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LITTORAL COMBAT SHIP OPEN OCEAN ANTI-SUBMARINE WARFARE

by

Team LCS
311-124O

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This capstone explored the littoral combat ship (LCS) and its potential to fulfill the anti-submarine warfare (ASW) mission for open ocean escort of high value assets. A systems engineering approach was used to develop requirements and implement modeling and simulation through a clearly defined prime directive and concept of operations, measures of effectiveness, and measures of performance. The effort was concentrated on the detection, identification and tracking variables of the ASW mission kill chain with an emphasis on active sonar. Data was entered into a Zwicky morphological box and a Pugh matrix to assess candidate solutions in an analysis of alternatives. To address Department of Defense fiscal constraints, the LCS will allow coverage for a wider spectrum of anti-submarine threats in a theoretically less costly platform than traditional nuclear submarines.

The ability for the U.S. Navy to maintain its open ocean dominance now and into the foreseeable future will depend on new and innovative threat capability designs. The modular concept of the LCS platform and its agile performance make it a candidate to satisfy a lower cost ASW mission platform while addressing the changing complexity of threat detection, identification and tracking of enemy subsurface threats. Network fusion and connectivity, integrated sensor capabilities and an eccentric mix of subsurface and aerial surveillance may be combined to meet the requirements for a reliable ASW platform. The LCS could provide ASW escort capability to allow high value units or non-combatants the ability to safely transit the open ocean.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of alternatives
AOR	Area of operation
ASOE	Affordable system operational effectiveness
ASW	Anti-submarine warfare
AWCS	Anti-Submarine Warfare Control System
BMS	Battle management system
BY	Base year
C4I	Command, control, communications, computers, & intelligence
CAIV	Cost as an independent variable
CAPTAS	Combined active and passive towed array sonar
CDD	Capabilities description document
CDS	Combat Direction System
CJCSI	Chairman of the Joint Chiefs of Staff Instruction
CONOPS	Concept of operations
COP	Common operating picture
CSG	Carrier strike group
CVN	Nuclear-powered aircraft carrier
DOD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DOE	Design of experiments
ESR	Estimated sonar range
FOM	Figure of merit
FTI	Frontier Technology, Incorporated
FY	Fiscal year
GAO	Government Accountability Office
HEFR	Hold enemy forces at risk
HVU	High value unit
ICE	Integrated cost estimation
IDEF	Integrated definition model
ISR	Intelligence, surveillance, and reconnaissance

JCIDS	Joint Capabilities Integration and Development System
JFC	Joint functional concept
KPP	Key performance parameter
KSA	Key system attribute
LCC	Life cycle cost
LCCE	Life cycle cost estimate
LCS	Littoral combat ship
LHA	Landing ship, helicopter assault
LHD	Landing ship, helicopter dock
LLA	Limiting lines of approach
M&S	Modeling and simulation
MCM	Mine countermeasures
MFTA	Multi-function towed array
MM	Mission module
MP	Mission package
MOE	Measure of effectiveness
MOP	Measure of performance
MOS	Measure of suitability
MS	Microsoft
NAVSEA	Naval Sea Systems Command
NPS	Naval Postgraduate School
O&S	Operations and support
OODA	Observe, orient, decide, and act
OPNAV	Office of the Chief of Naval Operations
OV	Operational view
PEO	Program Executive Office
PMP	Project Management Plan
QFD	Quality function diagram
RMMV	Remote multi-mission vehicle
ROE	Rules of engagement
RTVM	Requirements traceability verification matrix
SA	Situational awareness

SAR	Selected acquisition report
SE	Systems engineering
SEER-H	Systems engineering evaluation and research—hardware
SLOC	Sea lines of communication
SME	Subject matter expert
SFMA	Secure friendly maneuver area
SSBN	Ballistic missile submarine (nuclear)
SSGN	Guided missile submarine
SSN	Submarine (nuclear)
SubDNS	Subsurface distributed netted sensors
SurDNS	Surface distributed netted sensors
SurRE/SubRE	Surface and subsurface range extender
SUW	Surface warfare
SV	System view
TDC	Torpedo danger zone
TMA	Target motion analysis
TOC	Total ownership cost
TTP	Tactics, techniques, and procedures
UISS	Unmanned Influence Sweep System
UJTL	Universal Joint Task List
U.S.	United States
USCG	United States Coast Guard
USN	United States Navy
USV	Unmanned surface vehicle
USW	Undersea warfare
UUV	Unmanned undersea vehicle
VDS	Variable depth sonar
VTAV	Vertical take-off aerial vehicle
VTAUV	Vertical take-off aerial unmanned vehicle
WBS	Work breakdown structure
WSO	Weapon and sensor optimization

EXECUTIVE SUMMARY

The United States Navy littoral combat ship (LCS) is a class of small surface vessels intended to operate close to shore or in the littoral zone. This project explored the feasibility of utilizing this platform to perform an open ocean anti-submarine mission for escort operations and what combinations of assets could potentially be included in such a module if there were to be one. An open ocean ASW mission would require that the LCS be able to search, identify, and classify submarine threats throughout the water column and would utilize the sea frame in a manner outside of its originally intended reference profile. The team concluded that this platform could, in fact, be capable of providing this functionality and explored possible mission package configurations for further study.

The Navy has focused considerable effort toward the LCS program due to its modular design concept that allows the vessel to be reconfigured for different missions. This modular concept can support a host of roles and reduce the cost of specialized ships for specific mission areas. The LCS is currently planned to support surface warfare, mine countermeasures, and anti-submarine warfare missions utilizing specific mission modules. Joint Publication 3-32, *Command and Control for Joint Maritime Operations*, states:

> Control of the undersea portion of the operational area is vital to the success of joint operations. A principle threat comes from enemy submarines. A single un-located submarine could create a significant operational, diplomatic, or economic impact. To counter this threat, the Joint Functional Concept (JFC) will coordinate, and when required, integrate assets from the joint force to conduct ASW during all phases of the joint operation of campaign. ASW is an operation conducted with the intention of denying the enemy the effective use of submarines. (Joint Chiefs of Staff 2013, IV-9)

Modeling and simulation tools were used to provide analysis to determine if the LCS platform could perform the open ocean ASW mission utilizing a combination of on-board and off-board assets with a focus on active sonar. If a successful combination of

elements could be found to meet the functional requirements, the chosen module could ultimately reduce the demand on existing submarine forces and in the long term reduce the financial burden on the Department of Defense.

The threat environment encompasses several security situations. The *Naval Operational Concept 2010* defines these situations and risk areas, stating:

> Adversaries with blue water capabilities may threaten combat and support forces transiting from their forward station, forward presence operating area, or point of departure in the continental United States to the theater of operations. Although U.S. naval forces can be surprised while transiting in the blue water, there are few threats in the current security environment that can effectively challenge U.S. combatants in the open ocean. Thus, it is likely adversaries will focus on interdicting sealift, expeditionary strike force, and merchant vessels deploying and sustaining the joint force. Alternatively, or concurrently, adversaries may elect to interdict commercial shipping to degrade U.S. economy and capacity to support the conflict. In either case, naval forces will be required to neutralize or destroy air, surface and subsurface threats to high value vessels during their transit; using standard escort, area defense, integrated air missile defense, anti-submarine warfare tactics, techniques and procedures. (United States Navy, United States Marine Corps and United States Coast Guard 2010)

To effectively protect a high value unit, the LCS must be able to detect, identify, and track subsurface threats before they become a threat to U.S. or allied high value sea-going assets. The tactics, techniques and procedures necessary to neutralize a subsurface threat can be complex and elaborate. Simply preventing the enemy from firing its weapons through basic intervention thus preventing an attack requires a high degree of coordination and tactical expertise. Successful engagements depend on the detection range of the sensors, counter-detection range of the enemy sensors, and the range of the missile/torpedoes of both combatants. Based on the modeling and simulations of various scenarios and variables, the greatest impact to mission accomplishment seen in this experiment was the number of LCS platforms present in the search area followed by sensor capability, speed, and search time.

Attributes such as detection ranges, sensor capabilities, and weapons envelopes were used to identify the best combination of sensors and weapons to defend against an

ASW threat. Additionally, two key operational level objectives were used as variables in determining the best options: hold enemy forces at risk and secure friendly maneuver area, as outlined in the *ASW Concept of Operations for the 21st Century* (United States Navy, 2009). These additional key objectives manifested into additional attributes that supported the importance of the number of LCS used during the scenarios. Modeling and simulation outputs in a sound systems engineering process were utilized to conclude that the LCS is a viable option for the ASW open ocean escort mission. The Cost Analysis Appendix contains more information on cost estimations for specific technology combinations of on-board and off-board assets for an initial evaluation that would support a business case analysis for using this platform over the current legacy submarine forces.

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I. INTRODUCTION

A. BACKGROUND

> The security and prosperity of our nation, and that of our friends and allies, depends on the freedom of the seas, particularly at the strategic maritime crossroads. (Greenert 2012)

The LCS platforms, represented in Figure 1, are designed to be fast, agile, and networked surface combatants designed for operating in the littorals. The strength of the LCS lies in its reconfigurable design approach, applying modularity for operational flexibility. Fundamental to this design approach is the capability to install rapidly and integrate modular mission packages (MPs) onto the ship. As envisioned by the LCS Concept of Operations (CONOPS), the primary MPs of the LCS include anti-submarine warfare (ASW), mine countermeasures (MCM), and surface warfare (SUW).

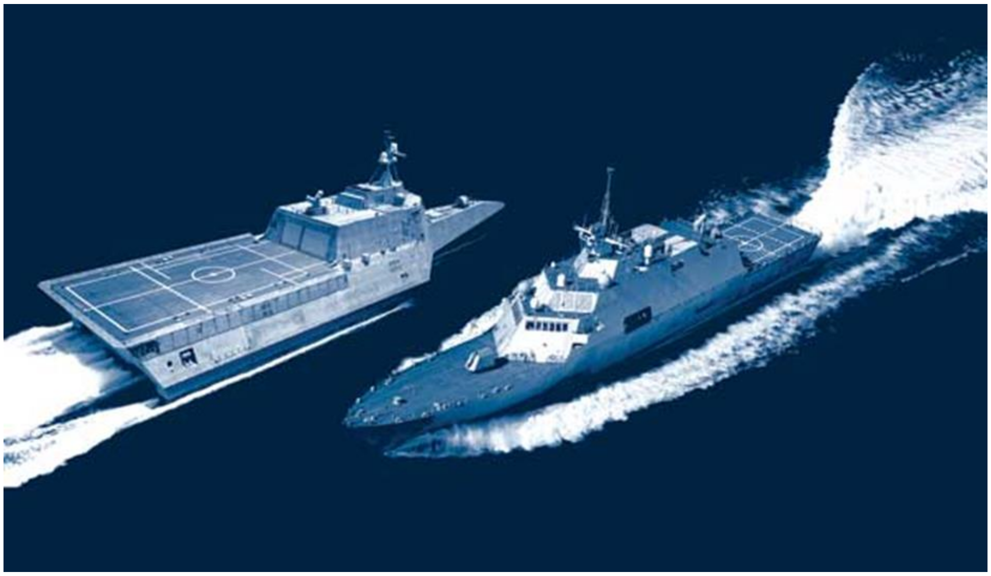

Figure 1. USS *Freedom* (LCS-1) and USS *Independence* (LCS-2) (from Jean 2010)

A MP consists of mission modules, mission crew detachments, and support aircraft. A mission module (MM) combines individual mission systems (vehicles, sensors, communications, and weapon systems), support equipment, and command, control, communications, computers, and intelligence (C4I) components.

The Navy is currently developing and procuring MPs to meet the joint war fighting requirements outlined in the *Flight 0+ LCS Capabilities Description Document* (CDD). Figure 2 illustrates a notional concept for an ASW MP for use in the littorals.

Figure 2. Mission Package Definition (after Czapiewski 2004)

Evaluating the ASW MP for the littorals gives rise to the question as to its applicability in the open ocean ASW role. What are the requirements and capabilities necessary to produce the most suitable active sonar based LCS ASW mission module (MM) that would enable the detection, identification, and tracking of enemy submarine threats to high value assets in an open ocean, deep water environment?

B. GOAL

What makes this project unique is that the LCS was not originally designed as an open ocean ASW platform. If the research and analysis outcome are favorable to the LCS having the capability to perform the ASW mission, then implicitly this new capability could result in a multi-role LCS that would lower costly submarine workload and ultimately lower surface warfare counter ASW cost. Figure 3 shows a notional operational scheme for potential ASW mission systems. Of note, this project was conducted independent of the Program Executive Office Littoral Combat Ship (PEO LCS). The team executing the study was limited to open source information that could be retrieved from the internet or other unclassified open source media.

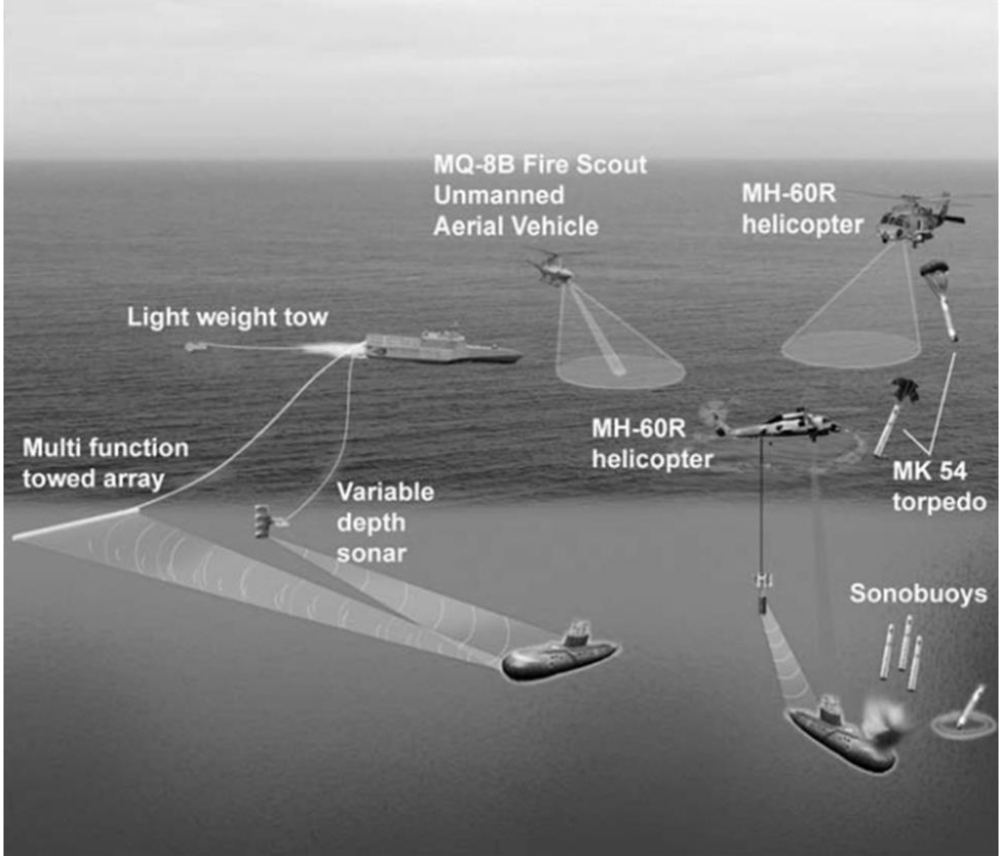

Figure 3. ASW GAO Graphic (from LaGrone 2013)

The open-ocean ASW role has several parts: Escort of high-value units (HVUs) such as battle groups and implicitly carriers; clearing areas of the ocean for operations; and surveillance and tracking of the submarine threat. The sensors used are primarily, but not limited, to a combination of active and passive sonar; radar, and infrared. The main research question is: what are the requirements for the LCS to perform the open-ocean ASW role? From that comes the question: can the existing MPs support the open ocean role and at what cost?

C. APPROACH

The open-ocean ASW role is threat driven. To define and scope the threat, open-source information about submarines was researched and explored to help understand the existing threat posed to high value assets. Not surprisingly, torpedoes and anti-surface missiles launched from enemy submarines were the most prominent threat. Open source research indicated that an average missile range for enemy submarines is 44 nautical miles while the average range for torpedoes is 10.65 nautical miles (Garrett et al. 2000; Sherman 2000). Other metrics obtained from unclassified and open source documents include enemy submarines’ operational depth, range, and endurance. Having metrics on enemy capabilities provided the data necessary for creating a viable model and simulation to evaluate requirements and capabilities.

Once the prime directive, threat, requirements, and system architecture were defined, open source information was again used to generate a range of feasible capabilities and their associated costs. These capabilities, when integrated, would result in requirements and architecture compliant LCS ASW mission module for open ocean escort missions.

The subsequent analysis is organized as follows: systems engineering process, requirements analysis to understand the needs, modeling and simulation, reducing the permutations for consideration in an analysis of alternatives, cost comparisons, and conclusions.

II. SYSTEMS ENGINEERING PROCESS

The goal of the research is to develop the system's requirements that address the stakeholder's needs to drive the systems development within cost, schedule, and performance. The feasibility of using the LCS to perform open ocean antisubmarine warfare is a complex problem requiring a structured process model and design methodology. Problem solving is an iterative process. Communication and coordination of activities are necessary when problem solving is conducted by a team. To tackle large and complex design problem, a design process structures the problem solving (Bucciarelli 1994).

In the opinion of this LCS capstone team, the systems engineering "Vee" model is the most suitable problem solving process model to use. The reason for this opinion is that it provides structured and repeatable design process that allows the team to analyze and design a system that is consistent with systems theory and systems engineering process. The Vee model was applied to the analysis efforts in this research with the end objective of achieving affordable system operational effectiveness (ASOE) (*Defense Acquisition Guidebook* [DAG] 2013). Initial efforts focused on the left side of the Vee model or the "customer wants/musts," which included system requirements definition, architecture development, and modeling and simulation (M&S). The right side of the Vee model was then exercised through a qualitative analysis of potential capabilities that met the requirements and fit within the developed architecture. Finally, life cycle cost (LCC) estimates were conducted on candidate solutions.

A. ANALYSIS PROCESS AND TOOLS

The analysis processes and tools that were applied in phases with the systems engineering process for this report are articulated in Figure 4. Analytical tools used include:

- ExtendSim^{TM} (ExtendSim) and Minitab^{TM} (Minitab) for M&S
- Microsoft Excel (Excel) for morphological box, quality function diagram (QFD), and Pugh matrix

- Frontier Technology, Incorporated's (FTI's) Integrated Cost Estimation (ICE) Software
- Vitech's CORE^{TM} (CORE) for requirements and architecture development

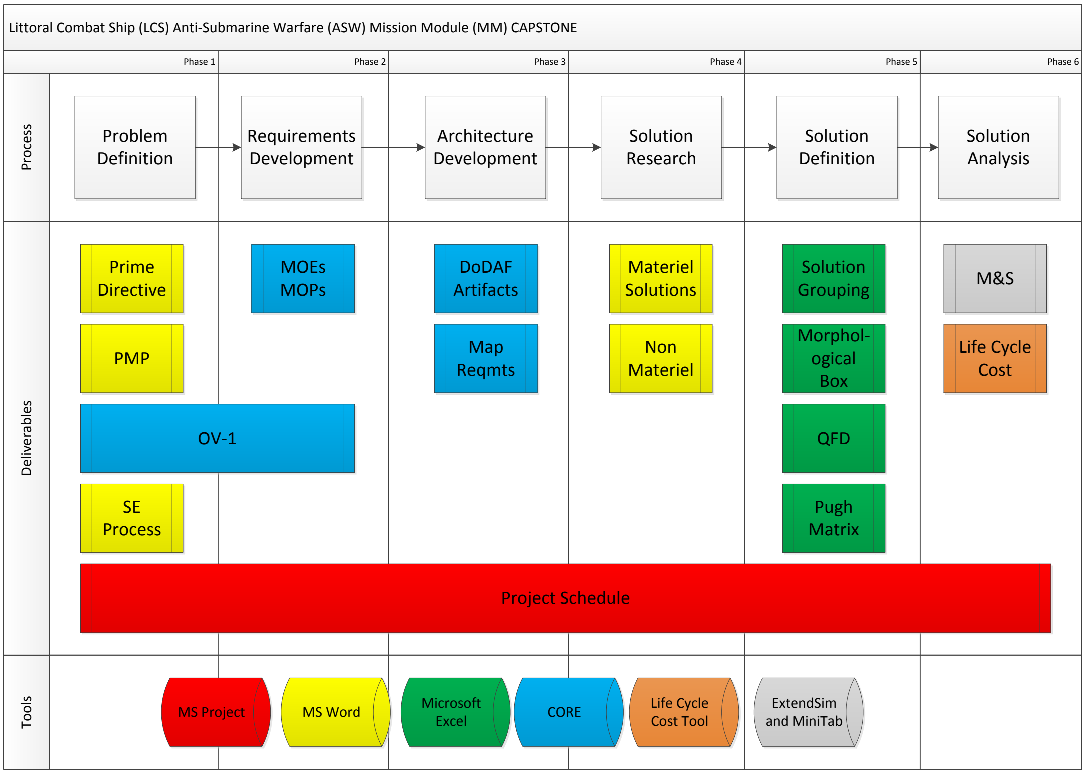

Figure 4. Capstone Planning Phases and Analytical Tools

B. PRIME DIRECTIVE AND THE SE PROCESS

The SE process for this research began with the need for an independent, objective systems engineering analysis of ASW requirements for the LCS platform. The analysis was carried out independent of ongoing LCS program ASW acquisition activities and associated ASW MM development.

The prime directive led the LCS team to conduct an analysis to determine the feasibility of utilizing the LCS platform to detect, localize and track enemy submarine threats to high value, non-combatant vessels during vulnerable transit periods in combatant areas of operation (AORs). Therefore, the SE process initially focused on the requirements, not on specific subsystems and hardware required for the LCS ASW MM.

Following the refinement of a prime directive, the initial concept of operations (CONOPS) was developed to support the systems engineering effort. This document described how the LCS ASW MM would function in its intended operational environment. For the functional architecture, the team used the Department of Defense Architecture Framework (DODAF) and Vitech’s CORE. These pictorial views helped ensure that requirements were not missed or overlooked.

Measures of effectiveness (MOEs), measures of performance (MOPs), and operational requirements were derived from the architecture and CONOPS. CORE was used to document and allocate requirements in order to maintain traceability between requirements and the functional architecture. M&S augmented requirements development to determine the importance and statistical significance of MOPs on system MOEs. Finally, a detailed analysis of alternatives (AoA) was conducted, which leveraged the system requirements, M&S efforts, qualitative analysis of viable capabilities, and LCC estimation.

C. SYSTEM ARCHITECTURE

The system architecture for this project breaks down the components and relationships between those assumed to be inherent capabilities to the LCS class and those that were investigated as part of the scope of this effort. The team focused on the battle management system functions for detection above and below the water line, the combat system, and the deception countermeasures functionality. Figure 5 illustrates graphically the relationships as broken down from the LCS Open Ocean ASW mission.

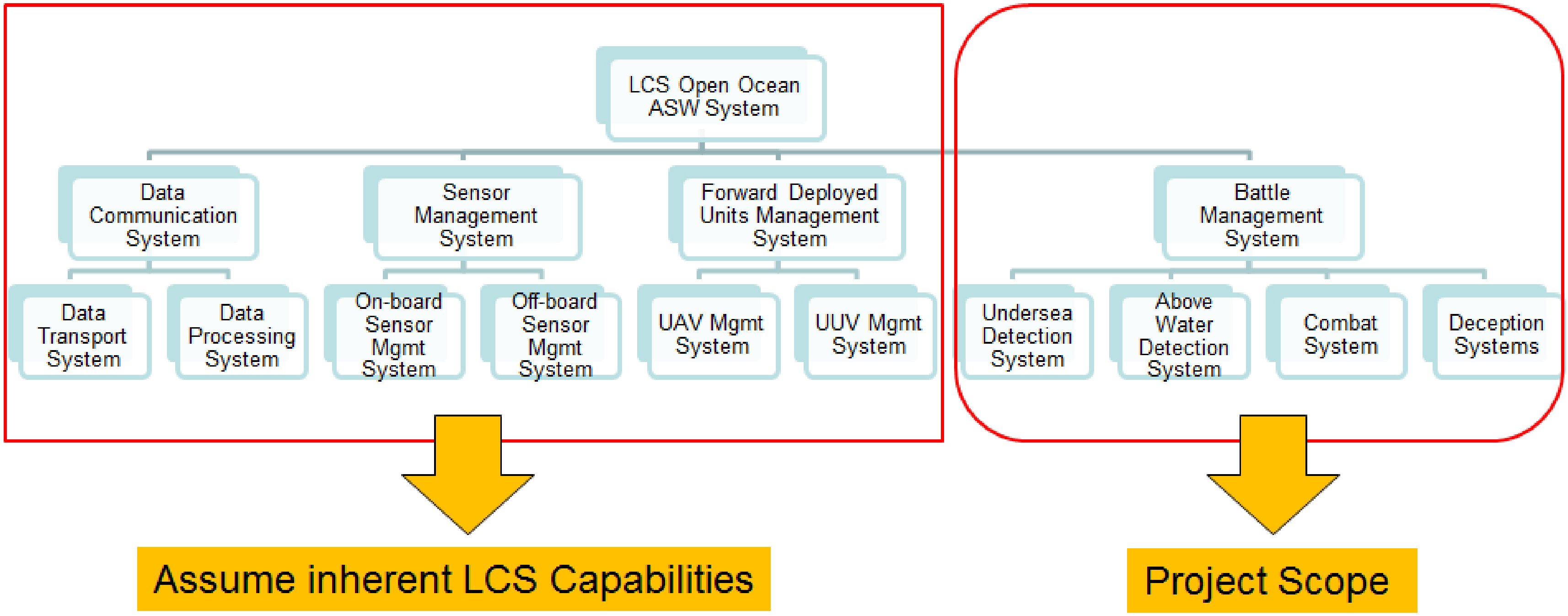

Figure 5. System Functional Architecture

This can be further refined into the three main functions of detect, control, and deception as illustrated in Figure 6. The architecture provides traceability between components and functionality for the system. It provides a description of the relationships among the CORE elements under review.

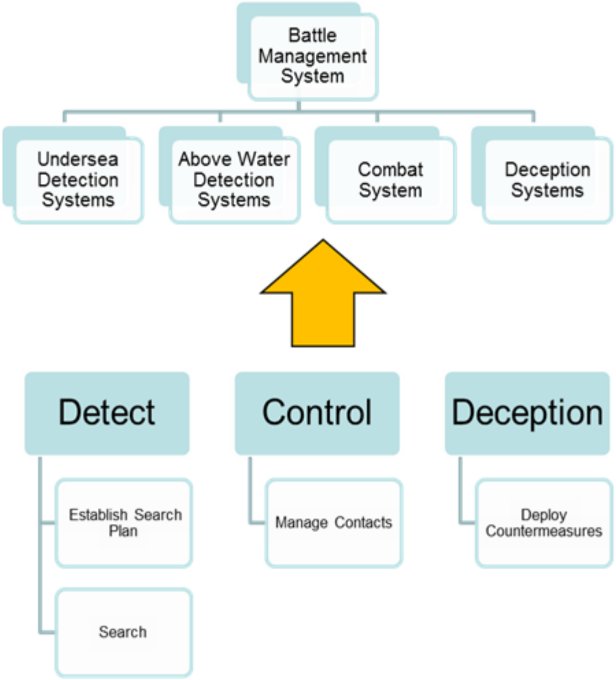

Figure 6. Functional Breakdown

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III. REQUIREMENTS ANALYSIS

A. PRIME DIRECTIVE

The prime directive is to analyze the feasibility of utilizing the LCS platform to detect, localize, and track enemy submarines that pose a threat to high value, non-combatant vessels during vulnerable transit periods in combatant areas of operation (AORs). The team conducted research to determine the military utility of the project as outlined in the previous sections. According to the current Department of Defense (DOD) command structure, Task Force ASW is the command responsible for developing near-term and far-term transformation for ASW capabilities. The Navy's Task Force ASW states in *Anti-Submarine Warfare Concept of Operations for the 21st Century* that the capabilities to secure the maneuvering area for friendly forces and to hold enemy forces at risk are both vital to achieving the prime directive (United States Navy 2009).

B. LITTORAL COMBAT SHIP ANTI-SUBMARINE WARFARE OPERATIONAL TASKS

Central to the protection of high value, non-combatant vessels during vulnerable transit periods in the combatant AOR is the ability to conduct both defensive and offensive operations that bring about the capabilities aforementioned. Specifically, the operational tasks include the capabilities to secure friendly maneuver area (SFMA) and hold enemy forces at risk (HEFR). Figure 7 illustrates representative ASW forces (McDonough 1966). To protect the force or the convoy, McDonough states:

> Surface ASW forces provide ASW screens around the "protected force" to prevent the attacking submarine from acquiring an attack position suitable for launching a torpedo. This ASW screen is designed to primarily locate, report, deter attack, and destroy submarines before they can gain attack position…Screening surface and air units operate in the area close around the force or convoy and provide the last opportunity for protection against enemy submarines. (1966, 9)

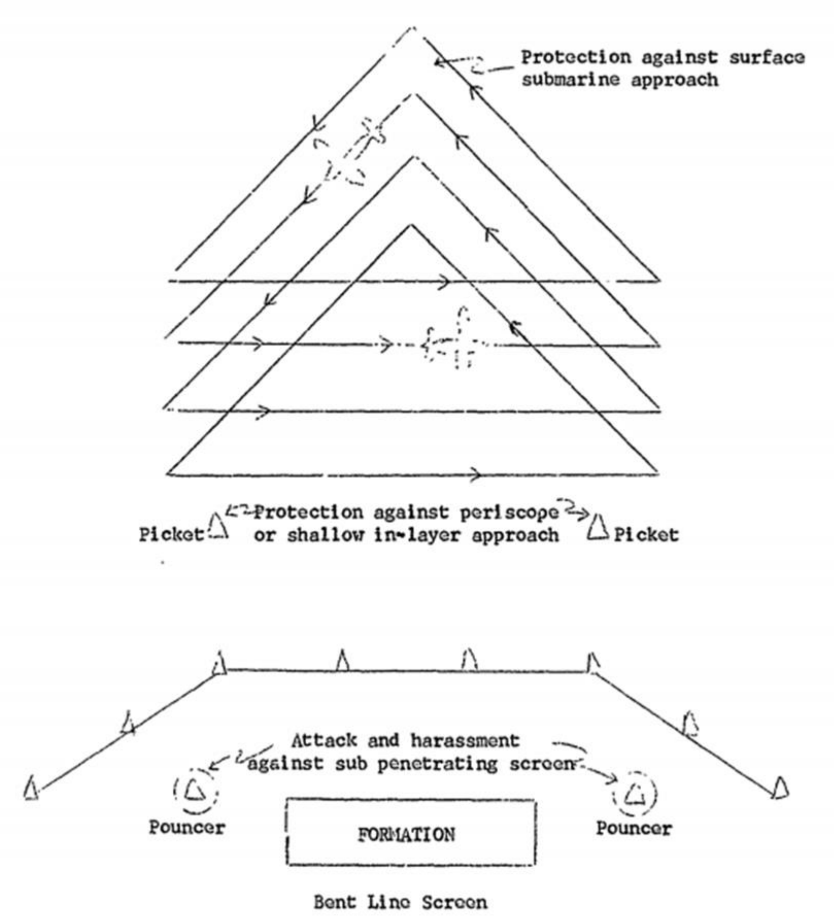


Figure 7. Traditional ASW Tactics (from McDonough 1966, 10)

The operational concept for the LCS Open Ocean ASW study proposes the high level operational tasks similar to the tasks as defined by Peter McDonough (1966). The LCS ASW operational tasks are outlined below:

1. Secure Friendly Maneuver Area

Secure friendly maneuver area is the capability to control and maintain the freedom to maneuver in an AOR. This operation includes both offensive and defensive tactics to deter and destroy enemy combatants. The Navy's Task Force ASW describes SFMA in the *ASW Concept of Operations for the 21st Century* and summarized it as an area where United States and coalition forces can freely sail between points of interests, especially while transiting through vital sea lanes (United States Navy 2009, 2).

2. Hold Enemy Forces at Risk

Task Force ASW shortly detailed the definition of hold enemy forces at risk as a posture to ensure that enemy submarines are aware of potential combat responses from U.S forces (United States Navy 2009, 2). Persistent offensive capability forces the enemy combatants to constantly take defensive actions thereby reducing the enemy’s ability to conduct offensive operations.

3. Search

According to the *Littoral Anti-Submarine Warfare Concept*, a search can be conducted once an operational area has been designated (Naval Doctrine Command 1998). The limitations on searches vary by mission.

4. Detection

As defined by the *Littoral Anti-Submarine Warfare Concept,* detection can be a simple act of receiving an unknown signal from either an off-board or onboard sensor. (Naval Doctrine Command 1998). Detection does not equate to a positive identification of an enemy submarine.

5. Classification

Classification is the ability to discriminate a contact as either a submarine or non-submarine and, if a submarine, determine its identity (Naval Doctrine Command 1998).

6. Targeting

Once an enemy submarine has been identified, friendly forces may begin to process a firing solution. In order to gain an effective solution, the target must be within a specified distance, depth, and other criteria as defined by the *Littoral Anti-Submarine Warfare Concept* (Naval Doctrine Command 1998).

7. Weapon and Sensor Optimization

The optimization of weapons and sensors depend on the best available asset within the operational area. Further defining the term, the *Littoral Anti-Submarine*

Warfare Concept added that weapons and sensors may be adjusted to obtain a specific result against an enemy submarine (Naval Doctrine Command 1998).

8. Battlespace Shaping

Battlespace shaping involves extensive planning and the utilization of various assets, sensors, and areas in order to achieve the most effective plan. According to the *Littoral Anti-Submarine Warfare Concept*, proper battlespace shaping inhibits the enemy submarine from entering an operational area (Naval Doctrine Command 1998).

C. OPERATIONAL CONCEPT

Figure 8 depicts the notional operational concept for open ocean ASW.

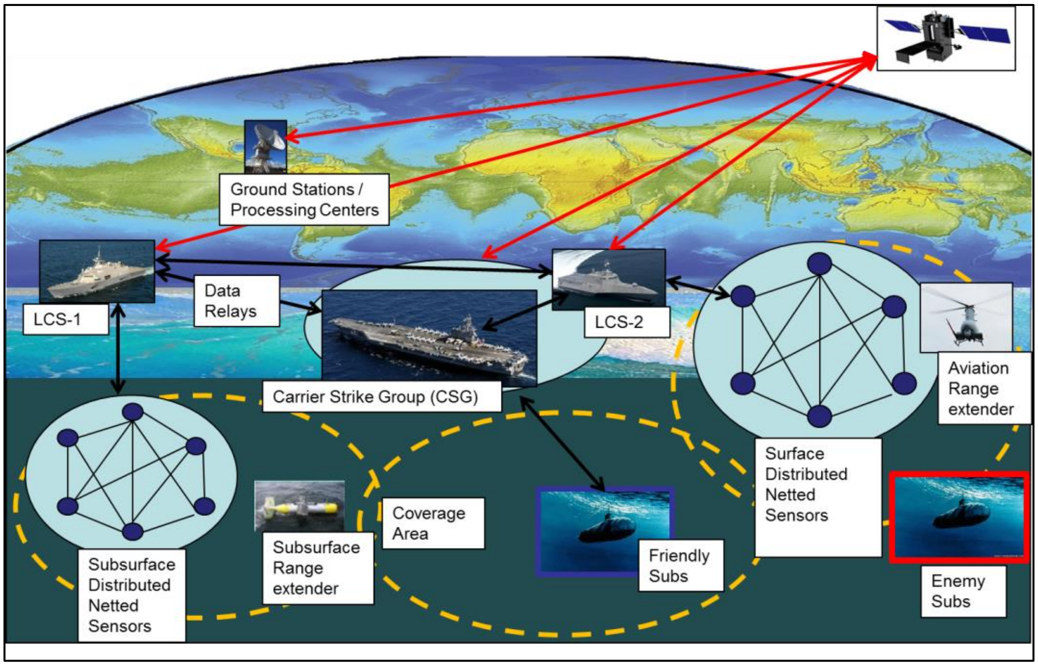


Figure 8. Littoral Combat Ship Open Ocean ASW Operational View (OV-1)

1. Background

This operational concept is traceable to the *ASW Concept of Operations for the 21st Century* written in 2009 that provides the DOD with guidelines to ensure the U.S. Navy minimizes or destroys submarine threats (United States Navy 2009). This developmental framework categorizes both near-term and far-term ASW capability development to reflect the desired force attributes of “persistence, pervasive awareness, speed and operational agility, and technological agility” (United States Navy 2009).

The ASW CONOPS further details the difference between near-term and far-term goals of anti-submarine warfare in several sentences. The goals focus on transformations in undersea warfare ranging from assets such as towed arrays to more advanced sensors and weapon systems. The near-term ASW transformation emphasizes the enhancement of current technologies to include assets such as towed arrays and sonobuoys (Navy 2009). The far-term ASW transformation focuses on the exploitation of near-term advances to shorten the sensor-to-shooter time by establishing the necessary infrastructure and force structure to achieve the aforementioned desired force attributes by utilizing assets such as advanced sensors, weapons, and relays (United States Navy 2009).

2. Concept of Operations

The LCS Open Ocean ASW concept of operations aligns with the *ASW Concept of Operations for the 21st Century* that approaches the ASW threats by prioritizing a series of assets (United States Navy 2009). In this prioritization, sensors and networks are placed above weapons and platforms in order to ensure development of capability preferences (United States Navy 2009). With operational principles and associated capabilities such as those outlined in the ASW CONOPS being developed, the undersea battlespace is able to be monitored and secured (United States Navy 2009).

The tactical employment of the LCS Open Ocean ASW system is to deploy with a convoy of high value combatant and non-combatant ships. The LCS mission is to protect the high value units (HVUs) during transit to the AOR and to secure the sea lines of communication. After arriving at the designated AOR, the LCS is to provide force protection by monitoring, patrolling, and defending the outer edges of the battle group. Successfully defending the strike group directly supports the application of Sea Shield, Sea Strike, and Sea Basing.

There are two modes of operations. The first mode of operations is the transit mode where the LCS is performing escort operation for the HVUs as they transit to the designated AOR. In this mode, the LCS primary mission is to ensure the sea lanes are free of submarine threats. The second mode of operation occurs once the HVU is at the designated AOR. In this mode, the primary mission is to provide force protection by patrolling the outer edges of the strike group or convoy to ensure freedom of maneuver within the AOR.

The transit mode requires the application of a moving screen. On-board sonar detection systems are deployed as the LCS moves ahead of the convoy. In the open ocean where the sonar environment is less cluttered than the littorals, passive sonar based detection is preferred. The effective sonar range of the sonar detection is used to establish the screen spacing of the LCS as well as establishing the location where the aviation range extender systems should provide coverage. The aviation range extender systems have the capability to provide detection via a mixture of sensors, covering a set of spectrum, on-board as well as advanced deployable systems to further extend the detection range. As the convoy and the LCS move closer to the deployable systems and sensors, these deployed systems and range extender are collected, refueled, and prepared for the next deployable area by the LCS personnel. Two sets of each system provide the necessary rotations to prevent the convoy from stopping.

In both modes of operation, off-board sensors move ahead of the convoy to prepare and monitor the battlespace. Off-board sensors include both surface distributed netted sensors (SurDNS) and subsurface distributed netted sensors (SubDNS) that are connected via satellites communication. Data from these sensors is uplinked via the satellite communication links back to the data processing centers on land and on the LCS to develop the common operating picture (COP) by the battle management system (BMS). Both the SurDNS and the SubDNS provide persistent detection and cueing.

Surface and subsurface range extender (SurRE/SubRE) is also forward deployed to increase detection and engagement range. Both SurRE and SubRE have the capability to engage and provide defense for the LCS as well as the friendly forces in the AOR. These systems are both standoff and non-standoff weapon systems, manned and unmanned, capable of prosecuting arms in an integrated fashion. These non-traditional systems and methods provide high volume search and kill rates resulting in the destruction of greater number of enemy submarines.

Sensors and weapons systems on-board the LCS provides another layer of offensive and defensive capability. Figure 9 uses the integrated computer aided manufacturing definition (IDEF0) for functional transformation through the search through engage sequence.

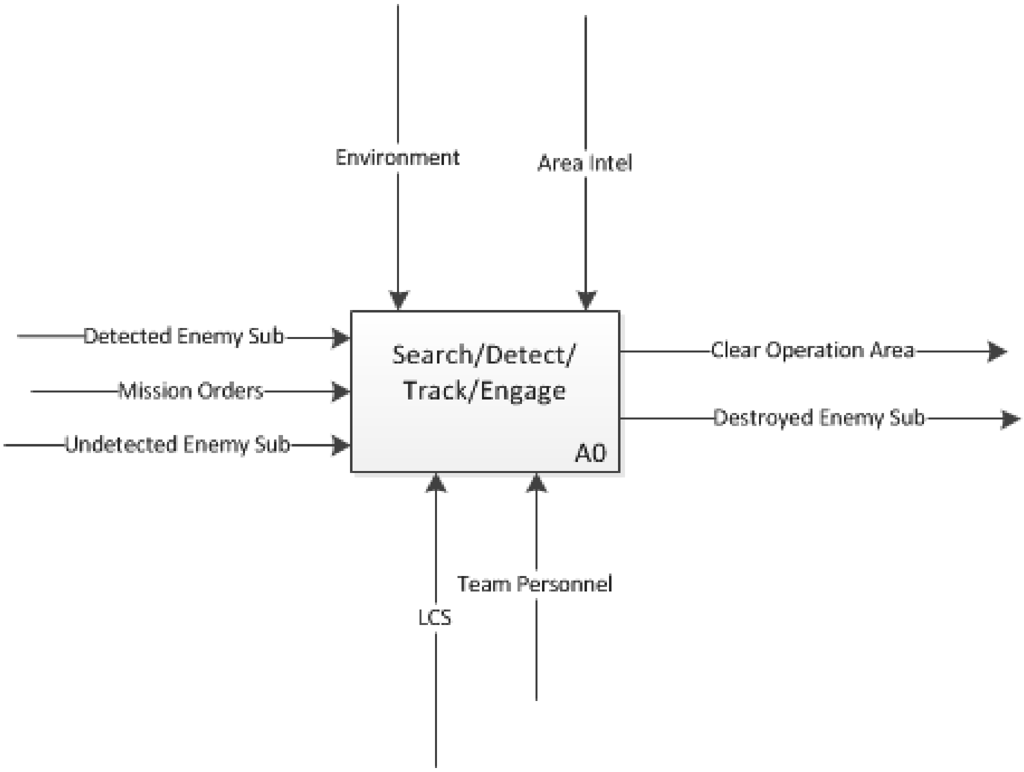
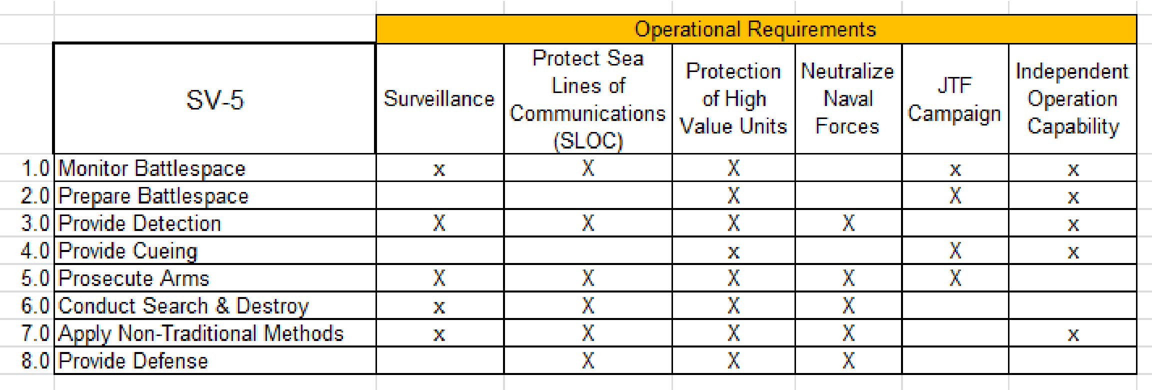


Figure 9. IDEF0 Context Diagram

The Navy’s Task Force ASW *Anti-Submarine Warfare Concept of Operations for the 21st Century* is the baseline requirements document for this research project (United States Navy 2009). Operational measures of effectiveness (MOEs) were developed through mapping of system functions to operational requirements in Service View-5 of the Department of Defense Architectural Framework (DODAF) (United States Navy 2009). Table 1 is the system view illustrating the qualitative process the team used to define the most suitable MOEs.



	SV-5	Operational Requirements					
		Surveillance	Protect Sea Lines of Communications (SLOC)	Protection of High Value Units	Neutralize Naval Forces	JTF Campaign	Independent Operation Capability
1.0	Monitor Battlespace	x	X	X		x	x
2.0	Prepare Battlespace			X		X	x
3.0	Provide Detection	X	X	X	X		x
4.0	Provide Cueing			x		X	x
5.0	Prosecute Arms	X	X	X	X	X	
6.0	Conduct Search & Destroy	x	X	X	X		
7.0	Apply Non-Traditional Methods	x	X	X	X		x
8.0	Provide Defense		X	X	X		

Table 1. SV-5 Mapping System Functions to Operational Requirements

D. MEASURES OF EFFECTIVENESS

The Defense Acquisition University (DAU) defines the MOEs as:

> The data used to measure the military effect (mission accomplishment) that comes from the use of the system in its expected environment. That environment includes the system under test and all interrelated systems, that is, the planned or expected environment in terms of weapons, sensors, command and control, and platforms, as appropriate, needed to accomplish an end-to-end mission in combat (Defense Acquisition University [DAU] 2014).

Another definition, from the Chairman of the Joint Chiefs of Staff Instruction (CJCSI 3170.01F), states that MOEs focus on outcomes (Sharp 2007). MOE is further decomposed into measures of performance (MOPs) and measures of suitability (MOSs). MOPs emphasize performance parameters (DAU 2014). MOSs are derived from the operational environment (DAU 2014). In this study, that would include the deep water transit areas where the LCS will operate alongside allied warships to protect high value units. MOE answers the question concerning what one wants the system to be able to do. Central to the HERF objective of the ASW CONOPS, the LCS’s ability to prohibit submarine attacks coincides with the Sea Strike and Sea Shield concepts of Sea Power 21

(United States Navy 2009). The third leg of Sea Power 21, Sea Basing, is then combined with and utilized by FORCEnet to ensure asset management in order to combat ASW threats (United States Navy 2009).

1. Protect High Value Units

Networked, distributed combat forces promote resiliency in a disaggregated architecture thereby reducing the loss of critical combat power when the combat capability is centralized in a single ship. Distribution and disaggregation can only do so much to reduce the reduction in combat power and combat capabilities. High value units (HVUs) provide the bulk of capabilities and combat power. The Chief of Naval Operations defines several high value units in OPNAV Instruction 3380.5 concerning HVU transit escort operations (Greenert 2010). According to the instruction, the U.S Navy (USN) and the U.S Coast Guard (USCG) policies designate and prioritize the SSBNs, aircraft carriers, guided missile submarines (SSGNs), attack submarines (SSNs), amphibious assault ships (LHAs/LHDs), and military sealift vessels as HVUs (Greenert 2010). Thus, it is appropriate that the MOE is the protection of HVUs.

2. Protect Sea Lines of Communication

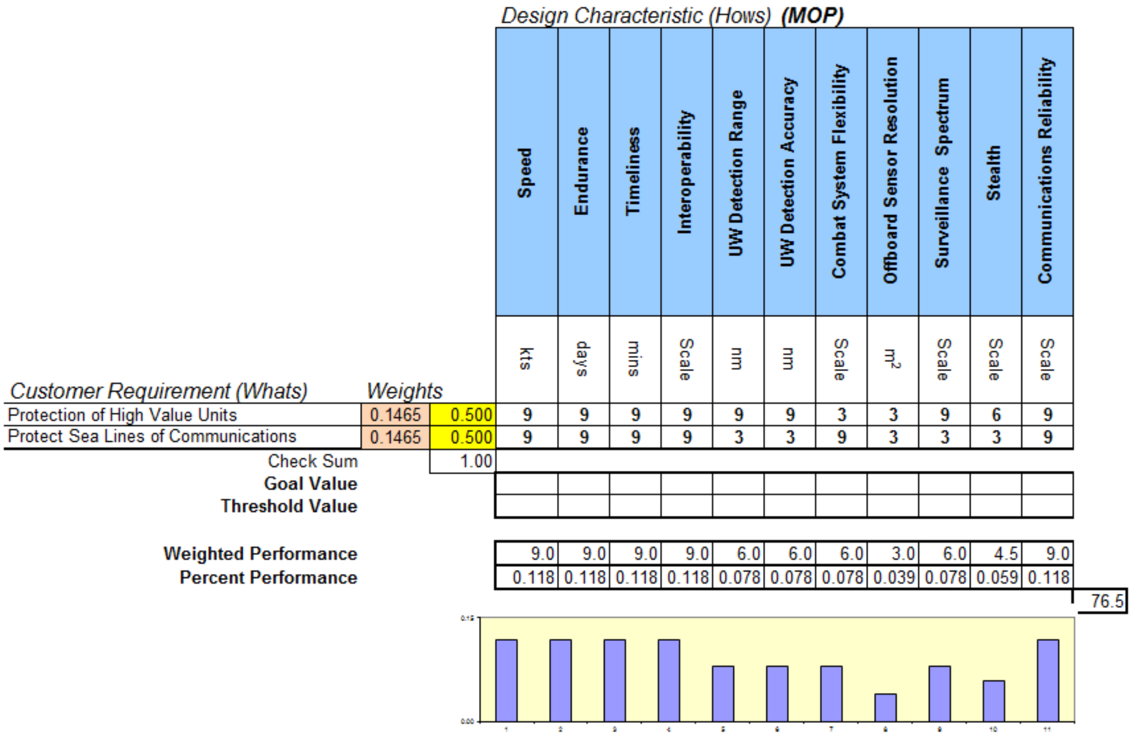
The protection of sea lines of communication (SLOC) is of utmost importance for many world powers. U.S Navy Captain John Morgan stated:

> ASW is a team sport that requires diverse platforms and capabilities in a highly variable operating environment. The undersea environment, ranging from the shallows of the littoral to the vast deeps of the great ocean basins—and polar regions under ice—demand multi-disciplinary approach, subsuming intelligence, oceanography, surveillance and cueing, multiple sensors and sensors technologies, coordinated multi-platform operations, and underwater weapons. (1998)

Focusing on SLOC enables surface combatants, particularly the LCS, to be used effectively to combat undersea threats. Captain Morgan also emphasizes that the use of emerging technology coupled with the understanding of requirements ensures high competency in ASW (Morgan 1998).

E. MEASURE OF PERFORMANCE

MOPs and MOSs may be combined to support one or multiple MOEs. While MOEs answer the question concerning what the system is able to do, MOPs are composed of key performance parameters (KPPs) that address the question of what capability the system provides. While the performance parameters associated with each of the MOPs is not provided due to the scope of this project, a list of MOPs are presented here along with rationales in the context of the concept of operations discussed in the previous section. Quality function diagram (QFD) was used to define and prioritize the MOPs and their contribution to the two MOEs defined previously. Figure 10 illustrates the QFD transforming user demands into design quality.



Design Characteristic (Hows) ***(MOP)***

Customer Requirement (Whats)	*Weights*		**Speed**	**Endurance**	**Timeliness**	**Interoperability**	**UW Detection Range**	**UW Detection Accuracy**	**Combat System Flexibility**	**Offboard Sensor Resolution**	**Surveillance Spectrum**	**Stealth**	**Communications Reliability**
			kts	days	mins	Scale	nm	nm	Scale	m^2	Scale	Scale	Scale
Protection of High Value Units	0.1465	0.500	9	9	9	9	9	9	3	3	9	6	9
Protect Sea Lines of Communications	0.1465	0.500	9	9	9	9	3	3	9	3	3	3	9
Check Sum		1.00											
Goal Value													
Threshold Value													
Weighted Performance			9.0	9.0	9.0	9.0	6.0	6.0	6.0	3.0	6.0	4.5	9.0
Percent Performance			0.118	0.118	0.118	0.118	0.078	0.078	0.078	0.039	0.078	0.059	0.118
													76.5

Figure 10. Measures of Performance

1. Speed

The concept of operation calls for the LCS to deploy with the convoy consisting of combatants and noncombatants HVUs performing escort operations. Figure 11 illustrates the convoy escort geometry requiring the LCS to stay ahead of the convoy within the limiting lanes of approach (LLA) to maximize the detection circle and force the attacking submarine outside the torpedo danger zone (McDonough 1966). This protects against the submarine's submerged approach from the front of the convoy.

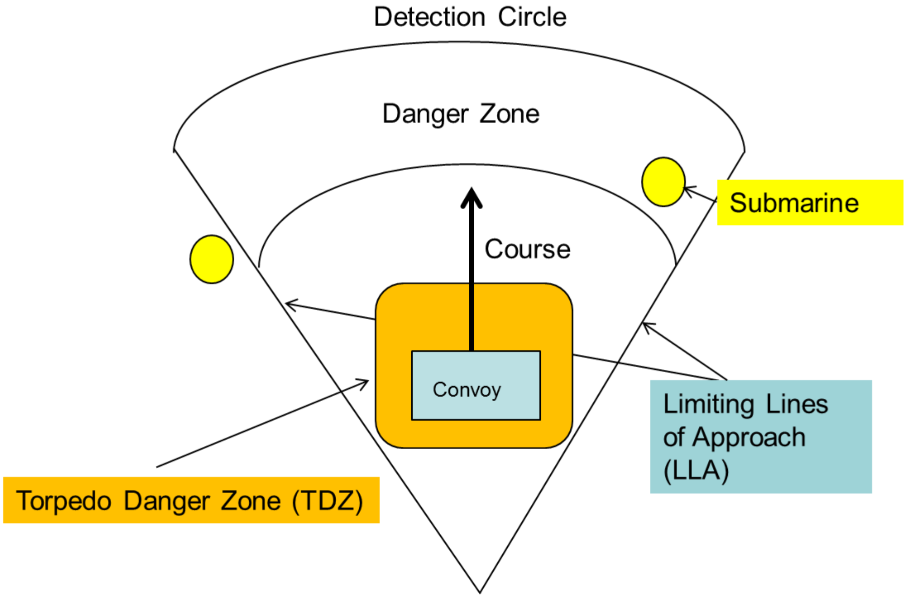


Figure 11. Convoy Escort Geometry (after McDonough 1966)

The attack submarine can approach the convoy from the rear if the speed of the convoy is less than the speed of the attack submarine. According to the Office of Chief Naval Operations, a submarine must maintain stealth and its defense in order to properly conduct an attack on a surface vessel (Sternhell and Thorndike 2014, 102). This statement underscores the importance of speed. Stealth restricts the submarine's speed and as such, it must maintain a slow approach. In having a slow approach to its target, the surface combatants can counter by increasing their speed (Sternhell and Thorndike 2014).

While the maximum speed of the current LCS platform is classified, according to the Office of Naval Research, the fifth installment of the LCS, *USS Milwaukee*, will be the first to benefit from new Axial-Flow Waterjet MK-1 that can propel the LCS to speeds greater than 40 knots (Office of Naval Research 2013). In the case of a convoy with an aircraft carrier, the speed of the convoy is determined by the aircraft carrier. The Nimitz class carrier can sustain speeds greater than 30 knots.

2. Endurance

The Universal Joint Task List (UJTL) defines different categories of mission duration ranging from very short mission duration of less than 30 days to very long mission duration greater than 365 days (Appendix A Joint Conditions 2007). According to Lockheed Martin, the Freedom variant of the LCS has the capability to cover greater than 1,000 nautical miles at a speed of greater than 40 knots and 3,500 nautical miles at cruise speed (Lockheed Martin Corporation 2012). In the context of HVU escort operations where both the combatants and non-combatants must transit the vast ocean, a group of LCS can forward deploy ahead to prepare the battlespace while another group of LCS deploys with the convoy. While the exact tactics are beyond the scope of this project, operational endurance is a key attribute that the LCS Open Ocean ASW system needs to consider. In line with the proposed concept of operations in the previous section, endurance is a capability that is not just levied upon the LCS itself but the off-board sensors and surface and subsurface systems that are to deploy from the LCS.

Advanced deployable systems envisioned in the concept of operations in the previous section call for the need to loiter in the AOR for long periods of time to monitor and prepare the battlespace. In line with the sensor over platform framework, endurance is the key enabler for intelligence, surveillance, and reconnaissance (ISR) providing critical and timely situational awareness (SA). Endurance allows the operational planners to “drop and forget” these systems laying a network of agents to monitor, report, and cue other assets. Mission duration for these deployable systems, including surface, subsurface systems and standoff weapons, vary depending on the type of conflict and the level of war. Regardless, the need for operational endurance is clearly an important system parameter and is a function of numerous factors. While a complete analysis of these factors is outside the scope of this paper, it is clear that to continue to operate in the AOR these systems need energy. Alternative energy is the enabler for endurance and endurance enables and supports the concept of sensor over platform called for in the ASW *Concept of Operations for the 21st Century* (United States Navy 2009).

3. Timeliness

The LCS Open Ocean ASW system is composed of sensors and platforms that operate on-board and off-board the LCS sea-frame. Advanced deployable surface and subsurface systems are themselves systems in the LCS Open Ocean ASW architecture. Together, these systems provide a coordination that is required to address the open ocean ASW threat in respect to the modes of operations as defined by the CONOP. This modular design requires the establishment of well-defined and standardized interfaces to create interoperability and facilitate coordination among systems. The coordinated effort necessary to share data requires robust and reliable communication and data relay pathways that are both secure and timely. Given the escort geometry (i.e., escort spacing relative to the HVUs), combined with the rapid advances in torpedo technology, such as the increase in torpedo range, the sensor to shooter time is highly compressed. Data from the sensors must be timely in order to provide the intelligence needed to make a decision and close the observe, orient, decide, and act (OODA) loop.

4. Interoperability

The paradigm shift to sensors over platforms as outlined in the *ASW Concept of Operations for the 21st Century* requires the fusing of data from multiple sources. In addition, the DOD will continue to operate under a resource and budget constrained environment while the required operational missions continue to rise as proliferation of technologies allow other nations to challenge the status quo. To satisfy such conditions, all resources will be required to work together. This shift from platform specific capabilities to more and more joint operations requiring capabilities of various platforms gives rise to the need to share data and information thus making interoperability critical to achieving the mission objectives.

In line with the *ASW Concept of Operations for the 21st Century* is the *FORCEnet Functional Concept for 21st Century*. FORCEnet is defined as “the operational construct and architectural framework for the naval warfare in the Information Age, integrating warriors, sensors, command and control, platforms and weapons into a networked, distributed combat force" (Clark and Hagee 2005, 1).

Additionally, in the context of the LCS Open Ocean ASW system, interoperability is required between the LCS, on-board sensors, off-board sensors, and advanced surface and subsurface deployable systems. The LCS is envisioned as the moving control node that manages, tasks, and operates the on-board/off-board sensors, and surface/subsurface advanced deployable systems. Data from these systems are transported back to the LCS to develop the common operating picture (COP) using the battle management system (BMS) on-board the LCS(s). The BMS shall provide the command and control construct to establish a COP for operational decision-making as well as to enable information sharing with platforms external to the LCS Open Ocean ASW system.

5. Under Water Detection Range

Concealment is the primary advantage that enables the submarine to be an effective instrument of war. The vastness of the ocean allows the submarine to operate freely and remain undetected as it conducts offensive and defensive operations from beneath the sea surface. However, once concealment is taken away, the effectiveness of the submarine is neutralized. Thus detection and position fixing are critical in antisubmarine warfare. The submarine's ability to stay undetected affords it the capability to conduct a clandestine attack. According to Chapter 8 on "Principles of Underwater Sound" in the *Fundamentals of Naval Weapons Systems*, the manipulation of energy plays a big factor in submarine detection (Academy 2008).

One possible tactic for conducting the open ocean ASW mission that might be employed from LCS would be to engage in a sprint and drift maneuver that would allow the LCS to search for threats while being forward deployed ahead of the high value asset. The ship would sprint up ahead possibly running active sonar search during this phase and then minimize its noise signature by slowing to bare steerage way or drifting at an all stop. Acoustic energy is the primary method used for actively searching for submarines.

It allows submarines to communicate and navigate and its manipulation greatly alters the submarine's capabilities (Academy 2008*)*. However, the constant changes in the ocean's temperature, salinity, and pressure limits the detection range as well as detection accuracy of acoustic based detection systems.

To overcome such limitations, an understanding of the operational environment within the AOR is required. Advanced deployable systems and sensors must be forward deployed to provide on-site environmental measurements. Understanding the pressure, salinity, and temperature, for example, will aid in the calculation of the figure of merit (FOM), a measurement used to define the sonar effective range. The FOM is the propagation loss of the acoustic signal that still produces a detection probability of 50 percent. The inconsistency between the environmental measurements, which affects acoustic propagation characteristics, allows the FOM to determine the effective sonar range based on the effects of the current operational environment. Peter McDonough further supports the importance of the environment by suggesting that the environment degrades any information received and given by ASW forces (McDonough 1966, 35).

The improvement in detection range is highly relevant to ASW tactics and operations. In screen and escort operations, the screen spacing is established based on the effective sonar range (McDonough 1966). By improving the effective sonar range, screen spacing and position of the escort units are able to be widened, which effectively increases the sweep width. The expansion increases the range to detect adversarial submarines thereby improving underwater detection range.

6. Under Water Detection Accuracy

Underwater detection accuracy requires an understanding of not only the sensor performance but also the intended operating environment. The constant changes in the ocean's temperature, salinity, and pressure, for example, limit the detection accuracy as well as detection range of acoustic based detection systems. Any improvement in the understanding of the immediate environment will improve sensor performance to include detection accuracy (McDonough 1966). As a result, improving detection accuracy supports the requirement to monitor the environment as called for in the *ASW Concept of*

*Operations for the 21st Century (*United States Navy 2009). Aside from sonar based detection techniques, detection accuracy can be improved by non-traditional methods. Non-traditional techniques (space based and laser) should be explored to improve underwater detection accuracy.

7. Combat System Reliability

Combat system reliability is required to neutralize enemy combatants. Combat system reliability is absolutely critical in a cooperative, time sensitive, and cueing environment as proposed in the CONOP. The escort geometry dictates the short distances between the escorts and the HVUs thereby compressing the sensors-to-shooters time. The weapon system closest to the area of detection will be tasked to engage the adversary and is expected to engage successfully and reliably each time. Combat system reliability has a unique relationship to and is affected by weapon pairing, which in turn is driven by its sensor performance.

8. Off-board Sensor Resolution

Sensor resolution specifies the technical performance of the sensor. Typically, the sensor resolution has a direct relationship to the performance of the sensor where an improvement in the sensor resolution yields an improvement in sensor performance. However, in line with systems thinking and the coordinated approach proposed in the concept of operation, this relationship may not be true. Algorithms must be defined to exploit the natural phenomena specific to the ASW mission. Improvement in the sensor resolution may or may not improve the quality of the data. Sensor resolution for each system in the LCS Open Ocean ASW can be traded to satisfy the mission. Regardless of the degree of performance of the sensor in terms of sensor resolution appropriate for the mission, sensor resolution has a place in defining the attributes of the system that are to be part of the ASW solution space from a defensive and offensive perspective.

9. Surveillance Spectrum

The key to successful battlespace dominance is ensuring detection of the adversary before they either detect us or get in range to effectively deploy their weapons.

Therefore, persistent surveillance over the battlefield is critical to detecting, identifying, locating, and tracking submarines. Constant surveillance along a specified range with specified sonar acoustic characteristics provides leads to optimum protection of the high value units. On-board and off-board sensors on both the LCS and the advanced surface and subsurface deployable systems will consist of a mixture of sensors that exploit a range of surveillance spectrum to sense the natural phenomena. Advances in technology allow the submarine to stay submerged for longer periods of time. However, to conduct its mission, the submarine is required to position itself relative to its target as well as to communicate with its command and control nodes. As the submarine maneuvers, it may disturb the natural environment that the netted sensors, using its diverse spectrum, will be able to detect. In addition, the submarine communicates with its command and control nodes using a combination of very low frequency, extremely low frequency, optical, or possibly other novel techniques. A wide range of spectrum used for surveillance aids in identifying, locating, and tracking submarines. Together, the sensors on-board the advanced deployable systems will complement current and future national intelligence assets to provide persistent surveillance capability over the battlefield.

10. Stealth

What makes the submarine such an effective weapon of war, among other things, is the ability to exploit its operational environment, the ocean, to covertly conduct its missions. Advances in quieting technologies further improve the covertness and stealth of the modern day submarine. Also, improved hull technology and coating material increases the operating depth to unprecedented levels making the act of detecting a submarine much more difficult. The LCS Open Ocean ASW must use stealth to combat stealth. The self-noise generated by the LCS as it maneuvers is unavoidable. Thus, efforts should concentrate on making the sensors and advanced deployable surface and subsurface systems as stealthy as practical.

11. Communications Reliability

The coordinated approach in the concept of operation calls for the fusion of sensors and platforms that require reliable communication. Nations that are capable of operating and sustaining a submarine force are highly likely to possess the capability to degrade and disrupt forms of communications. Whether the data is used for command and control, cueing, or situational awareness, communication lies at the heart of the concept of operation. In the contested environment, reliable communication is critical. A robust, jam proof, reliable communications and data relay system should be implemented that accounts for the enormous coverage area of a theater battlespace in addition to the multiple localized and restrictive operational areas

F. FUNCTIONAL REQUIREMENTS

The allocation of functional requirements was broken down into four main system tasks. These functions were defined as establishing a search plan, running the search, managing contacts, and engaging the enemy. These functions align with the "ASW Functional Analysis" white paper (ASW Functional Analysis 2014). The engagement portion was only partially explored to include assigning a target and managing tracks, but the rest of the firing solution was outside the scope of this paper. Figure 12 depicts the lower level functional decomposition.

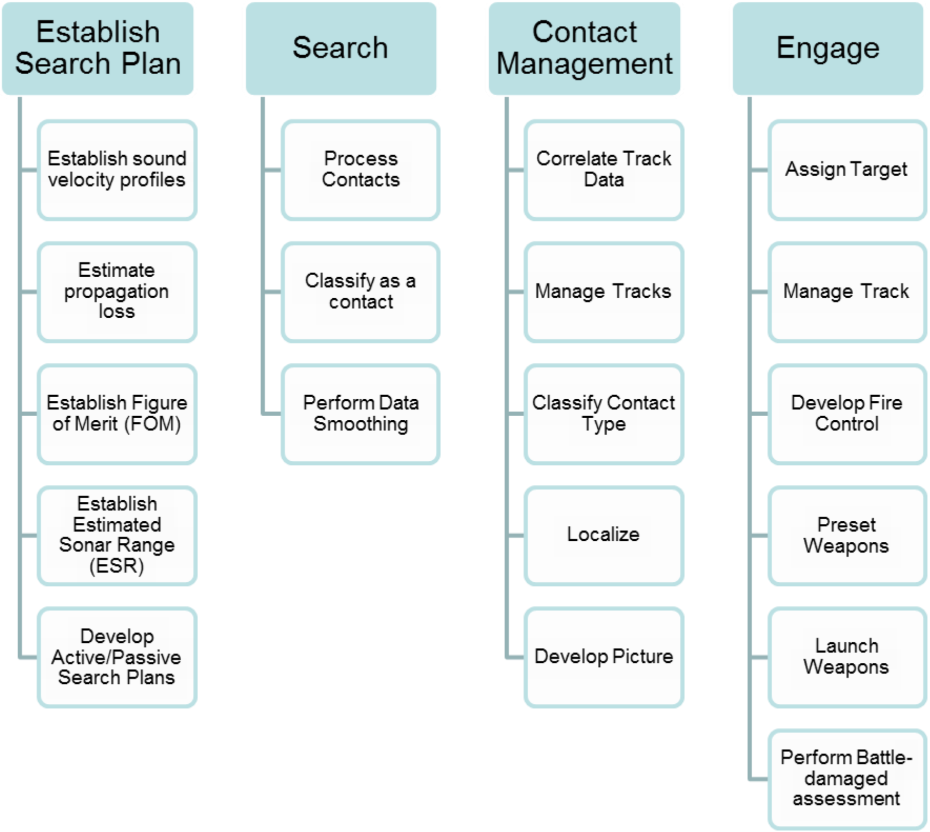


Figure 12. Functional Requirements Decomposition

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IV. MODELING AND SIMULATION

The MOPs were developed after the MOEs were defined. The two system-level MOEs are the protection of HVUs and the protection of SLOC. During the system architecture and requirements definition phase, the team consolidated a list of MOPs, and using the qualitative QFD process, generated the MOPs that supported the two MOEs. To provide a quantitative approach, the team constructed a model using ExtendSim to provide insight into the system MOPs. Specifically, the decision was made to conduct modeling, simulation, and design of experiments to quantitatively capture the MOPs that contributed to the protection of HVUs since the pillars of Sea Power 21 such as Sea Base, Sea Shield, and Sea Strike are centered on the HVUs such as the CVN.

As such, the application of modeling and simulation for this study focused on the LCS protecting an HVU, such as a nuclear powered aircraft carrier (CVN), from enemy submarine threats in an open-ocean environment. The model development was driven by the system-level MOPs rather than the overall concept of operations. This is due in part to the fact that an undetected submarine presents the greatest threat in any operational scenarios and that, first and foremost, mission success is driven by the timely detection of the submarine. Also, the kill chain analysis performed during the requirements definition phase places the need to timely detect, identify, and track the submarine to neutralize the threats to the HVUs. Thus, HVUs protection, in this case, is the operational tasks of detecting, identifying, and tracking the submarine threats in the open ocean.

The probability of detecting an enemy submarine is the most critical phase when it comes to neutralizing the submarine threats. Once the submarine is detected, successful engagement with the submarine depends on the weapon system effectiveness such as the probability of acquisition and hit, a function of weapon’s figure of merit and performance. While successful engagement with the submarine depends on numerous factors, the modeling and simulation efforts are focused on the probability of detection, which includes range (a function of sweep width), speed, and endurance (a function of search time). It is also important to note that the model was not designed to determine pass/fail criteria or the probability of successfully executing the mission. It was designed to provide insights into whether the LCS is a viable option for the ASW mission and if so what general specifications made the LCS acceptable, such as range, speed, and endurance.

According to the Naval Operations Analysis, detection ranges vary due to a submarine's relative motion (Wagner, Mylander, and Sanders 1999, 157). Once the target is within the sensor ranges, the measure of performance that can be used for determining the effectiveness of sensors is probability of detection. The probability of detection assumes that detection occurs at least once during a specified time interval. One of the parameters used in probability of detection is sweep width. Sweep width is defined as "a number that gauges a sensor's effectiveness under specified environmental conditions against a given class of targets. Each detection device (radar, sonar, eyeball, etc.) should be characterized by its capabilities by a single number that is operationally meaningful" (Wagner, Mylander and Sanders 1999, 165).

In line with sweep width is sweep rate. Sweep rate is a critical factor because "many sensors mounted on a moving platform have their detection effectiveness degraded when the speed of the platform is increased, that is the sweep width is a decreasing function of speed" (Wagner, Mylander and Sanders 1999, 167). This measure of performance is relevant because to effectively search for an object requires searching in many areas. Increasing search areas require the searcher to move thus making sweep rate a critical factor in the probability of detection.

The surface combatant conducting anti-submarine patrols may search in a predetermined or a random operational area. In a random search, the unidentified threat may be in any part of the area. The Navy Operations Analysis describes the probability of detection during a random search as a lower bound and equally distributed between search areas (Wagner, Mylander and Sanders 1999, 174). The team decided to apply the random search theory to the modeling and simulation efforts as described in the following sections. In addition, it is important to note that the values of the model are based on the envisioned concept of operations as well as open source information that may not be accurate performance values. However, the methodology is sound and can be repeated with actual performance values if the need should arise.

A. MODEL DESCRIPTION AND CONSIDERATIONS

The model performed a random search for enemy submarine threats using sweep width (w) and velocity (v) inputs to produce a probability of detecting a submarine in a given period of time (t).

1. Sweep width (w) was measured in nautical miles (nm) and defined as the width of the path that the sensors can sweep within a given period of time (t).
2. Search time (t) was measured in hours (h) and the baseline model started with a 2 hour (h) search time. The concept of operation envisions a moving screen therefore 2 hour search time is appropriate.
3. A circular area with a 22 kilometer radius (approximately 12nm radius) was used to define the search area. This distance was obtained based on an assumed maximum effective range of submarine launched torpedoes. The area of this region, A, is defined in the model as

$$Eq\ 1.)\ A = \pi(TorpedoRange)^2$$

4. Velocity (v) in these equations encompassed the range of speed and endurance characteristics for possible advanced deployable systems and sensor platforms that could be integrated in an LCS ASW mission module. It was measured in knots, nautical miles per hour (nm/h) and endurance was measured in (nm) or hours (h). Velocity range included the LCS itself, a sensor, or a range extender such as a Vertical Takeoff Aerial Vehicle (VTAV). The model did not discriminate which specific object was traveling at an assigned speed. Table 2 defines the speed in knots per hour (kt/h) and endurance characteristics that bounded the model and simulation.

Characteristic	**Cruising Speed**	**Max Speed**	**Endurance @ Cruise Speed**	**Endurance @ Max Speed**
LCS (Pike 2014)	18 kt/h	40 kt/h	3500 nm	1000 nm
VTAV (MH-60 R/S 2012)	70 kt/h	140 kt/h	2.7 h	No Data

Table 2. Speed and Range Variables

5. Equation 2 was used in this model to determine probability of detection.

$$Eq\ 2.)\ F_d(t) = 1 - e^{\frac{-wvt}{A}}$$ (Wagner, Mylander and Sanders 1999, 174)

The equation assumes that the patrolling vehicle searches at speed (v) through the region and that a systematic search path relative to the target is not used. Additionally, the model assumes there is always a target in the area where the convoy is transitioning in order to produce a probability of detection for all model runs.

6. For sweep rate calculations, which are a contributor to the probability of detection, Equation 3 shows the formula as speed (v) times sweep width (w).

$$Eq\ 3.)\ SR_{modelrun} = vw$$ (Wagner, Mylander and Sanders 1999, 167)

7. Different types of submarines emit different frequencies of detection. The signal strength of different submarines also varies drastically depending on submarine class. The model in this study does not take into consideration any of these effects and assumes very little is known about the enemy submarine. The model assumes a fixed submarine characteristic and does not use variables such as hull harmonics or engine noise correlation characteristics.

B. MODEL EXECUTION

A baseline model was built as a starting point for the modeling and simulation efforts. The baseline and subsequent analysis are represented in Table 3. Subsequent runs doubled speed (v), sweep width (w) and search time (t) inputs to assess the impact of such increases on probability of detection. Each had an equal impact on the probability of detection while only speed and sweep width had an impact on sweep rate.

Model Run/Characteristic	Probability of Detection	Sweep Rate (nm/hr)	Range (nm)	Search Time (hr)	Sweep Width (nm)	Speed (kt/h)
Baseline	0.043268	10	12	2	0.5	20
Double Speed	0.084664	20	12	2	0.5	40
Double Sweep Width	0.084664	20	12	2	1	20
Double Search Time	0.084664	10	12	4	0.5	20

Table 3. Random Search Results

To account for the impact of more than one LCS ASW mission model equipped ships, the variable (s) was used to indicate the number of LCS ships. The probability of detection for more than one ship is defined in Equation 4 as

$$Eq.\ 4.)\ P_{d(multi)} = \frac{Number\ of\ ways\ of\ detection}{total\ \#\ of detection\ and\ non\ detection\ outcomes}\ \text{(Hayter 2007, 159)}$$

When more than one ship is involved, the probability of detection is defined in Equation 5 as

$$Eq\ 5.)\ 1 - (probability\ of\ no\ detection)^s = \left(1 - \left(1 - P(d)\right)^s\right)\ \text{(Hayter 2007, 159)}$$

When two ships are randomly searching for the submarine in a uniformly distributed area, there is a possibility for search overlap to occur. By comparing two LCS ASW mission module equipped ships in the above equation to the baseline number of one LCS ASW mission module equipped ship that has doubled sweep width, search speed, or search time, it was determined that doubling the number ships has the same effect as doubling sweep width, search speed, and search time. As a result, Equation 6 of the random search model was simplified to provide probability of detection as

$$Eq\ 6.)\ F_d(t) = 1 - e^{-\frac{wvts}{A}}$$

Table 4 displays that increasing the number of LCS ASW mission module equipped ships provides statistically significant increases in probability of detection and sweet rate.

Number of LCS ASW MM	Probability of Detection	Sweep Rate (nm/hr)	Range (nm)	Search Time (hr)	Sweep Width (nm)	Speed (kt/h)
Baseline - 1	0.043268	10	12	2	0.5	20
2	0.084664	20	12	2	0.5	20
3	0.124269	30	12	2	0.5	20
4	0.16216	40	12	2	0.5	20
5	0.198412	50	12	2	0.5	20
6	0.233095	60	12	2	0.5	20
7	0.266278	70	12	2	0.5	20
8	0.298025	80	12	2	0.5	20
9	0.328398	90	12	2	0.5	20
10	0.357457	100	12	2	0.5	20

Table 4. Multi-Ship Random Search Results

C. SIMULATION WITH DESIGN OF EXPERIMENTS

The intent of the design of experiments (DOE) combined with the model was to determine which MOP had the most impact on probability of detection when uncertainty was introduced into the model. The simulation executed DOE on the sweep width, search time, velocity, and number of LCS ASW mission module equipped variables. The DOE used four factors for each parameter at 10 replications resulting in a combination of 2,560 events. For the overarching random search model, a binomial approach similar to a coin flip was taken. The 2,560 events were added to an ExtendSim simulation where range became a randomized parameter. For each run, the target was either found or it was not found. The ExtendSim simulation had a resolution of 50 opportunities for detection during each event. Results of the ExtendSim simulation were imported into the DOE software, Minitab, for analysis. Follow-on results of the DOE analysis are shown in Figure 13 and Figure 14.

Figure 13. Main Effects Plot for Detection

Figure 13 shows the response mean for detection for each factor level. As each data point increases in each factor, the probability of detection also increases. A practically important factor is determined by the steepness of the slope. The steeper slopes indicate important factors. Figure 13 illustrates that the effect of search time, sweep width, and speed are similar and have almost equal impact on the probability of detection. This similarity is represented by the similar steepness of their slopes. Based on a multilevel factorial design experiment, increasing the number of LCS ASW mission module equipped ships produces the greatest probability of detection. Analysis of the model also yielded that each factor is statistically significant with p-values less than 0.05.

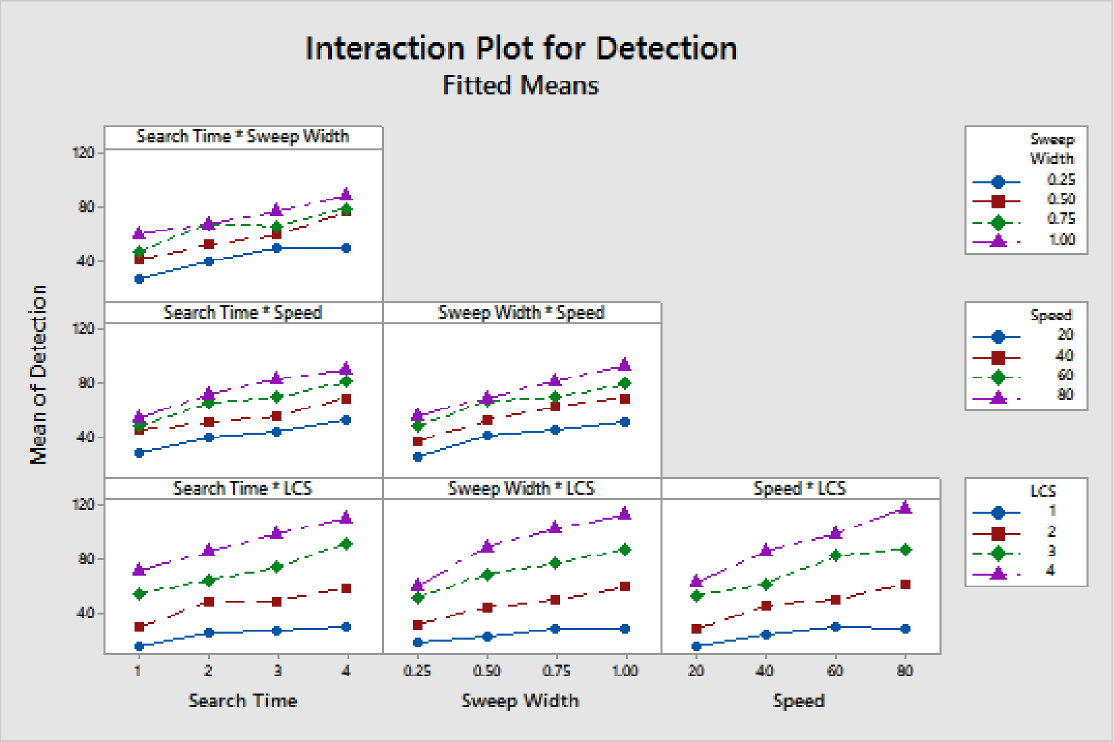


Figure 14. Interaction Plot for Detection

Figure 14 illustrates how the different parameters interacted with each other to affect the probability of detection from the simulation. A full factorial design resolution was used to produce the plots to ensure that all combinations were accounted. The search time, sweep width, number of LCS, and speed were analyzed to determine if interactions occurred between one another. Based on the simulation, as the number of each factor increased during comparison, the probability of detection also increased. As a guideline, interactions will be present when the lines intersect each other. Due to the parallel nature of each plot, no interaction between combinations of factors is present.

D. MODELING AND SIMULATION CONCLUSIONS

The greatest impact on increasing probability of detection will occur in the following priority order:

1. Increasing number of LCS
2. Increasing sweep width of sensors

3. Increasing speed of patrolling platforms
4. Increasing search time

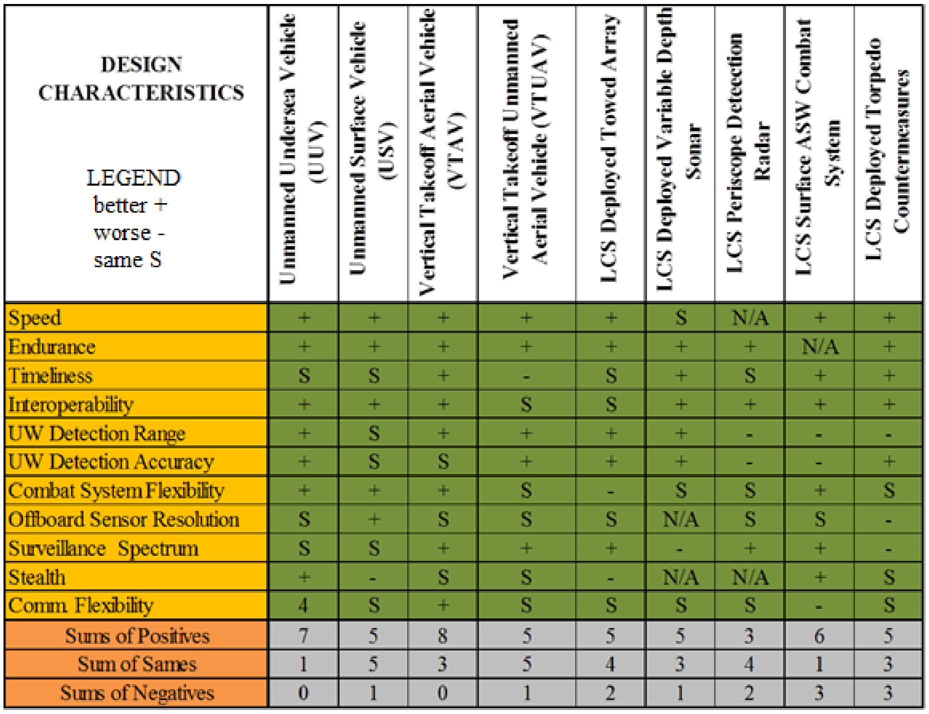
This model and simulation has important possibilities for future application for any analysts attempting to use it for more detailed decision-making. It is recommended that this model be decomposed with more detailed program specific, non-open source performance parameters and then broken out by individual capabilities included in the LCS ASW mission module if it is to be used outside of this study for programmatic decision-making.

V. ANALYSIS OF ALTERNATIVES

An analysis of alternatives was conducted based on the results of performance modeling, functional architecture and the cost analysis. To associate potential solutions, a Pugh matrix was used. The Pugh matrix, developed by Stuart Pugh, is a decision-making tool to provide systems engineering the ability to compare alternative solutions for a system (Burge 2009). They are generally used to subjectively reduce a set of alternatives to a subset that leave the most important characteristics included in the next steps of evaluation. For the comparison of alternative systems to be effective, the alternative systems must be compared to the baseline performance and cost of the existing system. The Pugh matrix facilitates this process by visually presenting which alternative systems are below the baseline performance and cost. These alternative systems are not included in the possible solution space so that only alternative systems that perform better than the baseline become part of the possible architecture. Follow-on solutions were then transposed using a morphological box to illustrate the best option or combination of options. Through the architecture, MOEs from stakeholder requirements and how each one can be achieved were defined. These MOEs were then used to define the functions of the LCS open ocean ASW mission module during the requirement analysis.

A. PUGH MATRIX

The Pugh matrix (see Figure 15) was used to compare alternative technologies for the Open Ocean ASW baseline. The Pugh matrix was also helpful for limiting the permutations of alternatives and enabling the focus to remain on ensuring the prime directive was maintained. A comparison through the requirement MOEs generated a solution based on the requirements alone.



DESIGN CHARACTERISTICS LEGEND better + worse - same S	Unmanned Undersea Vehicle (UUV)	Unmanned Surface Vehicle (USV)	Vertical Takeoff Aerial Vehicle (VTAV)	Vertical Takeoff Unmanned Aerial Vehicle (VTUAV)	LCS Deployed Towed Array	LCS Deployed Variable Depth Sonar	LCS Periscope Detection Radar	LCS Surface ASW Combat System	LCS Deployed Torpedo Countermeasures
Speed	+	+	+	+	+	S	N/A	+	+
Endurance	+	+	+	+	+	+	+	N/A	+
Timeliness	S	S	+	-	S	+	S	+	+
Interoperability	+	+	+	S	S	+	+	+	+
UW Detection Range	+	S	+	+	+	+	-	-	-
UW Detection Accuracy	+	S	S	+	+	+	-	-	+
Combat System Flexibility	+	+	+	S	-	S	S	+	S
Offboard Sensor Resolution	S	+	S	S	S	N/A	S	S	-
Surveillance Spectrum	S	S	+	+	+	-	+	+	-
Stealth	+	-	S	S	-	N/A	N/A	+	S
Comm. Flexibility	4	S	+	S	S	S	S	-	S
Sums of Positives	7	5	8	5	5	5	3	6	5
Sum of Sames	1	5	3	5	4	3	4	1	3
Sums of Negatives	0	1	0	1	2	1	2	3	3

Figure 15. Pugh Matrix of Design Characteristics versus Assets

Comprehensive research on current ASW threats as well as research on existing systems was conducted. From the research, a baseline was established that allowed for comparative values within the Pugh matrix. The baseline was then measured against the design characteristics and graded as whether it is better, "+," worse, "-," or the same, "S." Initial results of the Pugh matrix from the comparison between requirements and existing assets generated a solution indicating that the helicopter or vertical take-off aerial vehicle (VTAV) with sonar would be an ideal system for the LCS Open Ocean ASW mission module when concerned with the speed and distance that searches and detection only. When focusing on the submerged enemy threats, the interoperability of the LCS deployed variable depth sonar makes it an ideal solution when combined with the helicopter asset.

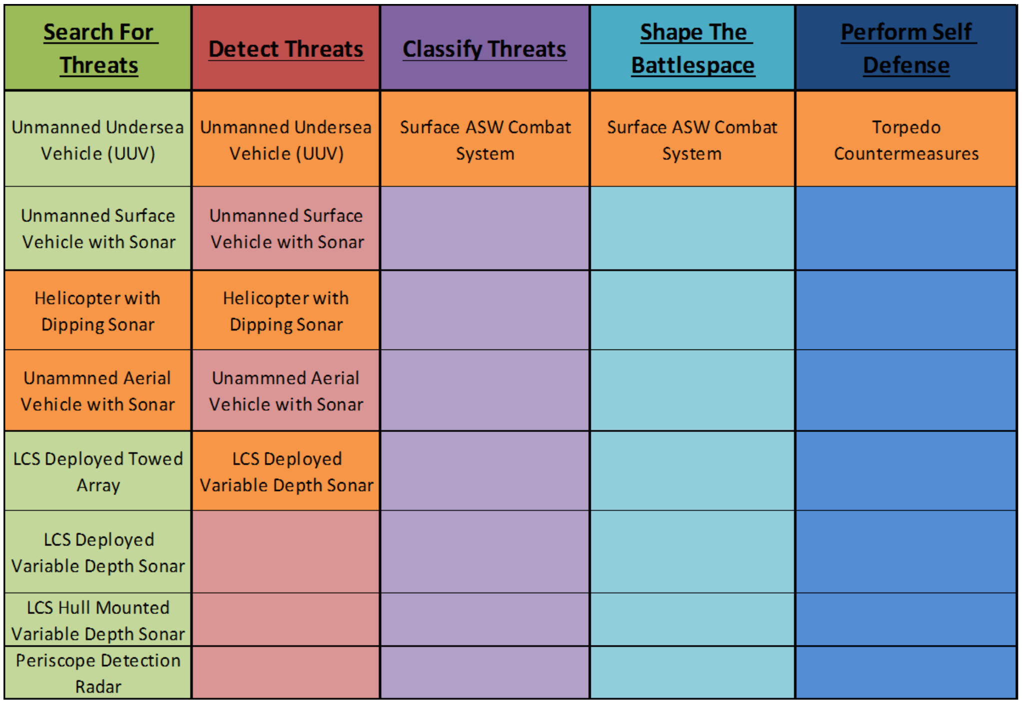
Additionally, various trade-off studies were conducted. off-board sensors such as those installed from external entities were compared to on-board tools. To add an additional variable to the assets, capabilities of unmanned vehicles were compared to their manned counterparts. A detailed cost analysis provided an asset's acquisition, integration, operations, support, and life cycle cost.

Incorporating cost into the evaluation, more detailed solutions were revealed during the Pugh matrix analysis. Ensuring that possible alternatives met the requirements criteria and followed the prime directive, the helicopter asset combined with the deployed variable depth sonar once again proved to be most viable solution; however it is the most expensive option with a total life cycle cost of over $2.4 billion, for the MH-60R, a vertical takeoff aerial vehicle asset, and the CAPTAS 2, a deployable variable depth sonar, with a total life cycle cost of $850 million. The combined cost also incorporates the ability to search, detect, and classify potential threats to the high value unit but lacks the ability to use an on-board process, adds another $920 million to the total. A potential alternative is the summation of two or three separate systems to achieve the same objective. In this alternative, adding the lowest costing assets capable of searching, detecting, and classifying, points to the combination of USV, AN/SQQ-89, and the MFTA produces a total life cycle cost of $1.7 billion. The comparison between a single solution to that of a compilation of systems allows the stakeholders and systems engineering practical options to support the prime directive. Based on the information from the Pugh matrix, any alternative must contain the LCS surface ASW combat system in order to ensure an on-board ASW combat system capability.

B. MORPHOLOGICAL BOX

Comparisons were made in a Morphological Box to help narrow down the field of concept alternatives reducing the design space to reveal a reasonable set of combinations of interest (see Figure 16). Deducing from the results of the modeling and simulation, it was discovered that as the number of LCS increase, the probability of detection also increased. To improve the analysis, adding more LCS seaframes to the battlespace will be dependent on the requirements of specific missions.

From the possible combination of alternatives in the morphological box, the MH-60R helicopter combined with the CAPTAS 2 and the AN/SQQ-89 provided the best capability to conduct detection, identification, tracking and engagement capabilities.



Search For Threats	Detect Threats	Classify Threats	Shape The Battlespace	Perform Self Defense
Unmanned Undersea Vehicle (UUV)	Unmanned Undersea Vehicle (UUV)	Surface ASW Combat System	Surface ASW Combat System	Torpedo Countermeasures
Unmanned Surface Vehicle with Sonar	Unmanned Surface Vehicle with Sonar			
Helicopter with Dipping Sonar	Helicopter with Dipping Sonar			
Unammned Aerial Vehicle with Sonar	Unammned Aerial Vehicle with Sonar			
LCS Deployed Towed Array	LCS Deployed Variable Depth Sonar			
LCS Deployed Variable Depth Sonar				
LCS Hull Mounted Variable Depth Sonar				
Periscope Detection Radar				

Figure 16. Morphological Box of Possible Combination of Alternatives cost analysis

Research and analysis was performed to characterize and evaluate feasible LCS capabilities that would enable it to execute the open ocean ASW operational tasks to search, detect, and classify targets. Permutations of weapons and sensors were investigated to establish combinations that could provide adequate capability to fulfill the requirements and CONOPS as defined for this project. System attribute data for commercially available systems, as well as U.S. Navy programs and capstones, was collected. For the purpose of developing life cycle cost (LCC) estimates, system attribute data collected included cost, technical maturity, basic capabilities, size, and physical composition.

VI. COST ANALYSIS

A. COST ESTIMATING METHODOLOGY

The DOD identifies four major analytical methods or cost estimating techniques used to develop cost estimates for acquisition programs: analogy; parametric (statistical); engineering (bottoms up); and actual costs (Department of Defense 1992). Estimating by analogy was used for LCC estimation in this analysis due to the unavailability of specific design and work breakdown structure (WBS) data for the commercial and DOD capabilities that were analyzed and to stay system agnostic throughout. Parametric analysis was performed on the individual capabilities based upon unit cost, weight, material composition, and estimated integration complexity in order to estimate acquisition and platform integration costs. Operations and support (O&S) costs were estimated based upon analogous system O&S costs or by utilizing the average percentage of LCC that acquisition costs typically account for, which is ~28 percent (Edwards 2010). Figure 17 represents the cost estimating process and methodology used for this analysis.

To simplify the cost estimating process, the Integrated Cost Estimation® (ICE^{TM}) software tool developed by Frontier Technology, Incorporated (FTI) was utilized. ICE integrates multiple parametric cost databases, provides a wizard driven process, and tailors estimates for service specific cost elements and system applications. For this estimate, Galorath's SEER for Hardware, Electronics, and System^{TM} (SEER-H), parametric cost analysis database was integrated with FTI's ICE software to aid in the development of acquisition and integration costs associated with the capabilities analyzed.

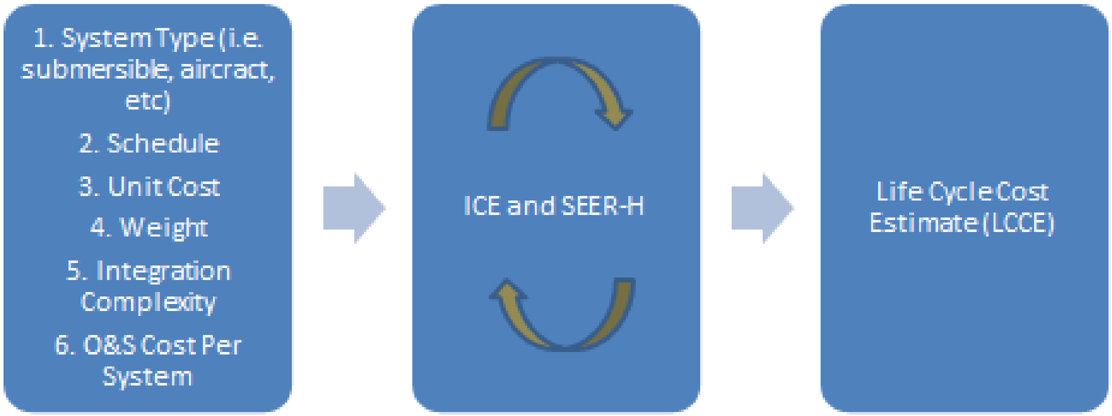


Figure 17. Cost Estimating Process

B. CAPABILITIES AND ANALOGOUS SYSTEMS

Based on the research performed, capabilities in many cases assist in the performance of multiple LCS ASW operational tasks. The groupings in the following subsections illustrate the various operational tasks used to construct the cost estimation analysis.

1. Search, Detection, and Classification

The following systems contribute to the initial functional blocks needed to satisfy the search, detect, and classify portions of the mission. Tables 5-11 provide descriptions for each of the mission systems identified.

Description	**Unmanned, autonomous, submersible operated and maintained from the Littoral Combat Ship (LCS)**
Capabilities	The UUV tows active transducer and a multi-function receive array, transmitting submarine contact data via data links to the LCS.
Analogous System	Remote Multi Mission Vehicle (RMMV)
Technical Maturity	Analogous system is delivered and deployed. Additional array and transducer capabilities exist today.

Table 5. Unmanned Undersea Vehicle (UUV) Description

Description	Unmanned, autonomous, surface vehicle operated and maintained from the Littoral Combat Ship (LCS)
Capabilities	The USV is equipped with a towed array, active source, and dipping sonar to detect enemy submarines and transmitting submarine contact data via data links to the LCS.
Analogous System	Unmanned Influence Sweep System (UISS)
Technical Maturity	Analogous system is delivered and deployed. Array, active source, and dipping sonar capabilities exist today.

Table 6. Unmanned Surface Vehicle (USV) Description

Description	Manned aerial vehicle that will be deployed from the LCS for submarine detection and communicate back with the LCS platform through real time data exchange.
Capabilities	The VTAV is equipped with long range active dipping sonar, radar with periscope detection capability, and acoustic processing for processing dipping sonar, and sonobuoys.
Analogous System	MH-60R
Technical Maturity	Analogous system is delivered and deployed.

Table 7. Vertical Takeoff Aerial Vehicle (VTAV) Description

Description	Unmanned, autonomous, aerial vehicle that will be operated and maintained from the Littoral Combat Ship (LCS)
Capabilities	The VTUAV is equipped with dipping sonar, radar with periscope detection capability, and acoustic processing for processing dipping sonar, and sonobuoys.
Analogous System	MQ-8B
Technical Maturity	Analogous system is delivered and deployed. Dipping sonar and sonobuoys capabilities exist today.

Table 8. Vertical Takeoff Unmanned Aerial Vehicle (VTAUV) Description

Description	Towed body and handling system resident on and deployed from the LCS
Capabilities	Medium frequency active sonar, torpedo detection, and receive array for Variable Depth Sonar (VDS)
Analogous System	Multi-Function Towed Array (MFTA)
Technical Maturity	Analogous system is delivered and deployed.

Table 9. LCS Deployed Towed Array Description

Description	Consists of a towed array and towed body deployed from the LCS.
Capabilities	The VDS Allows the ship to transmit and receive at the right depth with two separate arrays and maximize the detection of extremely quiet submarines. It is low frequency active and passive sonar.
Analogous System	Combined Active and Passive Towed Array Sonar (CAPTAS) (commercial)
Technical Maturity	Analogous system is delivered and deployed.

Table 10. LCS Deployed Variable Depth Sonar (VDS) Description

Description	X-band, pulse Doppler, frequency agile radar consisting of an above deck antenna unit, below deck cabinets, and a motor generator.
Capabilities	Performs periscope, Anti-Ship Cruise Missile (ASCM), surface threat, lower flying aircraft, UAV and helicopter detection and provides real time track information to the ship combat system.
Analogous System	AN/SPQ-9B
Technical Maturity	Analogous system is delivered and deployed.

Table 11. LCS On-board Periscope Detection Radar Description

2. Targeting and Weapon and Sensor Optimization

The combat system (see Table 12) implements the tasks for the functionality needed to satisfy the portions of the mission that perform targeting and optimization of weapons and sensors, as well as data management and command and control.

Description	Consists of Anti-Submarine Warfare Control System (AWCS) including processors, displays, software and a sonobuoys processing system
Capabilities	Integrates underwater warfare combat management, fire control and on-board training to detect, locate, track and engage submarine targets. It transmits and/or receives acoustic signals using a variety of sensors to provide target classification, as well as performing and controlling Target Motion Analysis (TMA) and controlling the setting of 'own ship' ASW weapons. In addition, it provides multi-sensor track correlation, track management control and forwards track data to the ship's Combat Direction System (CDS)
Analogous System	AN/SQQ-89(V)14
Technical Maturity	Analogous system is delivered and deployed. Additional array and transducer capabilities exist today.

Table 12. Surface ASW Combat System Description

3. Battlespace Shaping and Self Defense

The decoy systems are included to achieve the required abilities needed for battlespace shaping and self-defense (see Table 13).

Description	Consists of a towed decoy device and shipboard signal generator
Capabilities	The decoy emits signals to draw a torpedo away from its intended target. The signal emulates ship noise, such as propeller and engine noise, which is more attractive than the ship to the torpedo’s sensors
Analogous System	AN/SLQ-25
Technical Maturity	Analogous system is delivered and deployed.

Table 13. Torpedo Countermeasures Description

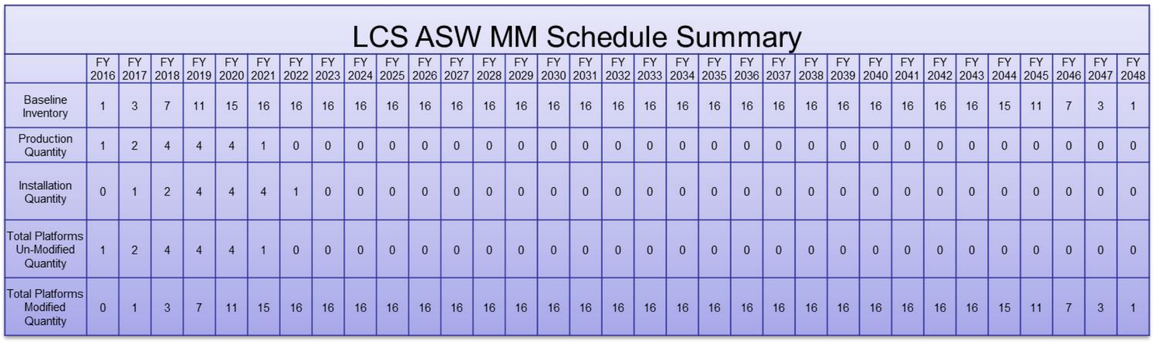
C. SCHEDULE, SERVICE LIFE, INFLATION, POPULATION, AND FISCAL YEAR

Table 14 lists schedule assumptions made in the cost estimate based upon the parameters in the December 2013 *LCS Mission Module Selected Acquisition Report* (SAR) (Defense Acquisition Management Information Retrieval [DAMIR] 2013).

Service Life	28 years
Development and Integration Start	FY15
Production Period	6 years
Development Period	2 years
Operations and Support Period	33 Years

Table 14. Schedule Assumptions

Table 15 is a direct export from the ICE software tool and presents the production and deployment schedule use in the cost analysis.



LCS ASW MM Schedule Summary

	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	FY 2030	FY 2031	FY 2032	FY 2033	FY 2034	FY 2035	FY 2036	FY 2037	FY 2038	FY 2039	FY 2040	FY 2041	FY 2042	FY 2043	FY 2044	FY 2045	FY 2046	FY 2047	FY 2048
Baseline Inventory	1	3	7	11	15	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	15	11	7	3	1
Production Quantity	1	2	4	4	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Installation Quantity	0	1	2	4	4	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Platforms Un-Modified Quantity	1	2	4	4	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Platforms Modified Quantity	0	1	3	7	11	15	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	15	11	7	3	1

Table 15. Schedule Summary

All costs were entered in the ICE tool in base year (BY) 2006 dollars. All cost outputs are presented in fiscal year (FY) 2015 dollars. There are a total of 16 mission modules and the cost estimation assumes that capability analyzed includes one system (e.g., one UUV or one USV).

D. CAPABILITY COST ESTIMATION

The following sections present the cost inputs and associated summary LCC outputs for each capability. The numbers are approximations and represent a rough estimate of acquisition, integration, operations, support, and LCC based upon analogous systems. Further analysis of classified and FOUO design information related to the LCS platform would be required if this cost model were to be used for decision making purposes. As such, this information can be considered open source.

COST INPUTS

Attribute	Value	Source
Unit Cost	~$32M	LCS MM SAR (Defense Acquisition Management Information Retreival [DAMIR] 2010)
Weight	14,500 lbs.	RMMV Fact Sheet (Remote Multi-Mission Vehicle 2013)
O&S Cost Per System	~$3.8M	% of TOC given 28% (procurement)/72%(O&S) (Edwards 2010)
Material Content	SEER-H Defaults	SEER-H

Environment Use	Submersible	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 16. UUV Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$680M	~$1.7B	~$2.4B

Table 17. UUV Cost Estimation Profile

COST INPUTS		
Attribute	**Value**	**Source**
Unit Cost	~$6.7M	LCS MM SAR (Defense Acquisition Management Information Retreival [DAMIR] 2010)
Weight	14,500 lbs.	ASW USV White Paper (Hillenbrand and Beeson 2006)
O&S Cost Per System Per Year	~$.8M	% of TOC given 28% (procurement)/72%(O&S) (Edwards 2010)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Sea - Surface	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 18. USV Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$250M	~$410M	~$660M

Table 19. USV Cost Estimation Profile

COST INPUTS		
Attribute	**Value**	**Source**
Unit Cost	~$38M	MH-60R SAR (Selected Acquisition Report (SAR) 2011)
Weight	21,650 lbs.	MH-60R SAR (Selected Acquisition Report (SAR) 2011)
O&S Cost Per System Per Year	~$3.5M	MH-60R SAR (Selected Acquisition Report (SAR) 2011)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Air-Manned	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 20. VTAV Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$840M	~$1,600M	~$2.5B

Table 21. VTAV Cost Estimation Profile

COST INPUTS		
Attribute	Value	Source
Unit Cost	~$10.4M	MQ-8B SAR (MQ-8B Selected Acquisition Report (SAR) 2012)
Weight	14,500 lbs.	MQ-8B Specification Sheet
O&S Cost Per System Per Year	~$2.6M	MQ-8B SAR (MQ-8B Selected Acquisition Report (SAR) 2012)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Air - Unmanned	SEER-H

Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 22. VTUAV Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$205M	~$1,300M	~$1,500M

Table 23. VTUAV Cost Estimation Profile

COST INPUTS		
Attribute	Value	Source
Unit Cost	~$4.4M	FY15 DDG51 P8A Budget Exhibit (DoD 2014)
Weight	1850 lbs.	The Naval Institute Guide to the Ships and Aircraft of the US Navy (Palomar 2013)
O&S Cost Per System Per Year	~$40,000	AN/SQQ-89 Visibility and Management of Operations and Support Cost (United States Navy 2014)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Submersible	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 24. LCS Deployed Towed Array Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$90M	~$21M	~$110M

Table 25. LCS Deployed Towed Array Cost Estimation Profile

COST INPUTS		
Attribute	Value	Source
Unit Cost	~$10.5M	LCS MM SAR (Defense Acquisition Management Information Retreival [DAMIR] 2010)
Weight	1850 lbs.	The Naval Institute Guide to the Ships and Aircraft of the US Navy (Palomar 2013)
O&S Cost Per System Per Year	~$1.3M	% of TOC given 28% (procurement) / 72%(O&S) (Edwards 2010)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Submersible	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 26. LCS Deployed Variable Depth Sonar Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$200M	~$640M	~$840M

Table 27. LCS Deployed Variable Depth Sonar Cost Estimation Profile

COST INPUTS		
Attribute	Value	Source
Unit Cost	~$5.8M	Northrop Grumman Contract Award (Northrop Grumman 2013)
Weight	1,185 lbs.	The Naval Institute Guide to the Ships and Aircraft of the US Navy (Palomar 2013)
O&S Cost Per System Per Year	~$2.6M	SPQ-9B VAMOSC (United States Navy 2014)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Sea	SEER-H
Development	Military Full	SEER-H

Standards		
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 28. LCS On-board Periscope Detection Radar Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$110M	~$1,300M	~$1,400M

Table 29. LCS On-board Periscope Detection Radar Cost Estimation Profile

COST INPUTS		
Attribute	Value	Source
Unit Cost	~$41M	FY15 DDG51 P-8A Budget Exhibit (DoD 2014)
Weight	4,000 lbs.	The Naval Institute Guide to the Ships and Aircraft of the US Navy (Palomar 2013)
O&S Cost Per System Per Year	~$380,000	AN/SQQ-89 VAMOSC (United States Navy 2014)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Sea	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 30. Surface ASW Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$720M	~$190M	~$910M

Table 31. Surface ASW Cost Estimation Profile

COST INPUTS		
Attribute	Value	Source
Unit Cost	~$1.3M	FY15 DDG51 P-8A Budget Exhibit (DoD 2014)
Weight	1,676 lbs.	The Naval Institute Guide to the Ships and Aircraft of the US Navy (Palomar 2013)
O&S Cost Per System Per Year	~$56,000	AN/SLQ-25 VAMOSC (United States Navy 2014)
Material Content	SEER-H Defaults	SEER-H
Environment Use	Submersible	SEER-H
Development Standards	Military Full	SEER-H
Application Type	Complex Assembly of Purchased Parts	SEER-H

Table 32. Torpedo Countermeasures Cost Estimation Inputs

COST PROFILE		
Acquisition and Integration Cost	**Operations and Support Cost**	**Life Cycle Cost**
~$36M	~$28M	~$65M

Table 33. Torpedo Countermeasures Cost Estimation Profile

E. LIFE CYCLE COST CONSIDERATIONS

LCC considerations are critical inputs to the AoA process used to determine the most affordable and operationally effective LCS ASW MM solution. The UUV, VTAV, VTUAV, and LCS on-board periscope detection radar represent significant LCC commitments for the LCS program, ranging from over $1 billion to $2.4 billion in total LCC. The USV, LCS deployed towed array, and VDS represent more affordable solutions ranging from $100 million to $800 million total LCC. The Surface ASW Combat System and torpedo countermeasures have a low LCC in comparison to their acquisition and integration cost due to the maturity of these systems and years of cost reduction initiatives.

VII. CONCLUSIONS

A. CONCLUSIONS

The LCS is a viable candidate for use in the open ocean ASW mission role. The LCS's ability to expand its capabilities through the use of changing mission modules makes it a unique naval vessel. In order for the LCS to perform the open ocean ASW role it must have carefully selected module components and associated host sensors to ensure ASW mission success. After careful modeling and simulation of the previously discussed parameters, the team used Pugh matrix and morphological boxes to help interpret the data and try to establish some recommended combinations of assets for potential ASW open ocean capability. The findings demonstrate that the recommended LCS open ocean ASW mission module should include the LCS ASW Combat System, an air asset such as the MH-60R with its capability to search, detect, and classify potential threats to the high value unit, and the CAPTAS 2. The low cost of the LCS when compared to the cost of a submarine allows for the use of multiple LCS's in this role. These multiple LCSs can search out large areas quickly and with the addition of the VTAVs will have increased search area and search speed. The added advantage of having these larger search areas and faster search speeds is earlier detection, which leads to higher probabilities of successful transit for high value units.

B. FUTURE WORK

The high cost of the MH-60 creates a challenging acquisition decision because it provides the required capabilities to detect, identify, and track but lacks sea depth detection fidelity and comes at a high operational cost. A more cost effective alternative to consider includes utilizing unmanned or internal assets such as a combination of the multi-function towed array with unmanned undersea vehicles and a host system comparable to the AN/SQQ-89.

At this point, further study of these options would be needed to assist in choosing the best alternative based on program management desires to balance risk and budget assessments. This study could be extended to include an evaluation of the LCS passive sonar performance and its capabilities in other ASW searches that were not covered in this report. Utilizing resources other than open sources may provide additional combinations that could reveal a more effective solution for the LCS open ocean ASW mission. Having realistic data for offensive and defensive anti-submarine warfare assets and threats would provide a more exact model to produce more accurate results. These results can be compared with the project’s cost estimation and help to gain insight for other potential new combinations of alternatives using off-board and onboard sensors and weapons.

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