire	6000 – 8000 m	0.6375 – 0.7125	8 – 18 seconds	2 – 4
LOGIR	4350 – 5800 m	0.4225 – 0.585	6 – 16 seconds	7 – 19
APKWS	4350 – 5000 m	0.4875 – 0.6175	8 – 20 seconds	7 – 19
DAGR	5250 – 7000 m	0.4875 – 0.6175	8 – 20 seconds	8 - 12

Sensors and Speed: Basic surface search with a detection range of 25 km and a classification range of 6 km. The UAV transits and attacks at a speed of 125 knots.

Personality Summary: The UAV is headed east to conduct surface search based on intelligence of Enemy missile boats in the area. They commence attack as soon as their sensors are within range to provide sufficient data to their missiles. If out of missiles, the UAV stays within sensor range to provide targeting data for the LCS.

WWW.NPS.EDU

APPENDIX B. EXPERIMENTAL DESIGNS

This appendix illustrates the Nearly Orthogonal Latin Hypercube (NOLH) used to conduct the simulation experiment. Due to the size of the full designs, only the first 50 rows are provided.

A. MH-60R SCENARIO DESIGN

A-t-S Missile	Ship S-t-S Missile	# Hellfires	# LOGIR	# APKWS	# DAGR	Hellfire Pk	LOGIR Pk	APKWS Pk	DAGR Pk	NLOS Pk	Harpoon Pk	Hellfire rate	LOGIR rate	APKWS rate	DAGR rate	NLOS rate	Harpoon rate	Hellfire MER (in	LOGIR MER (in	APKWS MER (in	DAGR MER (in	MH-60R Pd	LCS Pd
1	5	4	14	14	8	0.6375	0.4225	0.4875	0.4875	0.16	0.8075	5	6	5	5	4	4	6000	4350	4350	5250	0.5	0.5
4	6	8	38	38	24	0.7125	0.585	0.6175	0.6175	0.72	0.9405	13	17	13	13	20	10	8000	5800	5000	7000	1	1
2	6	4	16	37	8	0.65	0.576	0.592	0.495	0.347	0.895	8	16	8	11	18	5	7491	4364	4711	6229	0.819	0.768
4	5	8	26	23	21	0.7	0.451	0.534	0.517	0.653	0.85	6	12	7	12	18	6	6834	5479	4496	5606	0.728	0.874
1	5	8	23	35	20	0.641	0.461	0.497	0.577	0.48	0.895	6	10	12	12	20	5	7123	5176	4528	5438	0.73	0.954
1	6	4	25	15	9	0.709	0.551	0.578	0.519	0.244	0.839	5	10	12	12	13	7	7609	5576	4543	6596	0.516	0.717
2	5	4	33	38	11	0.651	0.443	0.525	0.547	0.69	0.817	7	13	7	7	12	10	6438	5372	4527	5346	0.677	0.729
1	5	4	38	21	12	0.705	0.579	0.556	0.53	0.18	0.838	9	10	12	7	5	6	6145	5292	4894	5945	0.818	0.589
2	5	8	35	25	12	0.647	0.432	0.571	0.584	0.385	0.85	8	14	12	12	16	7	7832	4895	4977	5301	0.836	0.515
4	6	4	25	37	18	0.659	0.456	0.528	0.538	0.557	0.859	11	14	6	5	7	10	6133	4727	4715	5842	0.63	0.679
4	6	6	17	19	10	0.706	0.559	0.612	0.583	0.507	0.827	6	14	7	7	12	5	7969	5034	4864	5565	0.794	0.625
1	6	4	24	19	8	0.709	0.569	0.542	0.56	0.453	0.867	8	7	12	12	7	7	7742	4489	4398	6349	0.761	0.55
1	5	4	16	14	16	0.638	0.456	0.585	0.594	0.466	0.916	8	9	6	6	16	6	7945	5397	4452	6863	0.543	0.977
2	6	8	27	34	21	0.651	0.577	0.584	0.503	0.33	0.889	13	10	12	12	11	6	7550	5238	4447	5562	0.788	0.882
1	6	8	24	23	22	0.691	0.551	0.598	0.512	0.508	0.937	13	13	12	12	6	7	7139	4804	4501	5860	0.524	0.869
4	6	5	36	22	16	0.673	0.561	0.506	0.559	0.216	0.888	11	10	12	12	9	7	7644	5267	4975	6685	0.764	0.715
4	6	4	33	31	10	0.706	0.471	0.544	0.501	0.527	0.847	9	14	7	8	6	6	7663	5766	4943	5329	0.584	0.612
1	6	5	33	38	11	0.676	0.453	0.52	0.608	0.355	0.852	6	14	12	6	13	7	6063	4466	4672	5527	0.855	0.734
2	6	4	36	24	12	0.647	0.427	0.57	0.523	0.235	0.838	7	10	6	12	7	6	7068	5037	4962	5952	0.623	0.726
4	5	4	21	31	13	0.705	0.527	0.565	0.616	0.268	0.92	7	14	7	7	13	7	6853	4708	4615	6743	0.943	0.977
3	6	8	19	33	9	0.689	0.505	0.489	0.587	0.213	0.825	13	6	12	12	15	7	6270	5496	4609	6360	0.729	0.984
4	6	4	14	18	16	0.663	0.434	0.517	0.576	0.273	0.843	12	13	12	12	4	7	7554	4475	4425	5979	0.821	0.815
4	5	4	29	37	14	0.704	0.577	0.504	0.534	0.628	0.876	7	10	12	12	4	5	7840	5000	4383	5942	0.713	0.95
3	5	7	16	18	9	0.655	0.542	0.575	0.523	0.592	0.907	6	7	6	12	10	5	7393	4835	4358	5432	0.723	0.983
2	6	5	15	15	16	0.689	0.45	0.604	0.584	0.586	0.831	10	14	12	12	6	6	6536	5669	4636	5836	0.53	0.538
1	6	7	28	22	12	0.683	0.582	0.618	0.497	0.378	0.829	9	10	12	5	11	7	6078	5130	5000	5733	0.769	0.702
2	6	8	26	19	24	0.648	0.519	0.538	0.496	0.579	0.897	8	13	12	6	5	6	6137	5142	4826	5250	0.949	0.866
3	6	5	30	30	19	0.651	0.424	0.588	0.488	0.476	0.868	8	9	6	12	13	10	7104	4503	4893	5682	0.735	0.523
4	5	6	31	25	18	0.7	0.532	0.602	0.538	0.3	0.925	13	14	12	6	5	6	6701	4991	4578	6223	0.632	0.721
1	5	4	27	23	19	0.688	0.464	0.543	0.558	0.529	0.854	5	13	12	12	7	6	7319	4685	4669	6856	0.968	0.788
1	6	7	28	18	9	0.642	0.549	0.588	0.551	0.346	0.936	6	13	6	6	17	6	6928	4393	4738	6161	0.57	0.666
4	6	6	18	25	20	0.708	0.559	0.578	0.598	0.404	0.923	12	10	12	6	15	5	7961	4617	4579	5257	0.96	0.877
2	6	5	21	34	10	0.66	0.445	0.499	0.527	0.427	0.813	9	17	12	6	6	5	7589	4716	4836	5692	0.776	0.659
4	6	8	15	16	12	0.694	0.517	0.565	0.571	0.604	0.86	13	6	12	6	18	5	6059	4801	4472	5620	0.82	0.617
4	6	5	32	27	22	0.64	0.562	0.517	0.569	0.517	0.855	12	7	12	5	12	5	7718	5329	4391	6250	0.734	0.616
4	6	4	37	31	17	0.692	0.452	0.613	0.543	0.56	0.894	9	9	12	6	10	6	7503	5567	4785	6202	0.892	0.87
3	6	4	34	35	15	0.648	0.492	0.512	0.607	0.227	0.939	8	8	6	6	12	6	7444	4719	4463	6945	0.521	0.643
4	6	7	31	31	17	0.677	0.44	0.591	0.528	0.561	0.817	9	11	12	6	18	6	7914	4662	4430	5788	0.555	0.902
1	5	7	18	27	14	0.682	0.583	0.508	0.561	0.202	0.903	5	8	6	11	17	9	7785	5071	4971	5688	0.653	0.58
2	6	7	24	26	10	0.656	0.572	0.588	0.544	0.505	0.844	10	15	13	6	18	5	7886	5774	4601	5411	0.616	0.597
4	6	4	27	35	15	0.657	0.452	0.53	0.491	0.712	0.874	6	15	10	10	9	5	7115	5786	4860	6038	0.627	0.614
3	6	5	32	31	17	0.648	0.502	0.61	0.545	0.242	0.858	11	9	6	6	10	4	6716	5335	4598	6438	0.795	0.587
4	6	8	35	31	13	0.662	0.541	0.606	0.496	0.66	0.87	9	8	13	13	17	4	6477	5079	4697	6719	0.965	0.641
3	6	4	37	22	23	0.691	0.444	0.562	0.571	0.182	0.818	12	14	5	13	11	10	7875	5755	4491	6137	0.856	0.929
1	5	8	25	27	18	0.658	0.497	0.547	0.613	0.186	0.827	9	11	8	10	9	6	6419	5721	4793	6188	0.602	0.676
1	6	6	19	32	8	0.657	0.5	0.549	0.596	0.443	0.815	11	14	13	7	15	9	7221	4676	4935	5384	0.974	0.823
4	6	5	35	19	13	0.67	0.436	0.503	0.49	0.46	0.926	6	11	11	6	9	4	7585	5428	4510	5589	0.872	0.71

B. UAV SCENARIO DESIGN

A-t-S Missile	Ship S-t-S Missile	# Hellfires	# LOGIR	# APKWS	# DAGR	Hellfire Pk	LOGIR Pk	APKWS Pk	DAGR Pk	NLOS Pk	Harpoon Pk	Hellfire rate	LOGIR rate	APKWS rate	DAGR rate	NLOS rate	Harpoon rate	Hellfire MER (in	LOGIR MER (in	APKWS MER (in	DAGR MER (in	UAV Pd	LCS Pd
1	5	2	7	7	8	0.6375	0.4225	0.4875	0.4875	0.16	0.8075	5	6	5	5	4	4	6000	4350	4350	5250	0.4	0.5
4	6	4	19	19	12	0.7125	0.585	0.6175	0.6175	0.72	0.9405	13	17	13	13	20	10	8000	5800	5000	7000	1	1
2	6	2	8	18	9	0.65	0.576	0.592	0.495	0.347	0.895	8	16	8	11	18	5	7491	4364	4711	6229	0.526	0.768
4	5	3	13	11	10	0.7	0.451	0.534	0.517	0.653	0.85	6	12	7	12	18	6	6834	5479	4496	5606	0.495	0.874
1	5	2	11	17	10	0.641	0.461	0.497	0.577	0.48	0.895	6	10	12	12	20	5	7123	5176	4528	5438	0.683	0.954
1	6	2	12	7	8	0.709	0.551	0.578	0.519	0.244	0.839	5	10	12	12	13	7	7609	5576	4543	6596	0.622	0.717
2	5	3	17	19	9	0.651	0.443	0.525	0.547	0.69	0.817	7	13	7	7	12	10	6438	5372	4527	5346	0.969	0.729
1	5	3	19	11	12	0.705	0.579	0.556	0.53	0.18	0.838	9	10	12	7	5	6	6145	5292	4894	5945	0.671	0.589
2	5	3	18	12	10	0.647	0.432	0.571	0.584	0.385	0.85	8	14	12	12	16	7	7832	4895	4977	5301	0.597	0.515
4	6	3	13	19	8	0.659	0.456	0.528	0.538	0.557	0.859	11	14	6	5	7	10	6133	4727	4715	5842	0.985	0.679
4	6	3	9	10	12	0.706	0.559	0.612	0.583	0.507	0.827	6	14	7	7	12	5	7969	5034	4864	5565	0.426	0.625
1	6	2	12	10	11	0.709	0.569	0.542	0.56	0.453	0.867	8	7	12	12	7	7	7742	4489	4398	6349	0.81	0.55
1	5	3	8	7	8	0.638	0.456	0.585	0.594	0.466	0.916	8	9	6	6	16	6	7945	5397	4452	6863	0.735	0.977
2	6	2	14	17	9	0.651	0.577	0.584	0.503	0.33	0.889	13	10	12	12	11	6	7550	5238	4447	5562	0.697	0.882
1	6	2	12	12	8	0.691	0.551	0.598	0.512	0.508	0.937	13	13	12	12	6	7	7139	4804	4501	5860	0.682	0.869
4	6	3	18	11	10	0.673	0.561	0.506	0.559	0.216	0.888	11	10	12	12	9	7	7644	5267	4975	6685	0.681	0.715
4	6	2	17	16	9	0.706	0.471	0.544	0.501	0.527	0.847	9	14	7	8	6	6	7663	5766	4943	5329	0.846	0.612
1	6	2	16	19	9	0.676	0.453	0.52	0.608	0.355	0.852	6	14	12	6	13	7	6063	4466	4672	5527	0.4	0.734
2	6	4	18	12	11	0.647	0.427	0.57	0.523	0.235	0.838	7	10	6	12	7	6	7068	5037	4962	5952	0.651	0.726
4	5	2	11	15	9	0.705	0.527	0.565	0.616	0.268	0.92	7	14	7	7	13	7	6853	4708	4615	6743	0.524	0.977
3	6	3	9	17	12	0.689	0.505	0.489	0.587	0.213	0.825	13	6	12	12	15	7	6270	5496	4609	6360	0.442	0.984
4	6	4	7	9	10	0.663	0.434	0.517	0.576	0.273	0.843	12	13	12	12	4	7	7554	4475	4425	5979	0.962	0.815
4	5	2	15	19	11	0.704	0.577	0.504	0.534	0.628	0.876	7	10	12	12	4	5	7840	5000	4383	5942	0.67	0.95
3	5	2	8	9	9	0.655	0.542	0.575	0.523	0.592	0.907	6	7	6	12	10	5	7393	4835	4358	5432	0.994	0.983
2	6	3	8	7	8	0.689	0.45	0.604	0.584	0.586	0.831	10	14	12	12	6	6	6536	5669	4636	5836	0.607	0.538
1	6	3	14	11	11	0.683	0.582	0.618	0.497	0.378	0.829	9	10	12	5	11	7	6078	5130	5000	5733	0.692	0.702
2	6	4	13	10	12	0.648	0.519	0.538	0.496	0.579	0.897	8	13	12	6	5	6	6137	5142	4826	5250	0.59	0.866
3	6	3	15	15	8	0.651	0.424	0.588	0.488	0.476	0.868	8	9	6	12	13	10	7104	4503	4893	5682	0.49	0.523
4	5	3	16	12	8	0.7	0.532	0.602	0.538	0.3	0.925	13	14	12	6	5	6	6701	4991	4578	6223	0.803	0.721
1	5	3	14	12	8	0.688	0.464	0.543	0.558	0.529	0.854	5	13	12	12	7	6	7319	4685	4669	6856	0.436	0.788
1	6	4	14	9	12	0.642	0.549	0.588	0.551	0.346	0.936	6	13	6	6	17	6	6928	4393	4738	6161	0.664	0.666
4	6	2	9	13	12	0.708	0.559	0.578	0.598	0.404	0.923	12	10	12	6	15	5	7961	4617	4579	5257	0.452	0.877
2	6	2	10	17	12	0.66	0.445	0.499	0.527	0.427	0.813	9	17	12	6	6	5	7589	4716	4836	5692	0.953	0.659
4	6	2	7	8	12	0.694	0.517	0.565	0.571	0.604	0.86	13	6	12	6	18	5	6059	4801	4472	5620	0.877	0.617
4	6	2	16	14	10	0.64	0.562	0.517	0.569	0.517	0.855	12	7	12	5	12	5	7718	5329	4391	6250	0.751	0.616
4	6	2	18	15	12	0.692	0.452	0.613	0.543	0.56	0.894	9	9	12	6	10	6	7503	5567	4785	6202	0.6	0.87
3	6	3	17	17	12	0.648	0.492	0.512	0.607	0.227	0.939	8	8	6	6	12	6	7444	4719	4463	6945	0.492	0.643
4	6	3	16	15	8	0.677	0.44	0.591	0.528	0.561	0.817	9	11	12	6	18	6	7914	4662	4430	5788	0.824	0.902
1	5	4	9	13	12	0.682	0.583	0.508	0.561	0.202	0.903	5	8	6	11	17	9	7785	5071	4971	5688	0.723	0.58
2	6	4	12	13	8	0.656	0.572	0.588	0.544	0.505	0.844	10	15	13	6	18	5	7886	5774	4601	5411	0.79	0.597
4	6	2	14	18	11	0.657	0.452	0.53	0.491	0.712	0.874	6	15	10	10	9	5	7115	5786	4860	6038	0.44	0.614
3	6	3	16	15	9	0.648	0.502	0.61	0.545	0.242	0.858	11	9	6	6	10	4	6716	5335	4598	6438	0.472	0.587
4	6	4	18	16	8	0.662	0.541	0.606	0.496	0.66	0.87	9	8	13	13	17	4	6477	5079	4697	6719	0.904	0.641
3	6	3	18	11	10	0.691	0.444	0.562	0.571	0.182	0.818	12	14	5	13	11	10	7875	5755	4481	6137	0.939	0.929
1	5	2	12	14	12	0.658	0.497	0.547	0.613	0.186	0.827	9	11	8	10	9	6	6419	5721	4793	6188	0.763	0.676
1	6	2	9	16	11	0.657	0.5	0.549	0.596	0.443	0.815	11	14	13	7	15	9	7221	4676	4935	5384	0.766	0.823
4	6	2	18	9	9	0.67	0.436	0.503	0.49	0.46	0.926	6	11	11	6	9	4	7585	5428	4510	5589	0.502	0.71

LIST OF REFERENCES

Abbott, B. P. (2008). Littoral Combat Ship (LCS) mission packages: Determining the best mix. Master's thesis, Naval Postgraduate School, Monterey, CA.

Abel, Heiko. (2009). Frigate defense effectiveness in asymmetrical green water engagements. Master's thesis, Naval Postgraduate School, Monterey, CA

Brannen, Kate. (2010, February 22). *U.S. NLOS-LS misses four of six shots in testing*. Retrieved from http://defensenews.com/story.php?i=4509667&c=AME&s=LAN

Brannen, Kate. (2010, May 12). *Committee shifts NLOS R&D funding to Navy*. Retrieved from http://www.armytimes.com/news/2010/05/military_army_navy_nlos_funding_051210w/

Cioppa, Thomas M. (2002). Efficient Nearly Orthogonal and Space-filling Experimental Designs for High-dimensional Complex Models. Ph.D. in Operations Research, Naval Postgraduate School, Monterey, CA.

Defense Tech. (2010, February 23). *Debating the Pros and Cons of LCS.* Retrieved from http://defensetech.org/2010/03/17/pros-and-cons-of-lcs/

Defense Tech. (2010, February 23). *NLOS Missile Not Very Precise*. Retrieved from http://defensetech.org/2010/02/23/nlos-missile-not-very-precise/

Efimba, M. E. (2003). An Exploratory Analysis of Littoral Combat Ships Ability to Protect Expeditionary Strike Groups. Master's thesis, Naval Postgraduate School, Monterey, CA.

Jackson, Paul, editor (2009). *Jane's All the World's Aircraft 2009-2010 Edition.* Sentinel House, Alexandria, VA, 100th edition.

Lauren, Michael K. and Stephen, Roger T. (2002, March). Map-aware Non-uniform Automata – A New Zealand Approach to Scenario Modelling. *Journal of Battlefield Technology, VOL 5, NO 1*.

Lockheed Martin (2009). AGM-114K Hellfire Mk. II. Retrieved from http://www.lockheedmartin.com/products/HellfireII/index.html

Long, Duncan and Johnson, Stuart. (2007, March). The Littoral Combat Ship: From Concept to Program. *Case Studies in National Security Transformation, Number 7.*

Global Security (2003, February). *Littoral Combat Ship Program*. Retrieved from http://www.globalsecurity.org/military/systems/ship/lcs-program.htm

Hooten, E. R., editor (2008). *Jane's Naval Weapon Systems 2007–2008 Edition.* Sentinel House, Alexandria, VA, 42nd edition.

Murphy, Martin N. (2010, March 3) Littoral Combat Ship: An Examination of Its Possible Concepts of Operation. *Center for Strategic and Budgetary Assessments.*

Naval Warfare Development Command. (2007, March 14). Littoral Combat Ship Warfighting Concept of Operations (Revision A).

Norman Friedman (2006). The Naval Institute Guide to World Naval Weapon Systems. *Naval Institute Press, 5th edition.*

O'Rourke, Ronald. (2010, April 8) Navy Littoral Combat Ship (LCS) Program: Background, Issues, and Options for Congress. Congressional Research Service.

Pike, J. (2007). AGM-114 Hellfire Employment. Retrieved from http://www.globalsecurity.org/military/systems/munitions/agm-114-employ.htm

Sanchez, S. M. (2005). Nearly Orthogonal Latin Hypercube Design Spreadsheet, 29 factor version. Retrieved from http://diana.cs.nps.navy.mil/SeedLab/

Saunders, Stephen, editor (2009). *Jane's Fighting Ships 2009-2010 Edition.* Sentinel House, Alexandria, VA, 112th edition.

Schogol, Jeff (2008). *Report: Iranians threatened U.S. warships*. Retrieved from http://www.stripes.com/article.asp?section=104&article=51467

U.S. Department of Defense (2007). A Cooperative Strategy for the 21st Century Seapower.

U.S. Department of Defense (2008). National Defense Strategy. Printed copy.

U.S. Government Accountability Officer. (March 2009). Defense Acquisitions, Assessments of Selected Weapon Programs. *Report to Congressional Committees.*

U.S. Government Accountability Officer. (March 2005). Defense Acquisitions, Plans Need to Allow Enough Time to Demonstrate Capability of First Littoral Combat Ships. *Report to Congressional Committees.*

U.S. Government Accountability Officer. (May 2001). Improved Littoral War-Fighting Capabilities Needed. *Report to the Chairman and Ranking Minority Member, Subcommittee on Military Research and Development, Committee on Armed Services, House of Representatives*

U.S. Navy. (2010, September 27). *SUW Mission Package Attacks Small Boat Threat for LCS*. Retrieved from http://www.news.navy.mil/search/display.asp?story_id=31482

Vego, Milan. (2008, July). Think Small. *Armed Forces Journal.*

Zahle, T. U. (1971). Hit Probability for a Chain-Like Series of Shots - A simple Formula. *Naval Research Logistics Quarterly. Vol. 18(2),* pp. 283–293.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Dr. Michael McCauley
   Naval Postgraduate School
   Monterey, California

4. Curtis Blais
   Naval Postgraduate School
   Monterey, California

5. Susan Sanchez
   Naval Postgraduate School
   Monterey, California

6. CAPT Jeff Kline, USN (Ret)
   Naval Postgraduate School
   Monterey, California

7. Dr. Thomas Lucas
   Naval Postgraduate School
   Monterey, California

8. LCDR Daniel Duhan
   N81
   Pentagon, Virginia

9. Terry Kasey
   Sea Shield (N81PB) Deputy Branch Head
   Pentagon, Virginia