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**NAVAL
POSTGRADUATE
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MONTEREY, CALIFORNIA

THESIS

**REAL OPTIONS VALUATION IN THE DESIGN OF
FUTURE SURFACE COMBATANTS**

by

Lauren B. Majchrzak

June 2017

Thesis Advisor:
Second Reader:

Johnathan Mun
Tom Housel

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**REAL OPTIONS VALUATION IN THE DESIGN OF FUTURE SURFACE
COMBATANTS**

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ABSTRACT

In a rapidly evolving world, the U.S. Navy must build an affordable, sustainable fleet of surface combatants that is capable of keeping pace with any threat. This can only be accomplished with a highly sophisticated fleet of reconfigurable vessels capable of meeting their service-life expectancy of 40 years. Modular Adaptable Ship (MAS) designs that include flexibility, decoupled payloads from the platform, standard interfaces, planned access routes, and growth margin for future technological advances present a viable option for the U.S. Navy. If the design approach to future surface combatants incorporates the use of Real Options Valuation (ROV) within the Integrated Risk Management (IRM) framework to account for unknown risk at the time of design, a reasonable portfolio of design options can be presented throughout the various stages of production. From our examination of the use of modular payloads on the Freedom (LCS-1) and Independence (LCS-2) classes and the planned access routes and growth margin for modernization on the San Antonio (LPD-17) class, a strong case can be made that a surface combatant designed with flexibility and adaptability would afford benefits, ultimately, to all entities within the Department of Defense.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	Amphibious Assault Vehicle
AAW	Anti-Air Warfare
AMCM	Airborne Mine Countermeasures
ASW	Anti-Submarine Warfare
ASUW	Anti-Surface Warfare
AWD	Air-Warfare Destroyers
BAE	British Aerospace
C5I	Command, Control, Communications, Computers, Collaboration, and Intelligence
CIC	Combat Information Center
CMS	Combat Management System
COTS	Commercial-off-the-shelf
CUO	Common Unit Output
ESG	Expeditionary Strike Group
ESSM	Evolved Sea Sparrow Missile
FASO	Flexible and Adaptable Ship Options
FREMM	Frégate Européenne Multi-Mission
FSD	Flexible Support Deck
FTI	Frégate de Taille Intermédiaire
IRM	Integrated Risk Management
IT	Information Technology
KVA	Knowledge Value Added
LCAC	Air-Cushioned Landing Craft
LCS	Littoral Combat Ship
LCU	Utility Landing Craft
MAS	Modular Adaptable Ships
MCM	Mine Countermeasures
MEC	Module Engagement Controller
MEKO	Mehrzweck-Kombination
MEU	Marine Expeditionary Unit

MOSA	Modular Open Systems Approach
MRV	Multi-Role Vessel
NLOS	Non-Line-of-Sight
RAN	Royal Australian Navy
RDN	Royal Danish Navy
ROI	Return on Investment
ROK	Return on Knowledge
ROKI	Return on Knowledge Investment
ROLO	Roll-on/Roll-off
ROV	Real Options Valuation
SEAMOD	Sea Systems Modification and Modernization by Modularity
SSMM	Surface to Surface Missile Module
STANFLEX	Standard Flex
VLS	Vertical Launch System

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I. INTRODUCTION

A. BACKGROUND

Seventy percent of the world is covered by water. To ensure freedom of navigation, economic independence, and national sovereignty, countries must maintain a highly efficient and technologically advanced fleet. With shrinking defense budgets, the current trend is to build fewer warships but maintain the same operational tempo. To continually meet the demands of a larger operational fleet, these new smaller fleets must be built on flexible and adaptable platforms with decoupled payloads that allow the vessels to accomplish a multitude of mission sets. Dr. Norbert Doerry from Naval Sea Systems Command has indicated that this type of modular design and build “offers an opportunity for a ship to affordably transform its mission systems over its service life to maintain military relevance” (Doerry, 2012, p.126). The design characteristics that allow these fleets to flourish are Modular Adaptable Ships (MAS) and Flexible and Adaptable Ship Options (FASO) (Mun & Housel, in press). MAS and FASO incorporated designs provide an economical platform for a seagoing navy to build highly effective warships capable of performing various missions in a multitude of environments.

Flexible and adaptable ship designs are centered on a standard hull with modular mission payloads that offer a wide mission set, affordable scalability, reduced operational downtime, increased availability of the ship, and a reduced total number of mission modules for the fleet (Thorsteinson, 2013). For navies with limited budgets, having a flexible and modular platform allows a vessel to perform at times like a frigate and other times like a corvette (Paris, Brussels, & Fiorenza, 2013). These new fleets of multi-mission vessels are already operational in blue water fleets around the world operated by countries including Denmark, Germany, France, Italy, Australia, and the United States.

Modular build and design has been in use since the mid-twentieth century. During World War II, Henry Kaiser's shipyards were able to produce Liberty Ships in minimal time due in part to the heavy use of modular construction, and the Germans constructed their Type 21 Submarines with modular build principles (Abbott, Levine, & Vasilakos, 2008). Starting in 1979, the German shipyard Blohm & Voss began building modular corvettes and frigates for third-world navies using a modular concept known as Mehrzweck-Kombination (MEKO). Shipbuilders ThyssenKrupp (2017) capitalized on the MEKO concept and through mature evolution, has produced the MEKO A-100, A-200, and now the MEKO A-400. In 1986, the Royal Danish Navy (RDN) began implementation of a modular concept called STANFLEX for a new class of patrol craft known as the Flyvefisken (SF 300) class (Abbott et al., 2008). The specific use of modular mission payload within the SF 300s directly translated into the future design and development of the RDN Absalon support ships and Iver Huitfeldt class frigates. The French and Italians have worked together to design a flexible multi-mission frigate known as the Frégate Européenne Multi-Mission (FREMM) class, while the Australian Royal Navy has the modular Anzac class of frigates and Hobart class of Air-Warfare Destroyers (AWD).

The United States Navy began to look at modular builds in 1975 with the Sea Systems Modification and Modernization by Modularity (SEAMOD) program (Abbott et al., 2008). SEAMOD focused on decoupling "the development of the payload from the development of the platform" (Doerry, 2012, p.126). This uncoupling provided two major benefits: it allowed the payload to be developed in parallel with the platform vice in series, which allowed the most recent technological systems to be installed onboard at the time the ship was put to sea; and it permitted rapid removal, replacement, or installment of mission payloads, preventing extended maintenance yard periods (Abbott et al., 2008; Doerry, 2012). SEAMOD evolved into the Modular Open Systems Approach (MOSA) and is characterized by "modular design, key interfaces, and the use of open standards for key interfaces where appropriate" (Abbott et al., 2008). These efforts led to the

development of the Littoral Combat Ship (USS *Freedom* (LCS-1) and USS *Independence* (LCS-2)), DDG 1000, Landing Platform/Dock (USS *San Antonio*, LPD-17), and the Future Frigate for the U.S. Navy (Abbott et al., 2008).

Glen Sturtevant, the Director for Science and Technology at PEO Ships—NAVSEA 21, has indicated that if future surface combatants are going to achieve their expected service life, the design must be flexible and adaptable. He noted these new warships should be built with “payloads that decouple from the platform, be configured with standard interfaces for technical modules, reconfigure rapidly, be designed with planned access routes, and have allowances for future growth margin” (Sturtevant, 2017). Growth margins allow for future technologies to be rapidly implemented into the existing design, preventing the vessel from having to enter into an extended maintenance overhaul period. Growth margins work hand in hand with the parallel development of mature payloads, ensuring that the latest technology can be installed as it is developed because of the standard interfaces. Sturtevant (2017) cites some of the following benefits of a flexible and adaptable design:

Separates payload development from the platform production;
Increased competition and innovation; Cross-platform commonality;
Rapid prototyping of payloads enables rapid acquisition of new capabilities;
Efficient technology refresh and incremental upgrades;
and paces the threat (Sturtevant, 2017)

B. PROBLEM STATEMENT

The problem is that traditional surface combatant designs leave little to no room for future growth or the ability to rapidly reconfigure as technology advances. This is a problem because payloads are installed as the ship is built, and too often the technology is obsolete by the time of commissioning. To reduce risk, typical surface combatant designs have altered either the hull and propulsion system but kept the same superstructure, or designed a new superstructure but left the hull untouched. For example, the DDG Flight III is built on the same hull as the DDG Flight IIA, but will incorporate a new superstructure to accommodate the Air and Missile Defense Radar, AN/SPY-6(V). Although this

model has served the U.S. Navy well, the DDG Flight III lacks any growth margin for future weapons upgrades and will require extensive yard periods and a midlife upgrade to remain relevant throughout the ship's life cycle. With the rising costs of ship maintenance, and the pace at which technology advances, this model puts surface combatants in danger of not fulfilling service-life expectancy. Moving forward, the U.S. Navy must incorporate flexible and adaptable ship design into all future surface combatants to ensure mission relevancy, reduce maintenance costs and extended yard periods, and keep pace with technological advances.

C. PURPOSE STATEMENT

By incorporating Modular Adaptable Ship (MAS) technologies and Flexible and Adaptable Ship Options (FASO) into ship design, the Department of the Navy will develop a fleet capable of meeting multiple missions with a single platform. The purpose of this study is to determine which capabilities (payloads) should be included in the ship design, so that a thorough evaluation of the possible risks can be identified and evaluated. Real Options Valuation (ROV), Knowledge Value Added (KVA), and Integrated Risk Management (IRM) through the use of Monte Carlo Simulation can provide ship designers and strategic leaders with the information needed to make critical decisions with respect to uncertainty and risk within the ship design. The output of this kind of analysis is important because if the United States Navy is to remain the world's preeminent sea power, we must find the best way to ensure that ship design will be flexible and adaptable.

By examining foreign navies that currently employ payload and combat system modularity, the U.S. Navy can make informed design decisions for future surface combatants. To develop a proof of concept methodology, this study used the Integrated Risk Management (IRM) framework to explore the benefits and risks of using a flexible ship design within the context of two case examples: weapon modularity on the Littoral Combat Ship (USS *Freedom* [LCS-1] and USS *Independence* [LCS-2]); and growth margin for future weapons capability and

technology upgrades on the new class of Landing Platform/dock (USS *San Antonio* [LPD-17]).

D. HYPOTHESES

This thesis addressed the following hypotheses:

- H_0 : Flexible and Adaptable ships are not able to maintain relevancy, rapidly reconfigure, or evolve during the course of their service-life expectancy.
- H_1 : Flexible and Adaptable ships are able to maintain relevancy, rapidly reconfigure, and evolve during the course of their service-life expectancy.
- H_0 : There is no advantage to building surface combatants with modular payloads developed in parallel to the platform compared with the current nonmodular shipbuilding approach.
- H_1 : There is an advantage to building surface combatants with modular payloads developed in parallel to the platform compared with the current nonmodular shipbuilding approach.
- H_0 : There is no future cost savings advantage to building a surface combatant with growth margin for weapons and technology upgrades over the life cycle of a surface combatant.
- H_1 : There is a future cost savings advantage to building a surface combatant with growth margin for weapons and technology upgrades over the life cycle of a surface combatant.

E. RESEARCH APPROACH

This thesis examined the effects of a modular approach to designing and building flexible and adaptable ships on cost and value by looking at two case studies. Case Study 1 examined the cost- and time-saving benefits of designing a surface combatant with weapons modules as compared to a structurally integral weapons payload. The original missile module for LCS was the U.S. Army's XM-501 Non-Line-of-Sight (NLOS). When the program was canceled in 2010, LCS was left without a missile module. The benefit of a modular design allowed LCS to continue production while an alternate missile module was developed in parallel.

Case Study 2 examined the long-term cost-saving benefits of having reserved weight and space for the future installation of the MK-41 VLS on the San Antonio class (LPD-17). LPD-17 through LPD-27 have trunk access and cooling requirements already in place for future installation, whereas LPD-28 will have weight and space reserved for VLS but will not install integration capabilities during production. Additionally, Case Study 2 reviewed the benefits of having designed one large main passageway that allows for ease of maintenance, troop movements, and technological upgrades.

F. THESIS STRUCTURE

Chapter II focuses on the current status of the Danish, German, French, Italian, Australian, and American navies with regards to their fleets of modular, flexible, and adaptable ships. The Danish, German, French, Italian, and Australian navies are constrained by smaller defense budgets and produce significantly smaller surface combatant fleets in comparison to the United States. By building modular and flexible vessels, these countries have been able to sustain operations in blue waters around the world with sophisticated and technologically advanced platforms that are capable of evolving with the threat with a smaller number of vessels. Cross-platform commonality with respect to weapons modules and the ability to rapidly change mission are essential design elements for these navies. Additionally, these navies recognize the advantage to leaving growth margin to rapidly integrate new technology as it becomes available.

Chapter III highlights the current problems within the U.S. Navy's approach to ship design of surface combatants. With current platforms losing 10–15 years of their service-life expectancy and incurring rising maintenance costs, the U.S. Navy needs to look at other ship design models. One alternative design model incorporates the use of modularity and flexibility to ensure surface combatants can maintain combat relevancy throughout their life cycle. A modular and flexible design reduces extended yard periods, allows for rapid

reconfiguration, and creates an environment where technology is produced in parallel with the platform.

Chapter IV discusses Case Study 1 and highlights the benefits of decoupled payloads. The fleet of Littoral Combat Ships has been operational since 2010, despite lacking a missile module to complement its Anti-Surface Mission Package. The advantage to having designed the surface combatant with modular payloads versus a structurally integral missile system allowed LCS to continue in production while the module was developed in parallel. With a modular missile payload, LCS was able to avoid an extensive yard period that would have been incurred if the missile had been structurally integral to the platform. Through the use of standard interfaces, a new missile module for LCS has been achieved with little to no added cost burden to overall life-cycle maintenance sustainment costs.

Chapter V discusses Case Study 2 and illustrates the need to reserve weight and space for payloads not installed at time of production. The 12 Landing Platform/dock vessels in the LPD-17 San Antonio class “were a functional replacement for four classes of amphibious ships: LPD 4s, LSTs, LKAs, and LSD 36s” (Jane’s IHS Markit, 2017b). With the ability to install the MK-41 Vertical Launch System (VLS) at a later time, the San Antonio class can evolve with the threat and ultimately act as a stand-alone platform if needed. Additionally, the San Antonio class was built with a large main passageway to facilitate the ease of maintenance, movement of troops, and the installation and replacement of server racks. This design aspect is a fundamental feature in a modular and flexible design that facilitates rapid technological advances.

Finally, Chapter VI includes recommendations for the design of future modular, flexible, and adaptable surface combatants with a strong emphasis on the need to reserve weight and space for future growth and technological advances. Additionally, Chapter VI looked at other areas within the Department of Defense where modularity and flexible and adaptable design could have future cost-savings impact.

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II. LITERATURE REVIEW

A. INTRODUCTION

When the U.S. Navy invests in the design and production of a fleet of surface combatants, there is an expectation that a vessel will remain combat relevant over its 40-year service life. According to Doerry (2012), U.S. surface combatants are currently falling short of their life-cycle expectancy by 10–15 years (Doerry, 2012). To ensure long-term combat relevancy, a surface combatant must be able to evolve with the threat and keep pace with technological advances. By examining the different modular designs currently in use by foreign navies, the U.S. Navy can capitalize on decades of successful flexible and adaptable ship design. Adopting a new approach towards the design of future surface combatants that heavily incorporates the use of modularity and standard interfaces to create a flexible and adaptable platform will allow the U.S. Navy to continuously evolve and keep pace with current threats.

B. FLEXIBLE AND ADAPTABLE SHIP DESIGN

Over the past 40 years, foreign navies have made continuous strides towards building and designing sophisticated, sustainable, and capable surface combatants. With smaller defense budgets in comparison to the United States, and constrained by high labor costs, foreign navies rely on ship designs that incorporate modularity, flexibility, and adaptability. These ship designs focus heavily on a standard hull with the same machines (propulsion), but offer a variety of modular payloads for specific mission sets. Decoupled payloads that integrate into combat management systems through standard interfaces allow these navies to swap out mission modules in a short period of time. With proven capabilities, these navies are deploying worldwide in support of ongoing initiatives to ensure freedom of navigation. Denmark, Germany, France, Italy, and Australia have proven fleets that incorporate modularity as a core component of ship design. For the U.S. Navy, the Littoral Combat Ship (LCS)

was a new design approach. Designed with three weapons modules that support different mission packages, it was the first surface combatant class of flexible and adaptable ships for the U.S. Although it failed to meet all of its modularity milestones at the time of production, LCS still deployed and met operational needs while payload development continued in parallel.

C. ROYAL DANISH NAVY

The Royal Danish Navy (RDN) has been at the forefront of modular ship design since 1987 when the first of 14 Flyvefisken class, or STANFLEX 300 (SF 300), multi-role vessels (MRVs) were commissioned. Naval Technology (2017c) found that the design was based on a standard hull that used modular bays to change mission type through use of the Standard Flex (STANFLEX) concept, and the fleet was ultimately decommissioned in October 2010 (Naval Technology, 2017c). The use of the Standard Flex concept played a fundamental role in the design and development of the larger follow-on modular designs seen in the Absalon Class Littoral Support Ships and Iver Huitfeldt class frigates.

1. Flyvefisken Class (SF 300)

The inception of the Flyvefisken Class and Standard Flex began as a feasibility study in 1982 (Global Security, 2017a). The Royal Danish Navy wanted to replace its fleet of 24 mission-specific ships (8 Fast Attack Craft (FAC), 8 patrol boats, and 8 mine countermeasure vessels) with 14 multi-role vessels (MRVs) and commissioned the SF 300 fleet between 1987 and 1996 (Global Security, 2017a). To meet the multi-role vessel mission, the SF 300 was built on a standard hull of nonmagnetic fiberglass reinforced plastic (FRP) that measured 54m in length and 9m in beam, with a crew that varied between 19 and 29 personnel depending on mission type and overall tonnage ranging between 320 and 485 tons specific to payload installed (Global Security, 2017a).

STANFLEX design capitalized on mission modularity by incorporating four interchangeable mission containers, one forward and three aft (Naval Technology, 2017c). The stainless steel containers measured 3m by 3.5m by

2.5m and housed all dedicated machinery and electronic payloads connected by a standard interface panel (Naval Technology, 2017c). “Each of these units can be (re)configured at a short notice for different roles, simply by installing the right combination of standard-size equipment containers in the four positions” (Global Security, 2017a). The ability to quickly and efficiently swap payload allowed these MRVs to serve the following mission sets: anti-air defense (AAW); anti-surface warfare (ASuW); anti-submarine warfare (ASW); electronic warfare (EW); mine countermeasures (MCM); patrol and surveillance; and pollution control (Global Security, 2017a).

The use of containerized weapon systems permitted the SF 300 to have an open architecture C4I system that allowed “new weapons systems to be added by creating new nodes” (Naval Technology, 2017c). Major technological upgrades were not required for the ship itself, but merely applied to the appropriate container. Global Security (2017a) stated that containers could be swapped out in 30–60 minutes pier-side using standard civilian cranes facilitating rapid mission change if necessary (Global Security, 2017a). Ultimately, 15 different mission modules were developed for the SF 300, which included weaponized containers for the Mk48 NATO Vertical Launch Sea Sparrow surface to air missile, Boeing’s Harpoon Block II surface-to-surface missile, and the 76mm Oto Melara Super Rapid gun (Naval Technology, 2017c).

The Flyvefisken Class demonstrated that a smaller number of multi-role vessels were capable of meeting the same mission demands of a fleet almost twice its size. STANFLEX and modular payload allowed for containers to be pre-staged for mission flex while simultaneously reducing downtime for upgrades. The success of the SF 300 fleet was the cornerstone for the RDN’s development of the Absalon Littoral Combat Ship.

2. Absalon Class Support Ships

The success of STANFLEX propelled the Royal Danish Navy to continue to design seagoing naval vessels with modularity as the core requirement.

Lundquist (2012) stated the Flyvefisken class was a coastal platform capable of performing a mission set designed to protect local waters, but it lacked the endurance to deploy to the Gulf of Aden or the Persian Gulf (Lundquist, 2012). The Flyvefisken Class served the RDN from the mid-1980s through the early 2000s, but left the Danish lacking a true blue water navy. With a firm commitment to NATO's Ocean Shield mission to combat piracy off the Horn of Africa (Lundquist, 2012), a need arose for a bigger platform capable of reaching distant locations like Somalia.

To meet the rising need for a blue water navy, the RDN commissioned two flexible support ships, HDMS Absalon in 2004 and HDMS Esbern Snare in 2005. Capitalizing on the success of the STANFLEX design and the use of payload modularity, the Absalon class was designed with the same containerized weapon packages as the SF 300 but also featured "significant internal volume inside the multipurpose flexible support deck (FSD) to support stern ramps for vehicles and boats" (Lundquist, 2012). The ability to launch and recover small boats or vehicles in conjunction with containerized weapon systems allowed the Absalon to float between two classes of warship: amphibious and combatant (Lundquist, 2012). Under the various configurations, the Absalon class could be "equipped for naval warfare, land attack, strategic seal missions, emergency disaster relief or as a hospital ship" (Naval Technology, 2017a).

The Absalon class was built on a frigate hull and measures a little more than two-and-a-half times the length of the Flyvefisken Class at 137m with a beam of 19.5m (Naval Technology, 2017a). Total tonnage is between 4,500 tons and 6,300 tons, depending on configuration (Global Security, 2017b). "The ship design, with 16 watertight sections or compartments and two airtight bulkheads, incorporates survivability and damage limitation including dual redundancy, automated damage control zones, damage detectors and smoke zones" (Naval Technology, 2017a). Focusing on long-term cost savings based on crew requirements, the Absalon class was outfitted with a maximum crew of 100, could accommodate 70 additional personnel and house another 130 in temporary

container facilities on the flexible support deck (Global Security, 2017b), and has personnel facilities and a galley for up to 300 embarked crew (Naval Technology, 2017a).

The Absalon class features five STANFELX container wells located amidships on the weapons deck (Pike, 2016; Lundquist, 2012). As with the SF 300, changing the combination of STANFLEX payloads allows the Absalon class to easily shift mission. Both Global Security and Naval Technology found that each of the five individual containers is capable of being loaded with either eight Boeing Harpoon Block II surface-to-surface missiles or 12 surface-to-air RIM-162 Raytheon Evolved Sea Sparrow Missiles (ESSM) (Global Security, 2017b; Naval Technology, 2017a). Additionally, the Absalon container wells are configured to handle “any combination of STANFLEX weapon/container suites developed for the Flyvefisken class” (Global Security, 2017b). By re-using existing containers and ensuring compatibility, the Absalon class created greater flexibility for mission type while proving to be a cost savings.

The modularity of the payload in conjunction with the flexible deck have allowed the Absalon class to be at the forefront of flexible and adaptable warship design. According to Naval Technology (2017a), the flexible support deck is 90m long, with 250m of parking lanes, and encompasses 915m² of total usable space (Naval Technology, 2017a). The FSD is designed for roll-on/roll-off (RO/RO) vehicles and the reinforced deck “can embark vehicles up to 62t such as the Leopard II Main Battle Tank” (Naval Technology, 2017a). The flexible multi-purpose deck can take

75% of an Army reconnaissance battalion, a containerized hospital with 40 beds and a capacity for 10 surgeries a day, a containerized command module for a staff of up to 70 personnel, a container accommodation for emergency evacuations, up to 300 mines in modular rails...or facilities for carrying two high-speed insertion craft Swedish Type SRC-90E at 7.4t each. (Global Security, 2017b)

The ability of the FSD to rapidly reconfigure missions based on the use of containers has allowed the Absalon class to effectively and efficiently meet all of its desired mission types.

Modularity with the Absalon class is not limited to containerized weapons and the flexible support decks. The Combat Information Center (CIC) has a Terma C-Flex combat management system and “virtually any console in CIC can be used interchangeably with the exception of the gun-firing console and Harpoon Block II consoles” (Lundquist, 2012). Finally, the flight deck is equipped with a hangar for two helicopters, rated at 20t, and when not in use for helicopter operation, it can store and stack cargo containers (Lundquist, 2012). The Absalon class demonstrated that modularity could be applied to larger combatant ships, and was not localized to smaller littoral ships. Continuing to capitalize on the growing success of its modular techniques, the RDN moved forward with designing and building a flexible and adaptable frigate fleet.

3. Iver Huitfeldt Frigates

The success of the Absalon class laid the keel for the Iver Huitfeldt Class Frigates, which comprises three operational frigates: Iver Huitfeldt (F361), Peter Willemoes (F362), and Niels Juel (F363). As Lundquist (2013) noted, the complement of the Absalon and Huitfeldt class added a true combatant element to an already formidable class of flexible support ships, providing the opportunity for the Royal Danish Navy to assume a more global blue water posture with extended deployments farther from native waters (Lundquist, 2013).

The Huitfeldt class was designed and built on the same hull used for the Absalon class creating an 80 percent shared commonality between the two classes (Lundquist, 2013). The Huitfeldt class is 138.7m in length with a beam of 19.75m, carries a crew of 101, and has accommodations for 165. (Lundquist, 2013). Where the Huitfeldt class lacks the flexible support deck found on the Absalon class, it has a more sophisticated AAW capability and quieter acoustic signature for ASW operations, and is twice as powerful (Lundquist, 2013).

The Huitfeldt class was built without the flexible support deck to accommodate the addition of the MK41 32-cell Vertical Launch System (VLS), which is capable of launching the Standard Missile-2 (SM-2), SM-6, as well as the RIM-162 Evolved Sea Sparrow Missile (ESSM) (Naval Technology, 2017e). Lundquist (2013) noted that in addition to the VLS, the Huitfeldt class continued with the modular mission payload design. He found that the Huitfeldt class has six slots for weaponized containers that can be loaded with additional ESSMs or Harpoon Block II missiles. He pointed out that the frigates capitalized on the reuse of design elements, and the stainless steel containers used on the Huitfeldt are the same containers used on Absalon: updated and modified containers from the cold-war era Flyvefisken class. He also noted that when a container is not being utilized, it can be stored, updated, or re-equipped. He concluded that by using a standardized interface, the weaponized containers represent flexibility and adaptability through their ability to plug and play on any Danish ship (Lundquist, 2013).

The Combat Information Center (CIC) modeled the flexible support ships CIC and utilizes the same Terma C-Flex combat management system (CMS) (Lundquist, 2013). “Modularity and the COTS (commercial-off-the-shelf) -based system with an open architecture-approach (OA) makes these ships easy to modify and less time consuming to upgrade” (Lundquist, 2013). Upgrades to IT systems, weapons, communications, and sensors are done through rack replacement on the standard civilian 19-inch racks installed throughout the frigate (Lundquist, 2013). Through the use of IT modularity, the fleet of RDN frigates is capable of upgrading and installing technology faster and more efficiently.

The Iver Huitfeldt class of frigates represents maturity in Danish modular ship design. Powerful and sophisticated, the frigate was built for \$325 million (Cavas, 2014), about one third of the cost of a U.S. Arleigh Burke Flight III class destroyer (USGAO, 2016). Cmdr. Senior Grade Hesselberg, who is in charge of the Danish frigate program, stated:

We have built in flexibility from the beginning. It's not that much more expensive in the beginning, but easier to update later on. It's the safe, low-risk option. We learned from our flexible support ships to have extra space for containers on the frigates. Modularity makes ships easier and more economical to build. It also makes them more efficient to operate, less expensive to maintain and to modernize. (Lundquist, 2013)

For the last 30 years, the Royal Danish Navy has significantly reduced the size of its fleet and replaced it with a smaller, powerful, cost-effective fleet. The RDN has proven that flexible and adaptable ships with modular payloads can accomplish a multitude of missions and play a significant role in international waters.

D. GERMAN NAVY

At the forefront of modular design for the German Navy was the German shipbuilder Blohm + Voss. The Blohm + Voss design concept known as Mehrzweck-Kombination (MEKO), which translates as “multi-purpose combination,” has been utilized in ship construction and design since the 1970s. According to Kamerman (2015), the success of the MEKO class can be seen in 13 navies worldwide in various corvettes and frigates (Kamerman, 2015). Shipbuilders ThyssenKrupp (2017) have capitalized on the MEKO design, and stated that modular mission payloads in 20ft standardized ISO containers create adaptability and flexibility and allow navies to rapidly reconfigure mission type based on operational needs. The shipbuilders pointed out that modules can be rotated for upgrades, maintenance or between ships, which reduces the number of overall payloads required for the fleet. The company noted that this simple reduction results in significant cost savings in procurement and maintenance over the life cycle of the ship. The MEKO class comprises the MEKO A-100 Corvette and the MEKO A-200 Frigate and is the backbone for the new German frigate class, the Baden-Württemberg (F125) (ThyssenKrupp, 2017).

Kamerman (2015) stated the German Navy will acquire four Baden-Württemberg class frigates to replace the eight frigates in the Bremen class (F122) commissioned in the 1980s. He found that the Baden-Württemberg frigate

design incorporated enhanced survivability capabilities to include floating, moving, and fighting after sustaining damage; the ability to embark and deploy Special Forces; maintaining prolonged periods at sea with little maintenance; and modular mission capabilities (Kammerman, 2015). The F125 is a new hull design drawing from the MEKO A-200 and the German F124, measures 149.5m in length with a beam of 18.8m, displaces 7,300 tons at full load, and will carry a crew between 105 and 120, but can accommodate up to 190 personnel to include a 20-person aircraft detachment and 50 embarked forces (Jane's IHS Markit, 2017a). The first frigate, Baden-Württemberg (F222) will be commissioned in 2017, Nordrhein-Westfalen (F223) in 2018, Sachsen-Anhalt (F224) in 2019, and Rheinland-Pfalz (F225) in 2020 (Pape, 2016).

Kammerman (2015) stated the F125 class is designed to experience prolonged deployment periods of 24 months and increased yearly hours of operation of 5,000h/yr. He found that this extended availability will be accomplished through a two-crew concept with crews swapping every 4 months in the given operational theater. He noted that through modernization, automation, and cross-rate training, the crew of the F125 is approximately half the size of the marginally smaller German Sachsen (F124) class frigates that currently deploy for six-month cycles and operate 2,500h/yr. The design flexibility of the F125 will double the availability of the current German frigate fleet while simultaneously reducing overhead (Kammerman, 2015).

The F125 will take advantage of MEKO technology. MEKO designs rely heavily on modularity, which increases the speed at which the ship can be built and facilitates faster upgrades and refits. According to Kamerman (2015), the F125 will feature weapon modules, electronic modules, mast modules, and a modular combat system with standard interfaces. He found that given the flexibility in the design, the F125 readily translates into an exportable frigate design within the MEKO family: the MEKO A-400 Generic Evolved MOTs Multi-Role Frigate. The MEKO A-400 will be built on the same class-standard hull with the same machinery as the F125 frigate, but offers foreign navies the flexibility to

specify any combination of combat systems from any supplier resulting in more than 80 percent commonality between the two classes of ships (Kammerman, 2015). This commonality creates a larger fleet of ships from which to draw resources, technical knowledge, and maintenance upgrades.

E. FRENCH NAVY

Similar to the Royal Danish Navy, the French Navy has made substantial strides over the last decade to replace three separate aging fleets with two smaller, state-of-the-art, flexible and adaptable fleets of frigates. Naval Technology (2017d) stated the Frégate Européenne Multi-Mission (FREMM) was a joint venture between the Italian and French navies, built and designed by the Direction des Constructions Navales Services (French naval defense company) (DCNS) and Orizzonte Sistemi Navali with Fincatieri and Finmeccania (Naval Technology, 2017d). These highly modular frigate designs allowed the French, Italians, and potential international clients a choice of equipment with regards to weapons and combat systems (Cavas & Tran, 2016). The newer Frégate de Taille Intermédiaire (FTI), specific to the French Navy, was unveiled in October 2016 (Peruzzi, Scott, & Pape, 2016). Designed by DCNS, it promotes modular design with potential international appeal (Cavas & Tran, 2016).

1. Aquitaine Class

Naval Technology (2017d) stated that the Aquitaine Class is comprised of FREMM frigates and will replace the nine D'Estienne d'Orves class avisos (A69 Type Aviso) and nine Tourville and Georges Legues class anti-submarine frigates (Naval Technology, 2017d). The modular design of the FREMM vessels allowed the French Navy to choose between two mission versions: a land attack version with torpedoes, vertical launch system, and cruise missiles; or an anti-submarine (ASW) version fitted with torpedoes, vertical launch system, and an active towed array sonar (Naval Technology, 2017d). Tomkins (2016) stated the French government originally committed to 17 FREMMs, but defense budget cuts reduced the class to 11 and then ultimately 8 vessels. He noted that the French

Navy has committed to building two FREMMs in the land attack configuration and six in the anti-submarine configuration. Aquitaine (D 650) was commissioned in November 2012, Provence (D 652) was commissioned in June 2015, and Languedoc (D 653) was commissioned in March 2016, each configured to ASW (Tomkins, 2016).

The French FREMM is 142m in length, has a beam of 20m, displaces 6,000 tons, and carries a crew of 108 (Naval Technology, 2017d). “The frigate’s layout has been designed to provide sufficient size for operational effectiveness, maintainability and sustained upgrades. The layout incorporates increased headroom between decks, deeper and longer engine compartments and larger equipment pathways for access and maintenance” (Naval Technology, 2017d).

Both the land attack and anti-submarine versions of the Aquitaine class feature the MBDA Exocet MM40 Block III for anti-ship and littoral attack capability and the MBDA Aster 15 and Aster 30 for air defense (Naval Technology, 2017d). The land attack vessels will also be equipped with MBDA SCALP naval cruise missiles (Naval Technology, 2017d). Additionally, both versions of the frigate boast an aft helicopter hangar and deck encompassing 520m², while the land attack frigates “are fitted for a tactical unmanned air vehicle and have the capability to control long-endurance, medium- and high-altitude unmanned air vehicles launched from ground sites or from other platforms” (Naval Technology, 2017d).

Similar to the Danish Absalon and Iver Huitfeldt classes, the Aquitaine class Combat Information Center (CIC) features a high-speed data network with an open architecture that will enable future weapon systems to be integrated into the frigates (Naval Technology, 2017d). With external communication equipment compliant with NATO standards, French FREMMs can operate on Link 11, Link 16, Link 22, and a JSAT tactical data link (Naval Technology, 2017d). This international NATO co-operability has resulted in the Aquitaine and Provence participating in joint exercises with the U.S. Navy’s Task Force 50 in the Persian-Arabian Gulf (Tomkins, 2016).

The design features of the FREMM have taken into account a flexible and adaptable modular build that allows for future growth in technology at a sustainable cost. Given choices between the various mission sets, growth margins for upgrades, and a relatively small and manageable crew size, FREMM is a viable option for a multitude of foreign navies.

(1) Italian Bergamini Class

Under the joint FREMM venture with the French, the Italian Navy has committed to the purchase of 10 frigates to replace the Lupo-and-Maestrale-class frigates built in the 1970s by Fincantieri (Naval Today, 2016). Known as the Bergamini class, Carlo Bergamini and Virginio Fasan were delivered in 2013, Carlo Margottini in 2014, Carabinieri in 2015, and Alpino was commissioned in September 2016 (Naval Today, 2016). The Italian Navy expects to have all 10 frigates delivered by 2020 and will operate four anti-submarine variants and six general purpose variants of the FREMM class (Naval Today, 2016).

(2) Foreign FREMM sales

Given the modular choices for combat systems and weapons, smaller crews, and the capability to carry out various mission types, the FREMM class is appealing to foreign navies. According to Tomkins (2016), both the Egyptian Navy and Royal Moroccan Navy each operate a FREMM ship in anti-submarine configuration but without a vertical launch system or jamming capabilities (Tomkins, 2016). Built by DCNS, FREMM Mohammed VI was delivered to Morocco in 2014, while FREMM Tahya Misr was delivered to the Egyptian Navy in 2015 (Naval Today, 2016).

2. FTI Class

The success of the FREMM class has pushed the French to continue to tailor their existing fleet into a smaller, highly effective combatant force. Peruzzi, Scott, & Pape (2016) noted that the Frégate de Taille Intermédiaire (FTI) is a medium-size frigate and will replace the five in-service La Fayette class frigates

starting in 2023 (Peruzzi, Scott, & Pape, 2016). “The 4,200-ton frigate is a fresh design, different from the preceding FREMM multi-mission frigates, and features an unusual ‘inverted bow’ intended to improve seakeeping in high sea states” (Cavas & Tran, 2016). The FTI will be a formidable platform capable of executing the following:

Anti-submarine, anti-surface, and anti-air warfare capabilities, the ability to deploy Special Forces projections, capable of supporting operations against asymmetric threats, able to operate as a single vessel or as part of a joint national or combined international task force, provide power projection at distance, conduct maritime interdiction, crisis prevention, and intelligence gathering operations. (Peruzzi et al., 2016)

According to Cavas & Tran (2016), the FTI will measure 122.25m in length, have a beam of 17.7m, and carry a crew of 125 personnel inclusive of a 15-person aviation detachment, and can accommodate an additional 50 personnel depending on the mission. The authors noted that each frigate will be equipped with two MBDA Aster 30 launchers, each comprising four cells as compared to the four launchers on the FREMM class. They also noted that FTI will be capable of launching the Aster, MM-40 Exocet Block III guided anti-ship missiles, and has a 76mm cannon. Finally, the authors pointed out that the compact frigate will reach speeds of 27 knots with an endurance of 5,000NM on a combined diesel and diesel (CODAD) engine arrangement. The compliment of the eight FREMM vessels (six anti-submarine configuration and two air defense configuration), five FTIs, and two Horizon class anti-air warfare frigates will make the French Navy a 15-strong frigate force by 2030 (Cavas & Tran, 2016).

The FTI is estimated to cost \$840 million, which is still 20–30 percent less than the 6,000 ton FREMM (Cavas & Tran, 2016). Despite this price tag, DCNS is committed to producing a flexible and adaptable frigate that delivers options to the buyer, be it the French Navy or the international naval community, and estimates it could possibly sell an additional 40 frigates of this design (Cavas & Tran, 2016). At the core of the FTI design are embedded evolutionary and adaptive capabilities based around a modular design (Peruzzi et al., 2016) that

offers freedom in a rapidly changing technical world for clients to pick and choose their combat systems and equipment (Cavas & Tran, 2016).

F. ROYAL AUSTRALIAN NAVY

Currently, the Royal Australian Navy (RAN) utilizes the Anzac class of frigates as its primary anti-submarine warfare platform. According to Naval Technology (2017b), the Anzac class was built by Tenix Defense Systems (now part of BAE Systems Australia), and eight were commissioned for the RAN between 1996 and 2006, and two were commissioned for the Royal New Zealand Navy in 1997 and 1999 (Naval Technology, 2017b). “Anzac frigates are long-range escorts with roles that include air defense, anti-submarine warfare and surveillance” (Kerr, 2017). Naval Technology (2017b) noted that the Anzac class displaces 3,600 tons fully loaded, has a length of 118m with a beam of 14.8m, and carries a crew of 174 personnel (Naval Technology, 2017b). The design of the Anzac is “based on the Blohm + Voss MEKO 200 modular design which utilizes a basic hull and construction concept to provide flexibility in the choice of command and control, weapons, equipment and sensors” (Naval Technology, 2017b). Given the success of the Anzac frigates, the RAN is moving forward with a new class of frigates that will need to incorporate a flexible and adaptable design to meet the growing demand for an efficient, sophisticated, and technologically advanced warship.

According to Goldsmith (2016), the new Future Frigate initiative launched by the Royal Australian Navy is known as the SEA5000 Program. Anticipating an increased military presence in the Asia-Pacific region from both non-state and state actors by 2035, the RAN will need a frigate capable of deterrence and power projection (Goldsmith, 2016). SEA5000 “will oversee the acquisition of nine high-capability Future Frigates and these major surface combatants will be capable of Anti-Air Warfare (AAW), Anti-Surface Warfare (ASuW), with a strong emphasis on Anti-Submarine Warfare (ASW)” (Goldsmith, 2016).

1. Future Frigate Mandatory Design Characteristics

Given the anticipated threat in the volatile regions of the South China Sea and East China Sea, the RAN has stated that five critical capability criteria should be incorporated into the Future Frigate design (Goldsmith, 2016). Goldsmith (2016) noted that these five characteristics are essential to the long-term success of a flexible and adaptable warship:

1. **Low Crewing Requirement:** Due to RAN personnel shortages, the Future Frigates must be capable of safely operating with crew of less than 174.

Goldsmith (2016) noted that due to manning shortages within the RAN, the Australian DOD has stated that the crew size must not exceed that of the current Anzac frigate, 174 personnel. He pointed out that since naval personnel account for about 50 percent of a ship's operating and sustainment life-cycle costs, it would be advantageous for the RAN to cut long-term costs by building a flexible and adaptable ship that reduces costs through manpower (Goldsmith, 2016).

2. **RAN Combat Capability Preferences:** The Future Frigates must be capable of supporting the CEAFAAR S/L/X radar suite with the SAAB 9LV Combat System and Aegis Fire Control System (FCS). It is also inferred that the RAN will insist on the inclusion of the multi-purpose Mk-41 Vertical Launching System (VLS) as the ships' principal weapons battery.

Given the rapid growth in technologically advanced weapons over the last two decades, the new Future Frigate must incorporate a design that allows for continued growth without major, costly overhauls. The Future Frigate design must have "sufficient growth margins to accept new technologies as they mature" (Goldsmith, 2016). To accommodate this growth margin, the original design must have "significant surplus space, weight, power and cooling margins" (Goldsmith, 2016).

3. **Flexibility:** The Future Frigates must be capable of accepting mission-specific modules, as well as providing full hangar and logistics support for two HM-60R helicopters.

4. **Ship Survivability:** The Future Frigates must be capable of operating in the projected higher-threat environment of future decades, even without access to 'external support'. The Future Frigates must also be capable of remaining partially functional even after suffering battle damage, and particularly due to the higher-threat operating environment of future decades. Ship survivability is a pivotal aspect of the Future Frigate design since the RAN major surface combatant fleet is numerically finite, thus cannot lose a single ship without severe repercussions for the RAN's capacity to sustain ship deployments over protracted periods.
5. **Growth Margin:** The Future Frigates must have sufficient surplus space, weight, electrical power and industrial-grade cooling to accommodate new 'game-changing' technologies as they mature in the period through 2035. For instance, high-energy directed energy weapons are anticipated to mature over this period and promise to revolutionise naval operations. (Goldsmith, 2016)

2. Potential Designs

Initial designs were submitted from eight different countries with a history of designing and building flexible and adaptable vessels including France, Germany, Britain, Spain, Denmark, The Netherlands, Italy, and Australia (Kerr, 2017). Ultimately, Fincantieri of Italy, Navantia of Spain, and British Aerospace (BAE) were selected to "refine their designs and prepare their commercial proposals for the comparative evaluation process (CEP) (Kerr, 2017). Kerr (2017) found that Fincantieri has built four FREMM frigates for the Italian Navy, with another four in production and two left to build. The RAN variant of the Bergamini class would not require modification to the existing hull design, already has twin helicopter hangars, and would create a large support structure with a family of 19 vessels (Kerr, 2017). Navantia designed the RAN Hobart class of Air Warfare Destroyers (AWD), and the Future Frigate design would be a modified F-100 Frigate (Goldsmith, 2016) that "would benefit from more than 75 percent of systems commonality with the AWDs and about 40 percent with the Anzac class" (Kerr, 2017). BAE has designed the Type 26 Global Combat Ship for the British Royal Navy, and the RAN version of the global combat ship stands to benefit

from the mature Type 26 design already in production (Kerr, 2017). Final design selection for the Future Frigate will occur in 2018 (Goldsmith, 2016).

The Royal Australian Navy is pushing the design boundaries of flexible and adaptable ships to meet the evolving needs of a global navy with a deep blue water reach and shrinking defense budgets. With a clear and concise list of critical capability criteria, the RAN will ensure that the Future Frigate will be able to meet the defense needs of the Australian people.

G. UNITED STATES NAVY

As the United States Navy began to phase out its fleet of 51 Oliver Hazard Perry class frigates, it began to look for a high-tech platform that could be used as a replacement (Osborn, 2015). The end result was the Littoral Combat Ship (LCS) in two variants: the trimaran-hull Independence and the mono-hull Freedom. Stashwick (2016) pointed out that the LCS concept was a highly flexible and adaptable ship that would allow the U.S. Navy to operate in littoral areas with a focus on maritime security and anti-piracy (Stashwick, 2016). “The ships were designed to be high-speed (over 40 knots) and highly maneuverable, with the ability to swap out modules to provide mission-specific capabilities like anti-submarine, anti-surface, and mine-clearing” (Stashwick, 2016). Doerry (2012) noted that both variants of the LCS included a mission bay in the design to house elements of mission packages. Within the LCS class, “mission packages are composed of mission modules, aircraft, and crew detachments to support the mission modules and aircraft” (Doerry, 2012, p.129).

1. LCS—Freedom

Currently, 13 Freedom class littoral combat ships have been ordered, and 4 have been commissioned. USS *Freedom* (LCS-1) was commissioned in November 2008; USS *Fort Worth* (LCS-3), in September 2012; USS *Milwaukee* (LCS-5), in November 2015; and USS *Detroit* (LCS-7), in October 2016 (Jane’s IHS Markit, 2016a).

The Freedom class is built on a steel mono-hull and is capable of performing three mission packages: anti-submarine warfare (ASW), anti-surface warfare (ASuW), and mine countermeasures (MCM) (Jane's IHS Markit, 2016a). LCS-1 has an overall length of 115.3m, and all subsequent Freedom class vessels are 118.3m to improve through-water performance; the beam of LCS-1 is 17.5m, while the remaining class is 17.6m; the bow of LCS-5 and all subsequent models have been modified from LCS-1 and LCS-3 (Jane's IHS Markit, 2016a). LCS-1 has a maximum tonnage of 3,360 tons and the remaining Freedom class reaches a maximum tonnage of 3,480 tons and all variants carry a crew of 50 (Jane's IHS Markit, 2016a).

The flexible design “incorporates a large reconfigurable seaframe to allow rapidly interchangeable mission modules, a flight deck with integrated helicopter launch, recovery, and handling systems and the capability to launch and recover maritime vehicles (manned and unmanned) from the stern side” (Jane's IHS Markit, 2016a). Modular payload on the LCS comprises three modular weapons stations that can accommodate either a gun (MK 46 30mm gun) or missile module (Lockheed Martin AGM 114L Longbow Hellfire) (Jane's IHS Markit, 2016a).

Stashwick (2016) found that the low total gross weight allows the LCS class to obtain speeds greater than 40 knots. He noted that the design trade-off for speed was sustained battle damage capability. He pointed out that where other surface combatants could withstand and potentially recover from sustained high-intensity conflict, the Freedom class would likely result in abandonment of the vessel in the same type of conflict (Stashwick, 2016).

2. LCS—Independence

The Independence class of littoral combat ships has commissioned four ships with another six in construction and four more ordered. USS *Independence* (LCS-2) was commissioned in January 2010; USS *Coronado* (LCS-4), in April

2014; USS *Jackson* (LCS-6), in December 2015; and USS *Montgomery* (LCS-8), in September 2016 (Jane's IHS Markit, 2016b).

The Independence class is designed on an aluminum trimaran hull form based on a commercial ferry design used by the Norwegian company Fred Olsen (Jane's IHS Markit, 2016b). As with the Freedom class, the Independence is capable of performing three mission packages: anti-submarine warfare (ASW), anti-surface warfare (ASuW), and mine countermeasures (MCM) (Jane's IHS Markit, 2016b). The Independence class has an overall length of 128.5m (about 10 meters longer than Freedom), with a top speed of 50kts (Jane's IHS Markit, 2016b). The beam of Independence is 31.6m (approximately twice that of Freedom), which can accommodate the MH-5E heavy-lift helicopter (used primarily for mine countermeasures), with a full load displacement of 3,188 tonnes, and a crew of 40 personnel (Jane's IHS Markit, 2016b).

The flexible design incorporates a "reconfigurable seaframe to allow rapidly interchangeable mission modules" that include three modular weapon stations (Jane's IHS Markit, 2016b). "The two gun modules are each built around a Mk 46 30mm gun" (Jane's IHS Markit, 2016b), and the missile module has been fielded with the Longbow Hellfire, a millimeter wave RF, fire-and-forget, high explosive anti-tank missile. The Independence class features a side-ramp with roll-on/roll-off capability, and can carry two 11m RHIBs (rigid hull inflatable boat) "available for use by boarding teams carrying small arms" (Jane's IHS Markit, 2016b).

3. Small Surface Combatant

The United States Navy originally contracted 52 Littoral Combat Ships, but in January of 2014 Secretary of Defense Chuck Hagel "instructed the Navy that there would be no new contracts awarded for LCS production beyond 32 ships" (Osborn, 2015). Osborn (2015) noted that in place of the remaining 20 littoral combat ships, the Navy will build a Small Surface Combatant ship and cited that on 15 January 2015, Secretary of the Navy Ray Mabus stated that the new class

of ship was required to have frigate-like capabilities and thus would change the designation of the last 20 ships from LCS to FF (Osborn, 2015).

The new frigate will capitalize on the two existing hull variants used in the Freedom and Independence classes (Eckstein, 2015b). Speaking at an American Society for Naval Engineers event, CAPT Dan Brintzinghoffer stated the new frigate would take the basic LCS design but differ in the following ways:

It will be more lethal, more survivable, and will be able to conduct surface warfare and anti-submarine warfare simultaneously, whereas the LCS had to choose only one mission package to work with at any given time. It will have a torpedo decoy, variable depth sonar and multi-function towed array permanently onboard, rather than included in a part-time mission package for LCS; will deploy two 7-meter rigid-hull inflatable boats rather than the 11-meter RHIBs on the LCS surface warfare package; and will retain the Mk 50 30mm guns rather than converting to the more common 25mm gun. The ship will be up gunned with a SeaRAM anti-ship missile system, a ship-launched Hellfire missile system and an over-the-horizon surface-to-surface missile system. (Eckstein, 2015b)

The new class of frigates will trade the high-speed capability of the LCS class in order to accommodate the additional weight created by the heavier armor for increased survivability (Eckstein, 2015b). To make the new frigate class cost-efficient, CAPT Brintzinghoffer stated commonality will be required across both variants and will likely need to share some modular aspects with the LCS class or some commonalities with other classes of surface combatants (Eckstein, 2015b).

This new class of frigates represents an opportunity for the U.S. Navy to build on an existing hull capitalizing on cost-savings in the early design process, and incorporate more advanced flexible and adaptable modules in the payload design. A proven example of a flexible and adaptable frigate with modular payload with similar tonnage is the MEKO A-200 class frigate. The MEKO class family is designed for sustained battle damage and could provide guidance for enhanced survivability options for this new class of American frigates.

H. REAL OPTIONS VALUATION WITH FLEXIBLE SHIPS

The United States Navy needs to develop a more sophisticated method for flexible and adaptable ship design if it is going to keep pace with a rapidly evolving worldwide threat. Caprace & Rigo (2010) noted that in the past, ship design relied on highly experienced naval architects who were well versed in a straight-forward ship design that was fixed and rigid (Caprace & Rigo, 2010). This outdated method of ship design is becoming cost-prohibitive when looking at the lifetime life-cycle cost for upgrades, overhauls, and drives inflexibility for rapid mission change (Koenig, Czapiewski & Hootman, 2008). Due to the rigidity in the build and failure to build with growth margin, U.S. Navy cruisers and destroyers are failing to meet their designed service lives by almost 10 years (Doerry, 2012).

Ship design needs to be approached using flexible and adaptable designs. This method assumes that the possible set of requirements for the ship design are so great, that it is prohibitively expensive to attempt to design a ship incorporating every desired feature (Mun & Housel, in press). Instead, “[t]he key to modular adaptable design is incorporating options in the design to be able to defer the exact configuration of the ship to that point in time when the requirements are known, and to have the capability to affordably modify the ship’s configuration to meet the requirements when they become known” (Doerry, 2012, p.127).

Moving forward with flexible and adaptable ship design requires sophistication and finesse. One valuable tool on the market to assist the U.S. Navy with evaluating the inherent risk in adaptable and flexible ship design is Real Options Valuation (ROV). Mun & Housel noted that Real Options Valuation is a systematic approach and integrated solution that uses various inputs including modeling, statistics, and economic analysis to provide decision makers a varied set of options from which to choose. They stated ROV is a powerful tool in this situation because traditional Return on Investment (ROI) cannot be applied to these assets (Mun & Housel, in press).

By examining the Knowledge Value Added (KVA) of the ship design, a common unit of output (CUO) will be developed that will allow decision makers to assess the actual cost and value of people, systems, or processes within the design (Mun & Housel, in press). KVA ultimately delivers two metrics—Return on Knowledge (ROK) and Return on Knowledge Investment (ROKI)—that can be used to generate input for real options analysis (Mun & Housel, in press). Finally, Integrated Risk Management (IRM) builds on the portfolio of options available in the design process by using quantitative software to provide objective quantification of risk, flexibility, strategy, and decision analysis (Mun & Housel, in press).

Real Options Valuation allows shipbuilders to design for uncertainty. “In the design state, options analysis enables more realistic assessments of technologies and design features that add flexibility during development and adaptability during the post-commissioning life cycle” (Koenig, 2009, p. 95). ROV creates five options: option to expand, option to contract, option to wait or defer an investment, option to choose between different assets, and option to vary the mix (Koenig, 2009). According to Mun & Housel (in press), Real Options Valuation is a quantitative approach to ascertaining the amount of risk in a modular build when the risk is unknown. They noted that by using simulation, a portfolio of options can be presented to the design team, allowing for a looser build that has margin for growth or mission change. The portfolio of options created using Real Options analysis can be cost driven or payload specific, forcing the design to accept some risk in the final product (Mun & Housel, in press).

By incorporating the theories of Real Options Valuation (ROV), Knowledge Value Added (KVA), and Integrated Risk Management (IRM) into existing design builds, the U.S. Navy can begin to design a “sufficiently sized and relevant future surface combatant fleet that can be built and supported within the available budget. Modular Adaptable Ships (MAS) technologies offer an opportunity for a ship to affordably transform its mission systems over its service life to maintain

military relevance” (Doerry, 2012, p.126). Mun & Housel (in press) point out that by using Monte Carlo Simulation, thousands of iterations can be run to determine possible outcomes for flexible and adaptable ship design. They conclude that ROV, KVA, and IRM can provide naval architects, senior leadership, and decision makers the opportunity to exercise the strategic ability to either move forward with a portion of the ship design or abandon it because the initial uncertain risk has become known over time (Mun & Housel, in press). Incorporating the use of Integrated Risk Management with flexible and adaptable ship design will provide the U.S. Navy with a future surface combatant fleet capable of sustaining rapid reconfiguration with growth margin for future technological advances to meet the evolving needs of a dynamic and uncertain world.

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III. BUILDING FLEXIBLE SHIPS

A. CURRENT CONVENTIONAL SURFACE COMBATANT SHIP DESIGNS

Faced with evolving threats in the South China Sea, the re-emergence of the Russian fleets in the Mediterranean and the Black Sea, and the required ongoing sustained presence in the Persian Gulf, U.S. Naval surface combatants must be capable of operating in diverse environments and have flexibility in their operational design. With computer processing power doubling almost every two years, declining Department of Defense budgets, and the rising costs of building and maintaining the fleet, future surface combatants need to be built with flexibility in order “to ensure affordable relevance over the ship’s life cycle” (Sturtevant, 2015).

Current surface combatant ship designs are bogged down by a myriad of legacy ship designs that exhibit limited or no growth margin for capability upgrades as technology advances. According to Sturtevant (2015), upgrades have become costly and prolonged due to inflexible architectures, and payloads (capabilities) are strongly coupled to the platforms (ships) (Sturtevant, 2015). Surface combatants are falling short of their expected life cycle and are “failing to stay relevant over their entire service life” (Sturtevant, 2015).

Figure 1 illustrates the current conventional surface combatant service life. A ship is expected to have a service life of 40 years, but even after Mid-Life Modernization, surface combatants are falling short of their service-life expectancy by 15 years. Figure 1 illustrates that the Mid-Life Modernization is providing only an additional 5 years of operational capability for a cost that was intended to last 20 years. By failing to meet expected life cycle, a tremendous financial burden is placed on the Navy to supplement the fleet with newer surface combatants. To break this trend, future ship design needs to move towards modularity, flexibility, and adaptability.

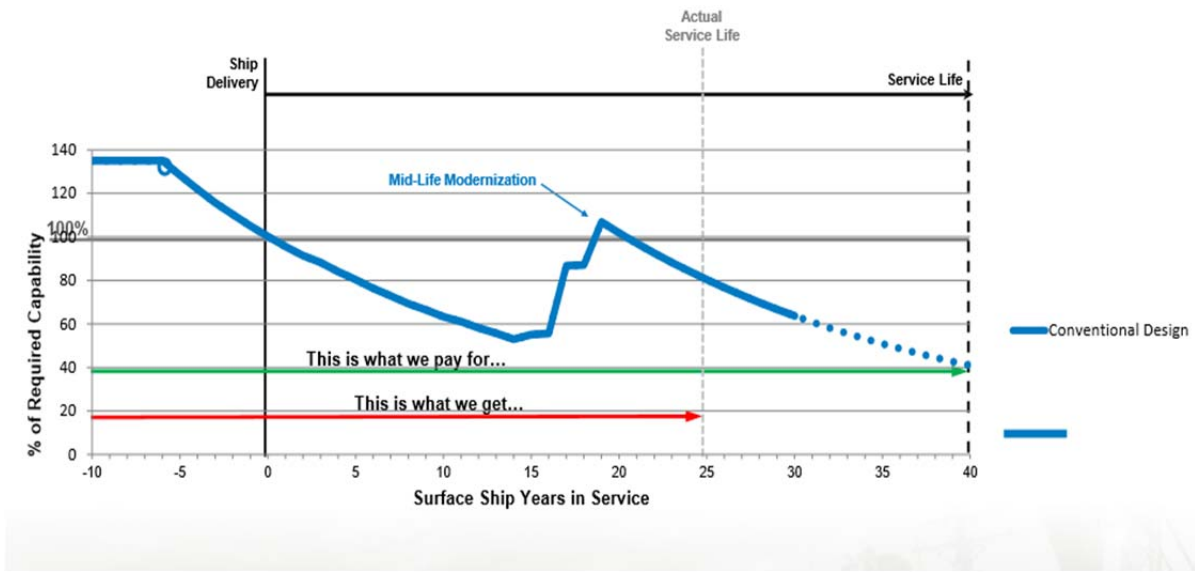


Figure 1. Conventional Surface Combatant Service Life Source: Sturtevant (2015).

B. FLEXIBLE SHIP DESIGN

In order to increase the longevity of surface combatants, future ship designs must incorporate weight and space allowances for upgrades and future technological advances. Built-in growth margin can reduce extended yard periods, allowing the platform to return to an operational readiness status in a shorter period of time at a reduced cost. In January 2014, VADM Thomas Rowden, Commander Naval Surface Forces, stated “Making the move to modularity will further allow us to maximize the service life of our ships as we will be able to upgrade the combat systems equipment to more and easily and affordably keep pace with rapidly advancing technology” (Sturtevant, 2015). By adopting flexible ship designs that incorporate modularity in both design and payload, the U.S. Navy will be able to continuously meet the evolving demands placed upon it.

1. Five Tenets of Flexible Ship Design

Sturtevant (2017) stated that flexible ship design is based on five primary tenets:

- Decoupled Payloads (capabilities) from Platforms (ships)
- Standard Platform-to-Payload Interfaces
- Rapid Reconfiguration
- Pre-Planned Access Routes
- Sufficient Service Life Allowance Growth Margins (Sturtevant, 2017)

Decoupling payloads from platforms allows the payload to be developed in parallel with the platform. As technology advances and processing power doubles every two years under Moore's Law, there is a significant cost savings advantage to installing a payload or C4I system just prior to or immediately following commissioning. In decoupled environments, "weapons or sensors can be easily replaced for ship mission adaptability" (Sturtevant, 2015). This type of decoupled payload can be seen in the Danish SF 300 class and the follow-on Absalon and Huitfeldt flexible ships.

Standard Platform-to-Payload Interfaces allow C5I (Command, Control, Communications, Computers, Collaboration, and Intelligence) modules or weapons modules to operate in a plug-and-play environment. These interfaces should maximize commonality to allow cross-platform use of the module. Using a specific module on more than one class of ship reduces the overall cost of the module and provides mission flexibility. Weapons modules built for the Danish SF 300 incorporated a standard interface that translated onto the Absalon and Huitfeldt ships. As the Navy moves forward with the new frigate on the hulls of LCS Independence and LCS Freedom, the frigate missile and gun module interfaces should be configured the same as LCS to capitalize on code cost savings.

Rapid reconfiguration refers to “specific C5I compartments that can easily be reconfigured with upgraded equipment or new systems” (Sturtevant, 2015). Navy CANES (Consolidated Afloat Network Enterprise Systems) is a primary example of a system that would benefit from flexible ship designs that incorporated rapid reconfiguration. CANES requires software upgrades every two years and hardware upgrades every four years, which means upgrades cannot wait until a Mid-Life Modernization. In a flexible ship design, server racks and network access points are located in highly accessible areas. This design feature would facilitate rapid CANES upgrades with minimal loss of operational time for the ship.

Pre-planned access routes are “used for the easy removal and replacement of interior equipment or systems” (Sturtevant, 2015). This implies that pre-planned access routes need to exceed the standard-size passageway. The incorporation of a larger or broader passageway(s) can increase the size and weight of a ship during design, increasing the overall cost. The long-term advantage to these larger passageways is the ability to remove or add equipment without having to undergo an extensive yard period that could potentially involve the need to cut the hull of the ship or cut large holes in the superstructure. LPD-17 incorporated the use of a larger “main” passageway as part of its flexible design. CANES hardware upgrades is an example of a C5I system that would benefit from a pre-planned access route.

Sufficient Service Life Allowance Growth Margins incorporate “space and weight for future capabilities, and provision for projected demand for distributed systems such as electric power, cooling, and network bandwidth” (Sturtevant, 2015). A ship designed with zero growth margin will undergo sustained and costly yard periods for technological upgrades that could require extensive cuts to the hull and superstructure. Additionally, without growth margin, a ship may not be able accommodate newer technology, leaving the Navy with a platform that will not be able to meet service-life expectancy. In a flexible ship design, as with the LPD-17, weight and space were reserved for the Vertical Launch System

(VLS), although it has not been installed. By reserving the weight and space for this system and equipping the space with the correct standard interfaces, distributed power, and cooling, LPD-17 can choose to install VLS at a later time without significant cuts to the hull or prolonged delays in its return to operational readiness.

2. Benefits of Flexible Ship Design

If incorporated into the design of future combatant surface vessels, Sturtevant's five tenets of flexible ship design will create a naval force capable of rapid deployment into any environment with the ability to change configuration to meet mission requirements. According to Sturtevant (2015), flexible design embodies adaptability, modularity, commonality, and scalability, and he concluded that the following benefits are derived from flexible ship design:

separation of payload development and platform production; affordable alternate business model to lengthy and costly ship production work; increased competition and innovation; cross-platform commonality; rapid prototyping of payloads enables rapid acquisition of new capabilities; modular open systems enable acquisition agility; efficient technology refresh and incremental upgrades; and paces the threat. (Sturtevant, 2017).

Figure 2 illustrates the benefits of flexible ship design. Unlike conventional ship design, flexible ships do not undergo one large Mid-Life Modernization. Instead, flexible ships undergo periodic payload replacement and technology refresh, which allows the vessel to maintain a higher readiness rating. The flexible ship model should allow a platform to meet its life-cycle expectancy while maintaining combat relevance.

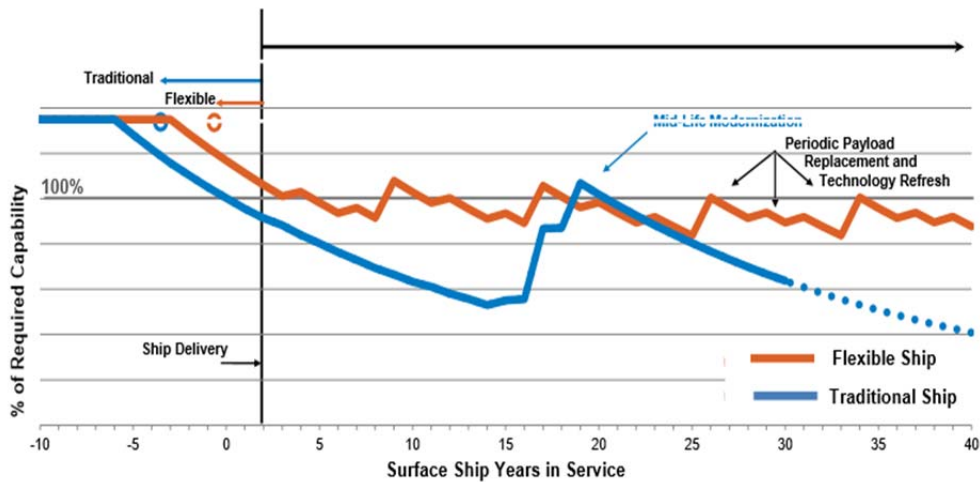


Figure 2. Potential Benefits of Flexible Ship Design.
Source: Sturtevant (2015).

C. CONVENTIONAL/FLEXIBLE CASE STUDY

Moving forward, the U.S. Navy needs to design future surface combatants that will meet life-cycle expectancy. The following chapters looked at two individual case studies that highlight the benefits of building flexible ships. Case Study 1 examined the benefits of building modular payloads and specifically addresses the missile payload for LCS. Case Study 2 examined the use of a planned access route to assist with future installation of IT assets, movement of troops, and ease of maintenance on LPD-17. Additionally, Case Study 2 reviewed the benefits of reserving weight and space for the future installation of VLS on LPD-17 if ever required.

IV. CASE STUDY 1—LCS MISSILE MODULE

A. LCS MISSILE MODULE BACKGROUND

LCS Freedom and Independence were designed to incorporate modular payloads and both classes of ship have three modular weapons stations that can accommodate either a gun or missile module (Janes, 2016a; Janes, 2016b). The Surface to Surface Missile Module (SSMM) serves as the principal weapon within the LCS Anti-Surface Warfare Mission Package (Scott, 2017). The initial LCS modular missile payload was to be fielded by the U.S. Army's XM-501 Non-Line-of Sight (NLOS) modular missile and was in development to become the "cornerstone of the new, highly maneuverable light brigade" (Defense Update, 2010). The modular design of NLOS had immediate crossover capability for the U.S. Navy and was a perfect fit for LCS. According to Defense Update (2010), the NLOS program was canceled in 2010 after a review of its precision fires capabilities and requirements when it struck only two of six targets during its Limited User Test (LUT) (Defense Update, 2010).

As the primary anti-surface weapon for LCS, NLOS had over-the-horizon targeting with a range of 30 nautical miles and could be launched as individual missiles at a specific target or in salvos of multiple missiles to cover larger areas in support of friendly forces ashore (Defense Update, 2010). It consisted of two separate variants: the Precision Attack Munition (PAM) and Loitering Attack Munition (LAM) (Rogoway, 2014). Designed for modularity, NLOS could be "rapidly rearmed at sea by helicopter, therefore extending its combat endurance over extended missions" (Defense Update, 2010). With LCS Freedom and Independence already commissioned at the time the program was cancelled, the Navy was left without a missile payload but continued to meet deployment cycles with a limited Anti-Surface Mission Module.

The initial replacement for NLOS was Raytheon's Griffin B missile. Rogoway (2014) noted that the Griffin B missile relied on either GPS/inertial

guidance (exact coordinates programmed before launch) for successful engagement or laser targeting (operator pinpoints target until contact). He pointed out that using laser pinpoint or GPS/inertial guidance in a swarming boat attack were time-intensive evolutions that prevented LCS from performing its mission effectively. He found that that in order to alter the Griffin B missile to make it a more desirable missile for LCS, Raytheon would have had to “integrate a new RF (radio frequency) seeker into the missile” (Rogoway, 2014). The time required and the cost for upgrades to make the Griffin B a viable option forced the Navy to look for alternative potential missile modules (Rogoway, 2014).

Rogoway (2014) stated that with NLOS and Griffin B no longer options, the Navy decided to look at existing inventory that could be modified to meet the LCS missile module. He pointed out that this decision ultimately led the Navy to look at the Army’s Apache Longbow Hellfire AGM-114L by Lockheed Martin. He noted that the Longbow is a millimeter wave RF, fire-and-forget, high-explosive anti-tank missile with demonstrated effective performance against maritime targets. It has a range of 6–8 km (well short of NLOS’s 30NM) and there are thousands of Hellfires in DOD inventory (Rogoway, 2014). Unlike the Griffin’s laser pinpoint requirements, the fire-and-forget technology of the Hellfire allows LCS to fire at a target, or multiple targets, and immediately flee (Rogoway, 2014). With a large existing Hellfire inventory and proven technology, the Navy modified the AGM-114L to meet the vertical launch needs of the LCS Surface Warfare Mission Module and “engineering development tests of Longbow Hellfire missiles modified for use on LCS vessels were successfully conducted in June 2015” and “on 28 February, the U.S. Navy conducted a successful structural test firing of the LCS SSMM from the Freedom variant LCS USS *Detroit* (LCS 7)” (Scott, 2017).

B. ADVANTAGE OF MODULARITY

NLOS was designed to serve as a “missile in a box” (Defense Update, 2010) and fulfills three of Sturtevant’s primary flexible ship tenets: decoupled

payload, standard interfaces, and rapid reconfiguration. If NLOS had been designed as a structurally integral part of the ship, program cancellation would have resulted in extended and expensive yard periods with significant loss in LCS operational tempo while the old system was ripped out and a new structurally integral system was installed. With NLOS being modular, LCS was able to continue in production and meet deployment obligations while a new missile system was developed in parallel. With module development happening in parallel, the U.S. Navy created an environment where it could explore multiple viable options before deciding on the Longbow Hellfire as a capable substitute module for NLOS.

1. Standard Interface

Development of a missile module in parallel with the platform can only be accomplished through the use of standard interfaces. Standard Interfaces within a ship's Combat Management System (CMS) allow weapon modules to be removed and replaced without disruption to the system. Within the framework of LCS's CMS is the Module Engagement Controller (MEC), which features two standard interfaces: one for the gun engagement processor and one for the missile engagement processor. The Module Engagement Controller is able to communicate with the vessel's CMS whether zero, one, or both modules are connected. This feature enabled LCS to continue to deploy, and engage and fire the gun module without a fielded missile module connected to the system. Figure 3 illustrates the LCS Combat Management System with the Gun Engagement Processor connected and capable of engagement without having a missile module connected. Figure 4 illustrates how the missile module rapidly integrates into the Module Engagement Controller and communicates with the Combat Management System. The overall architecture of the CMS demonstrates the added benefits of a decoupled payload that employs a standard interface.

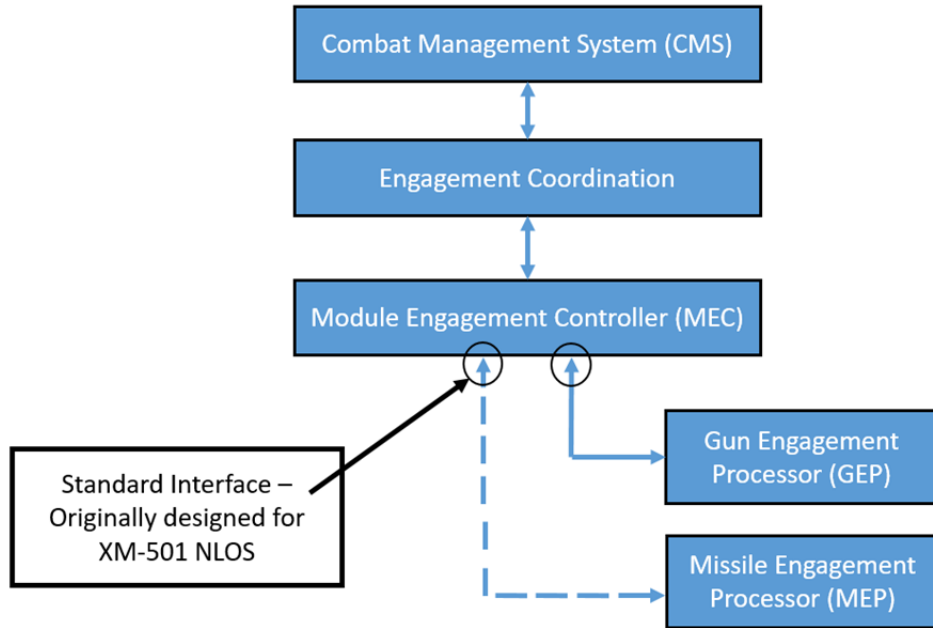


Figure 3. LCS Combat Management System with the Gun Module Integrated through a Standard Interface

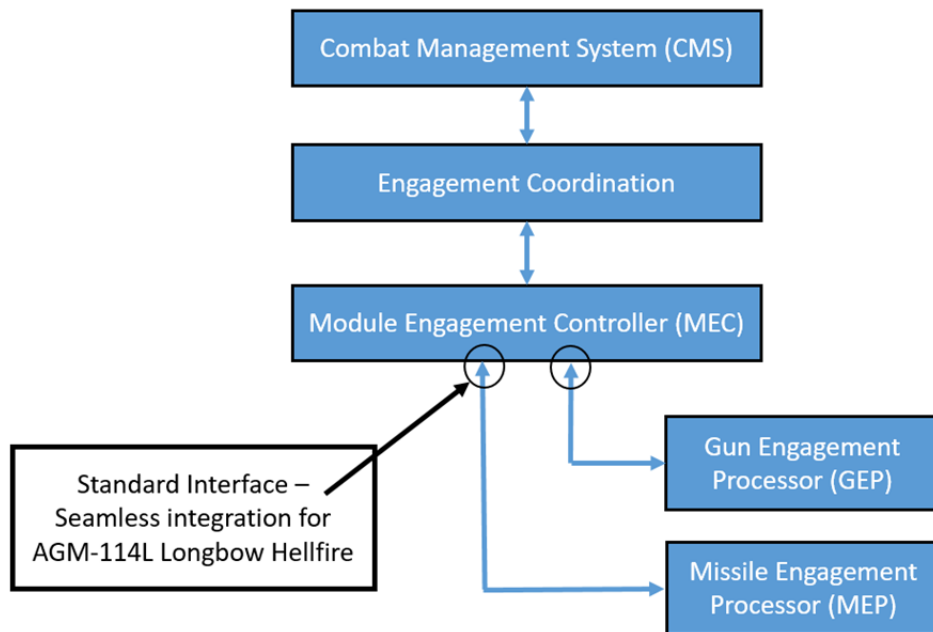


Figure 4. LCS Combat Management System with Missile and Gun Modules Integrated through Standard Interfaces

The use of a standard interface on the Module Engagement Controller forces contractors and vendors to code any potential future missile module to meet the specific parameters of that interface. This design prevents potential massive recoding costs to the entire Combat Management System architecture. Standard interfaces prevent the insertion of new coding into the CMS that could require middleware to link legacy code and new code throughout the life cycle of the CMS. By placing the burden on the contractor to build to a standard interface, the U.S. Navy is reducing long-term maintenance costs while achieving the following benefits of modularity noted by Sturtevant (2017): affordable alternate business model to lengthy and costly ship production work (in this case study, lengthy ship production equates to recoding requirements to the CMS); increased competition and innovation; cross-platform commonality (in this case study, LCS modules are to share cross-platform commonality with the new Frigate); rapid prototyping of payloads enables rapid acquisition of new capabilities; modular open systems enable acquisition agility; efficient technology refresh and incremental upgrades; and paces the threat (Sturtevant, 2017).

2. Flexible or Rigid Design for Weapons Modules

The advantage to modularity and the use of decoupled payloads allows a vessel to continuously evolve and grow as the threat and technology evolve and grow. Through the use of a standard interface, new modules can be designed in parallel with the platform, preventing extended yard periods for structural refit. Figure 5 illustrates a real options valuation decision tree for continued module technological growth and capability on LCS.

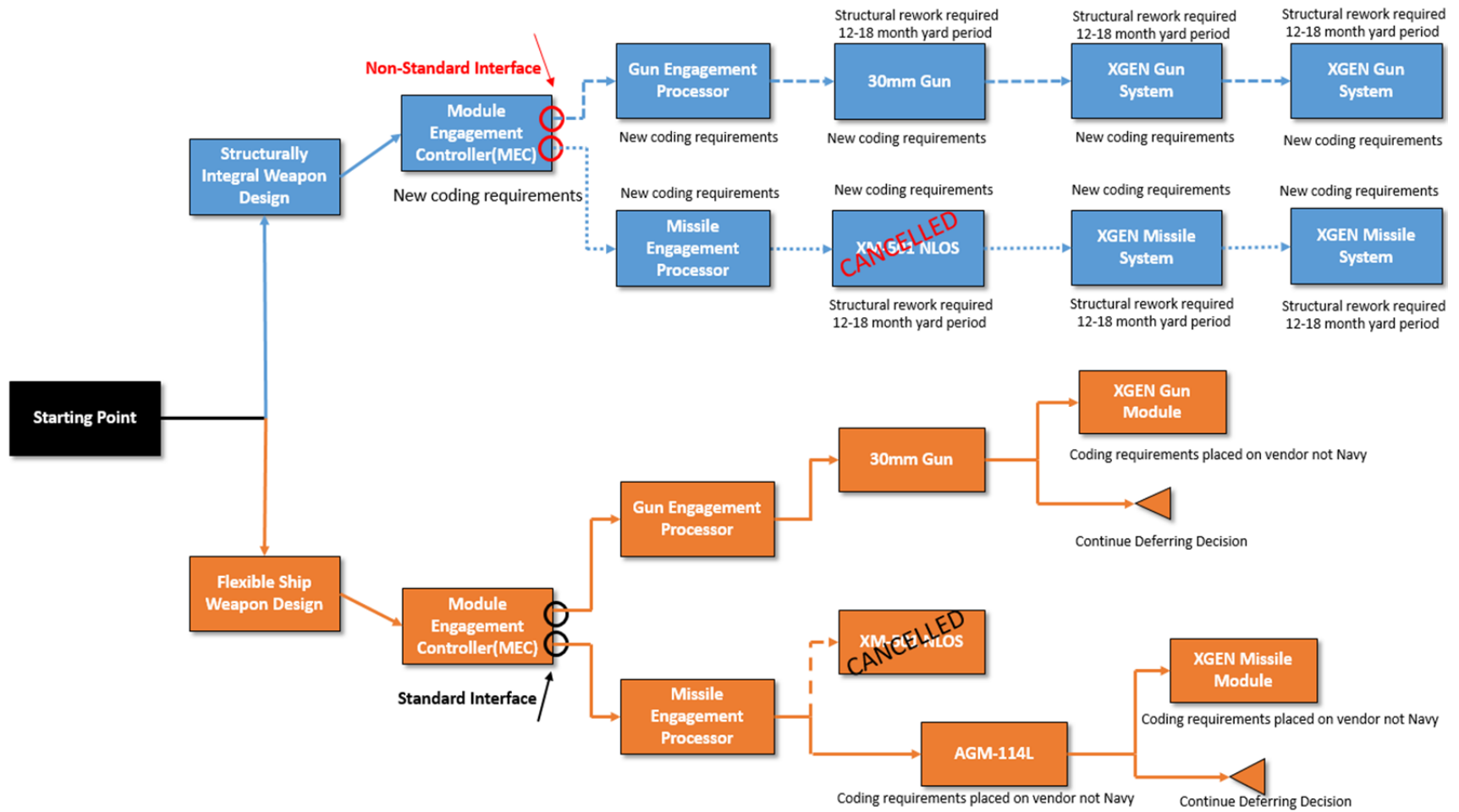


Figure 5. LCS Weapons Module Decision Tree

(1) Structurally Integral Weapons Design

If the design incorporates structurally integral weapons systems that interact with the Combat Management System through the use of non-standard interfaces, future upgrades will require prolonged yard periods (12–18 months) and extensive rewrite to the CMS architecture when the system is finally upgraded. Given the expense of ripping out and installing a new weapons system, the ship is less likely to experience as many upgrades as a flexible and adaptable ship. If the XM-501 Non-Line-of-Sight had been built as a structurally integral part of LCS, the U.S. Navy would have faced two decisions: continue and finalize development of a missile program the Army canceled at its own expense; or redesign the ship for a different structurally integral weapons system. Both options would carry significant increased contract costs and experience protracted time delays in future LCS production.

A more rigid design only allows upgrades to happen in series and not in parallel as illustrated by Figure 5. Weapons development in series does not offer the U.S. Navy the option to defer and wait as with the flexible design. Weapons development in series limits the U.S. Navy to one specific design that could potentially be technologically outdated by the time it is installed on every platform. Structurally integral weapons prevent a platform from rapidly evolving as the mission evolves, and subsequently the ship fails to meet its intended life cycle through extended maintenance costs and obsolete weapons technology.

Figure 6 illustrates the complicated recoding of the Combat Management System architecture that would be required when non-standard interfaces are used on systems that are structurally integral to the ship. Without the use of a standard interface, LCS would need to recode the CMS, Engagement Coordination, and the Module Engagement Controller in order for the new weapons system to interact with the Engagement Processor. Again, this could introduce middleware that poorly interacts with CMS architecture legacy code and could cause delays in the deployability of the system.

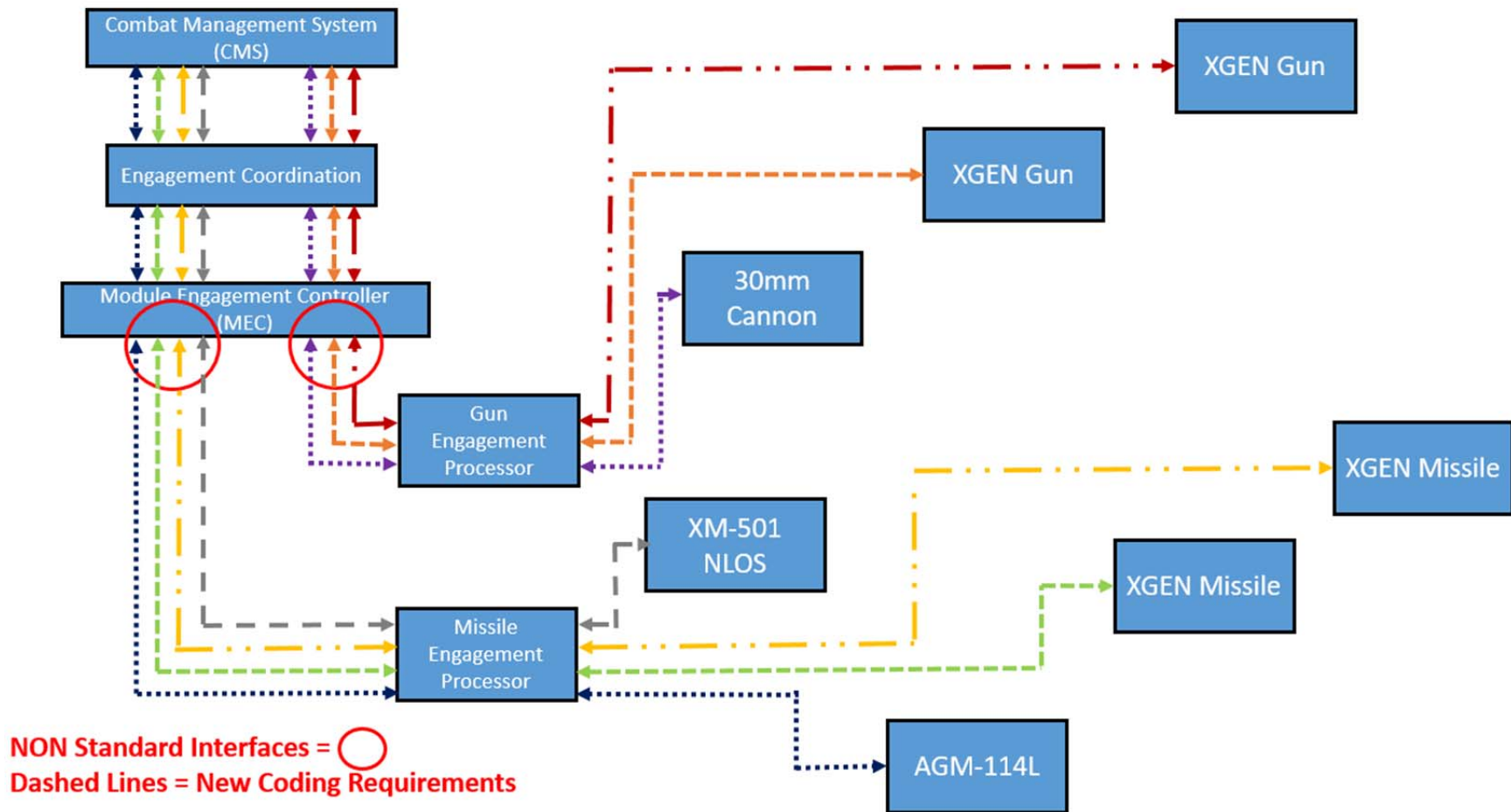


Figure 6. LCS Weapons Module Coding Requirements through the Use of Non-standard Interfaces

(2) Flexible Ship Weapons Design

Rigid, structurally integral weapons systems are expensive and time intensive to remove and replace. A flexible module design for the weapons system permits the payload to be developed in parallel to ship production, creating an environment where the platform is ready to receive weapons technology that mirrors the most current capabilities.

The decision tree in Figure 5 illustrates weapons module development in parallel. With NLOS cancelled, the U.S. Navy did not have to delay LCS production as it would have with a structurally integral vertical launch missile system. The “plug-and-play” standard interface allowed industry to innovate and compete to present the U.S. Navy with a new missile module, with the onus on the vendor to correctly code for smooth integration with the Combat Management System. When Raytheon’s Griffin B proved an unsuitable match for the missile module as the initial replacement for NLOS, LCS’s operational tempo was not hindered and a “better fit” solution was developed—the Longbow Hellfire.

Employing the tools of Real Options Valuation is evident in the flexible weapons design. Figure 5 presents the U.S. Navy with choices and decisions throughout the life cycle of the ship. Through the use of standard interfaces, the U.S. Navy can continue to use the current weapons module while simultaneously evaluating newer, more sophisticated alternatives. If the new alternatives do not meet the evolving threat or needs of the platform at the time, the U.S. Navy can defer the decision to integrate a new module until a later point. With a rigid design, there is no deferment option due to the structural overhaul required. Modularity facilitates rapid removal and replacement of a system with extremely limited down time. The benefits of standard interfaces are represented in Figure 7. Standard interfaces remove a substantial financial burden to the U.S. Navy by forcing the vendor to code the new weapons module to the existing CMS architecture and not the other way around.

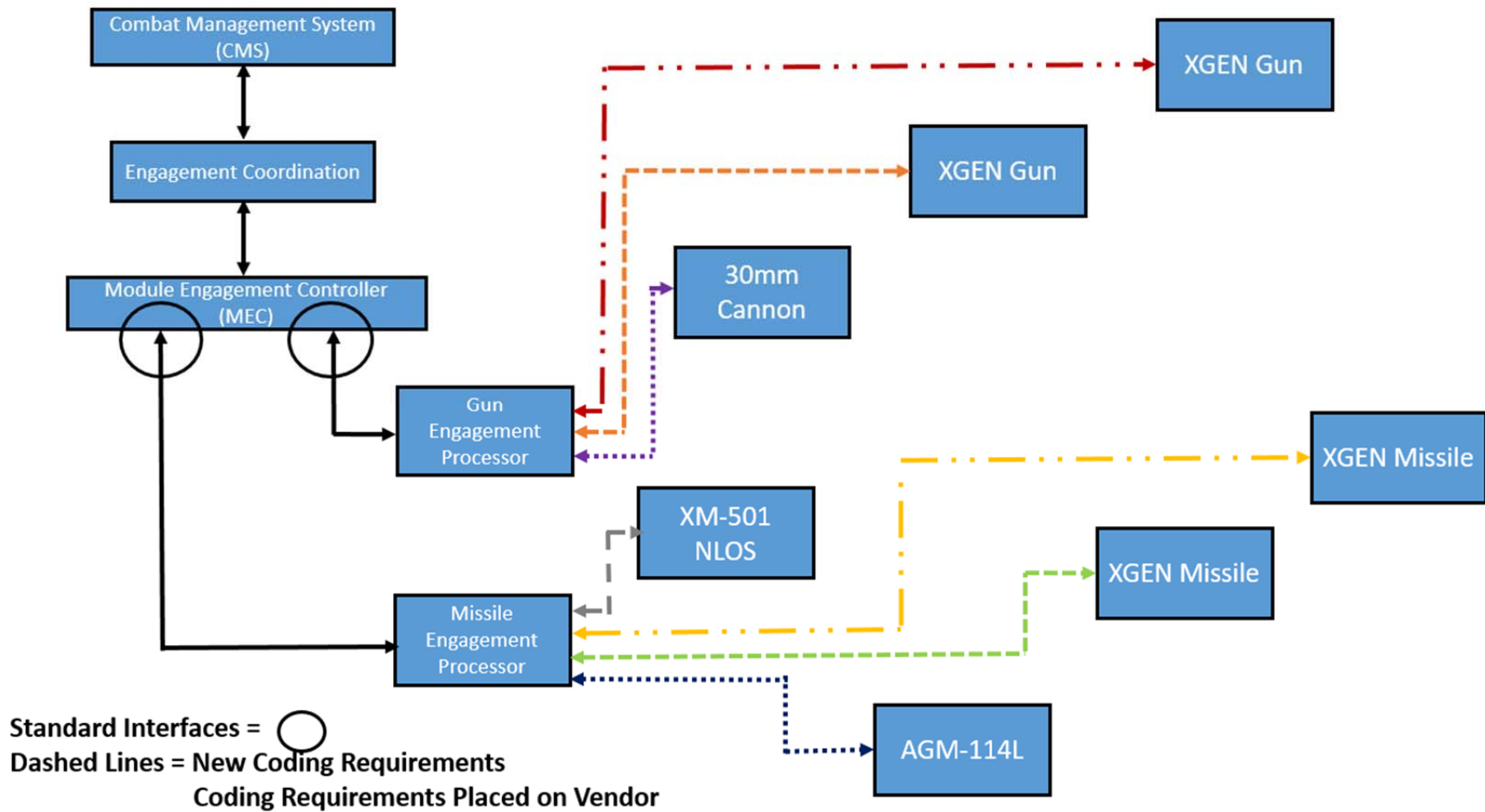


Figure 7. LCS Weapons Module Coding Requirements through the Use of Standard Interface

C. CONCLUSION

When the U.S. Army cancelled the XM-501 Non-Line-of-Sight modular missile program, the U.S. Navy was left without a missile module for the Anti-Surface Mission Module package for LCS. If NLOS had been structurally integral to the LCS ship design, LCS would have experienced significant and prolonged production delays, or immediate overhaul after production to rip out the NLOS structure and install the new missile system. In actuality, the cancellation of NLOS is a case study for why modularity works. Figures 3 through 7 highlight and illustrate the benefits of modularity: the ability to continuously develop and integrate a new module without extensive loss of operational deployability or prolonged and expensive yard periods. Table 1 is a summation of the benefits of using a flexible weapons module design versus a conventional, structurally integral weapons system.

Table 1. Flexible Ship Design versus Conventional Ship Design with Regard to Payload

	Flexible Ship Design	Conventional Ship Design
Platform decoupled from payload	✓	
Standard platform to payload interface	✓	
Rapid Reconfiguration	✓	
Allowance margins for modernization	✓	
Prolonged yard periods for payload upgrades		✓
Shorter yard periods for payload upgrades	✓	
Payload upgrades done in series		✓
Payload upgrades done in parallel	✓	
Vendor responsible for coding requirements to meet payload standard interface	✓	
Platform responsible for coding upgrades with every new payload		✓
Creates increased competition and innovation	✓	
Cross-platform commonality	✓	

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V. CASE STUDY 2—FLEXIBILITY AND ADAPTABILITY OF LPD-17

A. BACKGROUND

In January 2006, the U.S. Navy commissioned the first of 12 vessels in a new class of amphibious ship, USS *San Antonio* (LPD-17). Design plans for LPD-17 began in the early 1990s to replace “41 current and decommissioned ships, including the Anchorage (LSD-36) class of dock landing ships, the Newport (LST-1179) class of tank landing ships, the Charleston (LKA-113) class of amphibious cargo ships, and the Austin (LPD-4) class of landing platform/dock ships” (Hyde, 2016). The San Antonio class serves as the main expeditionary platform within an Expeditionary Strike Group (ESG), and the warship is used to “embark, transport, and land forces and their equipment and supplies for expeditionary warfare” (Hyde, 2016). LPD-17 is maintained by a crew of 374 personnel (Jane’s IHS Markit, 2017b) and can accommodate a Marine Expeditionary Unit (MEU) comprising 699 personnel (Balle, 2014).

The upgrades from LPD-4 to LPD-17 are substantial in both size and cost. The Austin class (LPD-4) had a displacement of 19,313.6 tons at full load (Jane’s IHS Markit, 2015), while the San Antonio class (LPD-17) has a full displacement of 27,447.6 tons (Jane’s IHS Markit, 2017b), a tonnage increase of 42 percent. The increase in tonnage came with a substantial price tag of approximately \$1.6 billion (Defense Industry, 2016) per ship, almost two times the original expected outlay of \$836 million per ship (Director of Operational Test and Evaluation, 2000) . Although the final cost per ship far exceeded the original cost estimation, LPD-17 adopted a flexible and adaptable design that resulted in a “modern, sea-based platform that is networked, survivable, and designed to operate with 21st weapon systems” (Balle, 2014).

B. FLEXIBLE AND ADAPTABLE DESIGN FEATURES

The design approach for the San Antonio class incorporated a multitude of features essential to building flexible and adaptable ships capable of meeting service-life expectancy. Recognizing the advancements to be made in vertical lift and Advanced Assault Amphibious Vehicles (AAAVs), LPD-17 was designed for future growth margin to accommodate new technologies and platforms working from the well deck and flight deck. Additionally, LPD-17 was designed with larger main passageways that could facilitate the rapid movement of battle-dressed Marines, and assist with the removal and replacement of technological equipment such as racks and servers. Finally, in an effort to ensure that LPD-17 could be capable of distributed lethality, LaGrone (2016) noted that weight and space were reserved for the MK-41 Vertical Launch System (VLS) in the bow of every San Antonio class ship (LaGrone, 2016).

1. Growth Margin

Anticipating technological advances in vertical lift, the San Antonio class was designed with growth margin to accommodate future vertical lift platforms like the tiltrotor MV-22 Osprey. The MV-22 is a V/STOL aircraft, with the ability to perform vertical take-off and landings, or short take-off and landings. This type of platform requires the flight deck to be rated for the extremely high heat signature generated by the V/STOL capability. In anticipating the production of a future vertical lift aircraft with V/STOL parameters, LPD-17 would have referenced the heat signature ratings used for the AV-8B Harrier, the other V/STOL aircraft in Marine Corps inventory.

At the time of LPD-17 design, the MV-22 was in initial design phase. Adding the tonnage required to rate the flight deck appropriately was a risk the Navy accepted in the design approach. By anticipating the need to launch and recover V/STOL aircraft on the flight deck at the time of production was a long-term cost-savings measure that put additional cost on front-end production. Had the San Antonio class not anticipated future technological advances in tiltrotor

aircraft, each platform stood to lose significant operational deployment time for extended and expensive yard periods to refurbish the flight deck when the technology became available. Once refurbished, the ship would then need to re-certify the flight deck before deployment, losing additional operational time.

Designing for future capabilities was not limited to the flight deck. The size, space, and weight reserved for the well deck is substantially larger in comparison to the Austin class. As catalogued in Jane's (2017b), the well deck is large enough to support two air-cushioned landing craft (LCAC), or one utility landing craft (LCU) capable of carrying the M1 Abrams tank ashore (Jane's, 2017b). The well deck can also store/support 14 Expeditionary Fighting Vehicles (EFVs) or Amphibious Assault Vehicles (AAVs) (Jane's, 2017b). According to Cavas (2016), the Marine Corps is moving forward with design and development of a new Advanced Amphibious Assault Vehicles (AAAV), but in the interim will retrofit its existing inventory to bridge the gap. He noted the retrofit includes "upgrading the 392 AAV74A1s with an extensive survivability upgrade intended to keep the vehicles effective in an IED environment...and installed 18 new shock-mitigation seats, replacing the benches in older AAVs" (Cavas, 2016).

These upgrades amount to additional weight on the vehicle, which directly translates to an increased load that the well deck must be able to support, multiplied by at least 14 vehicles. If the LPD-17 well deck had not been designed with weight and space reserved for future, heavier, advanced technology, the Marine Corps would not be able to effectively protect its Marines and would severely diminish the capabilities of the MEU. By designing an expeditionary platform that incorporated growth margin into the design of the ship, the San Antonio class can more readily maintain combat relevancy throughout its life cycle.

2. Planned Access Routes

The San Antonio class design incorporated planned access routes by incorporating larger main passageways and larger ladderwell openings

throughout the ship to accommodate ease of movement. Traditional, standard-size passageways found on the Austin class of LPDs had proved to be both bottlenecks and ineffective in the movement of combat-loaded Marines. By designing passageways that allowed freedom of movement in a high-stress, high-tempo environment, Sailors and Marines could focus on the task at hand. The psychological effects of creating a more readily accessible space by removing the stresses incurred in small, tight cramped quarters can contribute to an expeditionary force more relaxed and better prepared to fight.

These larger, planned access routes benefit both personnel and technology. By creating wider main passageways, information technology (IT) equipment can be removed and replaced without having to enter extended yard periods to facilitate updates and upgrades. As the U.S. Navy looks to replace Raytheon's Shipboard Wide Area Network (SWAN) onboard the San Antonio class with the Consolidated Afloat Network Enterprise System (CANES), the larger main passageways can facilitate the rapid removal and replacement of the SWAN servers with the CANES servers. CANES is designed to undergo software refresh every two years and hardware refresh every four years. If the planned access routes did not exist, then the ship could potentially experience a minimum of 10 extensive yard periods during the course of its service life to accommodate the technology refresh. The planned access routes within a flexible and adaptable ship design allow for rapid reconfiguration of IT equipment, and future designs should recognize the need to place IT equipment in readily accessible areas located on the planned access routes.

3. Weight and Space Reservations—VLS

For a surface combatant to achieve service-life expectancy, it must be able to evolve and keep pace with the threat. Despite cost overruns, the San Antonio class reserved weight and space for future installation of the MK-41 VLS in the bow of all 12 ships. Each ship should could potentially install two "8-cell modules designed to accommodate a wide variety of missiles" (Seck, 2017). The

choice to reserve space and weight specifically for the MK-41 VLS was a strategic decision based on the success of the same modular missile cells currently installed on Arleigh Burke class destroyers and Ticonderoga class cruisers. Should the system be installed at a later point in time, LPD-17 through LPD-27 have VLS trunk access and cooling capabilities prepositioned.

The VLS represents an allowance margin for modernization. Had the weight and space, access trunk line interface, and cooling capabilities not been reserved and installed at the time of production, the San Antonio class would have lost the ability to potentially provide distributed lethality for Marines going ashore without a costly and lengthy overhaul that would have resulted in a significant loss to operational deployment time. As recently as December 2016, Commandant of the Marine Corps, General Robert Neller, had been pushing for the Navy to explore the option of installing VLS on the San Antonio class and equipping it with Tomahawk missiles to provide the Marines with longer-range fire support (LaGrone, 2016; Seck, 2017).

Figure 8 represents the current decision tree for LPD-17 through LPD-27. Given a standard interface at the VLS trunk access point, the San Antonio class can readily accept VLS into its Combat Management System with little to no recoding required. Given the modularity of VLS and the standard interface, future VLS systems can be developed in parallel, driving industry competition and innovation. As a decoupled payload, the coding requirements to seamlessly integrate with the VLS standard interface fall on the vendor, a long-term cost savings for the U.S. Navy. Additionally, the ability to provide longer-range fire support could potentially reduce the number of escort ships (cruisers and destroyers) required within the ESG, reducing the burden on other platforms or possibly reducing the total number of ships required to meet national security directives. Ultimately, the San Antonio class can defer installing any type of VLS if it is determined that that form of strike capability is not required to keep pace with the evolving threat.

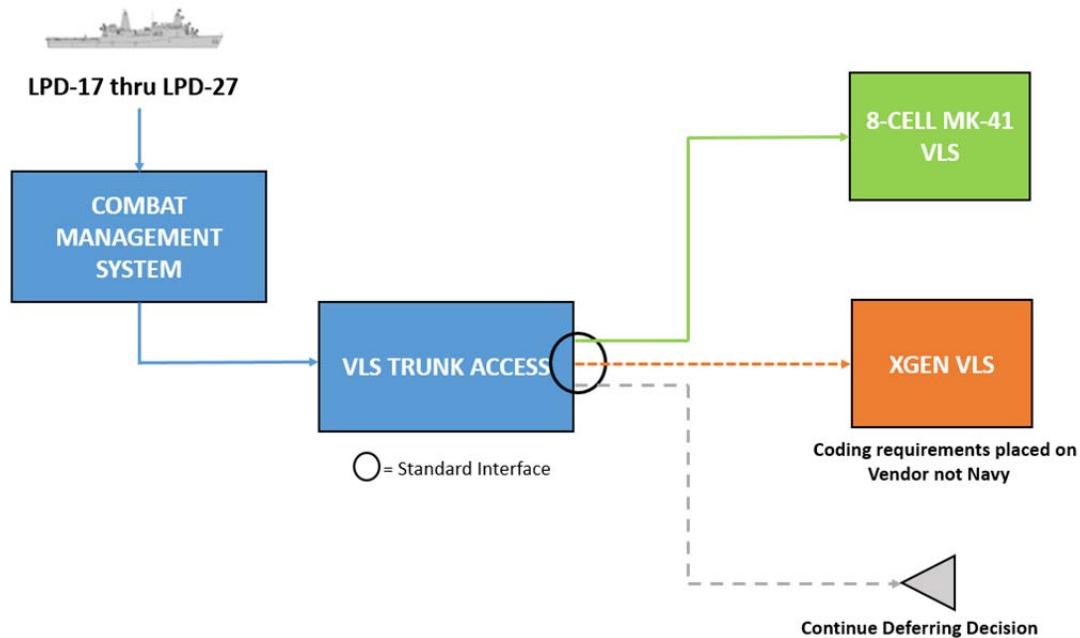


Figure 8. LPD-17 through LPD-27 VLS Decision Tree

C. LPD-28 DESIGN DECISIONS

As the U.S. Navy begins to enter the design phase for the upcoming class of amphibious transport docks known as LX(R), the last ship in the San Antonio class (LPD-28) has the unique opportunity serve as a bridge for future LX(R) requirements (Rogoway, 2016). Ordered but not yet in production, LPD-28 allows ship designers to build a more flexible and adaptable ship that will have cross-platform commonality with LX(R). The additional design costs incurred by LPD-28 serve as long-term savings cost for LX(R) by reducing uncertainty and risk.

One potential design change for LPD-28 would be the installation of the AEGIS Combat Management. AEGIS provides “a higher level of defensive capabilities, independence, and situational awareness” and if installed on LPD-28, the ship could “operate independent of, and in better concert with the Navy’s already over-tasked AEGIS equipped destroyers and cruisers” (Rogoway, 2016). There is little risk associated with the installation of an AEGIS Combat Management System. A proven capability, it is currently operational on 62

Arleigh Burke destroyers and 22 Ticonderoga class cruisers (Rogoway, 2016). If equipped with AEGIS, LPD-28's mission flexibility increases with the added ability to operate in moderate to high threat combat environments by transiting independently of AEGIS equipped escorts (Rogoway, 2016).

Moving forward, the design approach for LPD-28 would benefit from examining all the available options and creating a portfolio to optimize flexibility and adaptability within a constrained budget. Integrated Risk Management and Real Options Valuation would provide the design team the opportunity to view potential long-term cost savings by investing in up-front growth margins for modernization and standard interfaces that allow for more rapid technological advances. One option would be to equip the VLS trunk access with multiple standard interfaces that directly translate to the AEGIS Combat Management System. One interface accepts the firing sequence for Tomahawk Land Attack missiles and one interface accepts the firing sequence for the Evolved Sea Sparrow surface-to-air-missiles. Both standard interfaces place the cost of coding on the vendor for seamless integration with AEGIS.

Figure 9 represents three possible design options available for LPD-28: installation of AEGIS and VLS trunk access, AEGIS installation, or VLS trunk access. The first option would prove to be the most costly design, but would reduce long-term maintenance costs and provide cross-platform risk reduction for LX(R). Figure 10 illustrates the added benefits of distributed lethality if LPD-28 was equipped with the AEGIS Combat Management System with standard interfaces to accept multiple VLS modules.

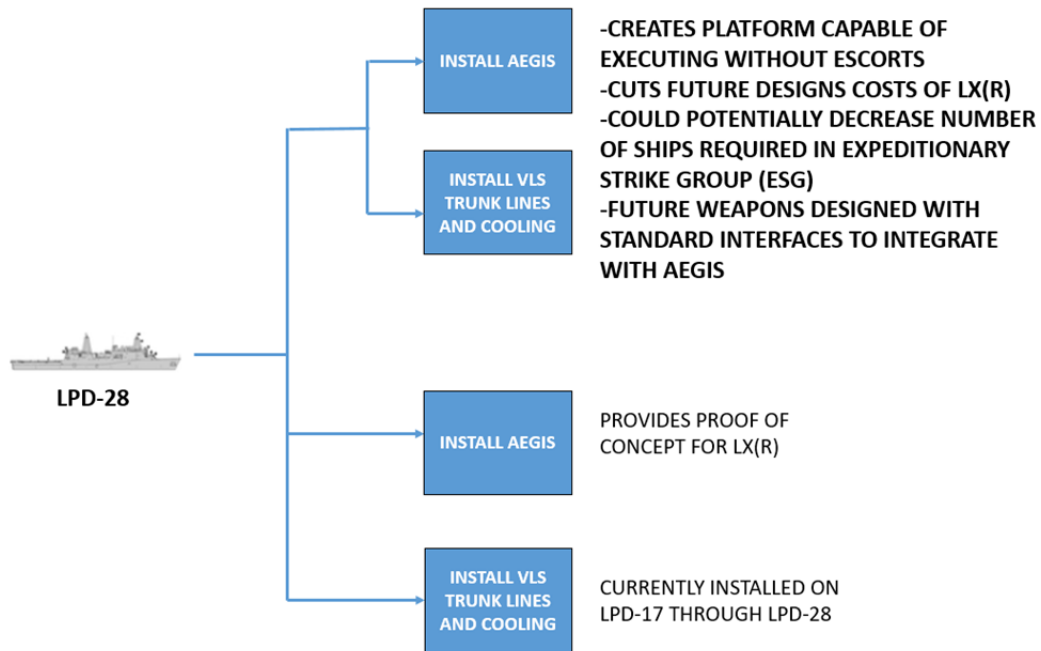


Figure 9. Possible Configurations for LPD-28

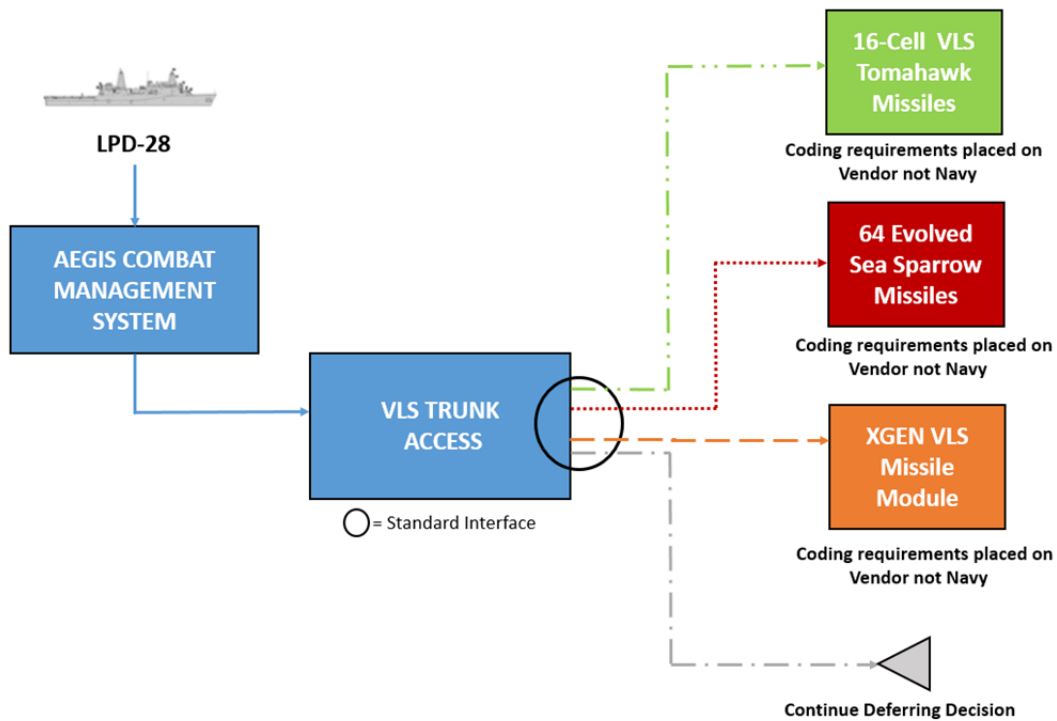


Figure 10. LPD-28 with AEGIS Combat Management System

D. CONCLUSION

The San Antonio class of amphibious transport dock ships was designed with weight and space reservations that created allowance margins for modernization. The design approach anticipated technological advances in vertical lift and well-deck capabilities, which resulted in a combat relevant platform capable of accepting new equipment as it became available. Planned access routes assist with ease of movement, increase operational readiness, and allow for the rapid removal and replacement of technological equipment. Finally, As LX(R) enters the design phase, LPD-28 can assist with assessing the costs of installing different weapon modules and combat systems that can increase the multi-mission capabilities of LX(R). Table 2 summarizes the added benefits of designing and building modular, flexible, and adaptable ships.

Table 2. Flexible and Adaptable Attributes of San Antonio Class

	LPD-17 through LPD-27	LPD-28
Weight and Space Reservations	✓	✓
Allowance Margins for Modernization	✓	✓
Decoupled Payloads	✓	✓
Distributed Lethality Enabler	✓	✓
Planned Access Routes	✓	✓
Cross-Platform Commonality	✓	✓
VLS Trunk Access and Cooling Requirements	✓	
Potential for AEGIS Combat Management System		✓
Potential Stand-Alone Strike Platform		✓
Potential VLS Capabilities for Multiple Missile Modules		✓

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VI. CONCLUSION

The traditional approach to designing surface combatants has left the U.S. Navy with a fleet of warships that exhibit little to no margin for future modernization and without the ability to rapidly reconfigure. To meet future demands, keep pace with the threat and maintain combat relevancy, the U.S. Navy needs to transition away from the traditional, rigid design of surface combatants and instead incorporate adaptability and flexibility in the design. As seen with the Danish, German, French, Italian and Australian navies, surface combatants with multi-mission capability and decoupled payloads are vital to the long term sustainability of their navies and their ability to effectively operate as a deep water navy.

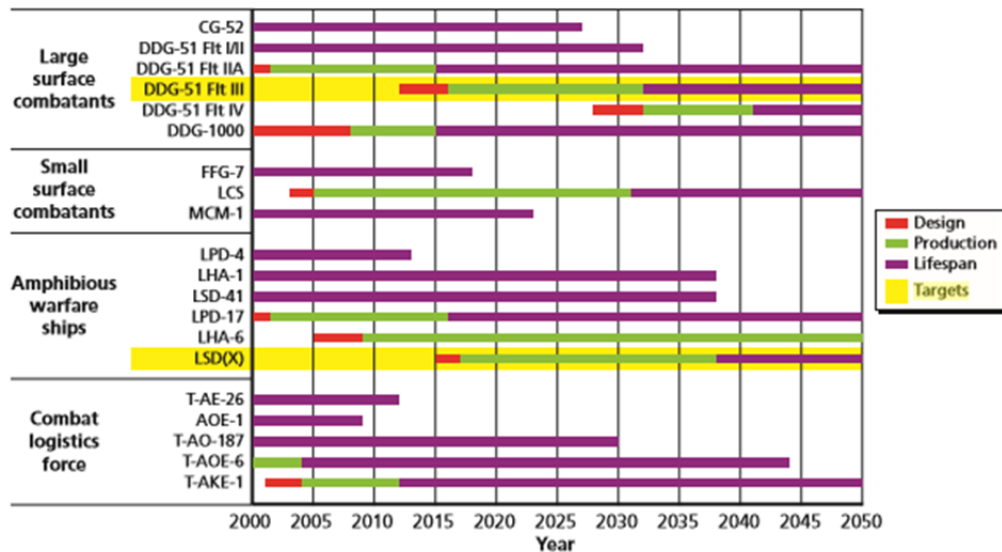
With rising long-term maintenance costs and shrinking defense budgets, any new class of surface combatant must be designed with a multi-mission capability that will see them through a 40-year expected service life. Flexible and adaptable ship designs encounter higher initial outlays, but allow for shorter, cheaper, and less intrusive maintenance periods over the service life of the vessel. Modular payloads with standard interfaces facilitate parallel payload development, place the cost of integration on the vendor, and ensure the latest and most technologically advanced equipment is available to the warfighter. By designing warships with reserved weight and space for future technological upgrades and advanced weapon systems, the surface combatant fleet can rapidly reconfigure and continue to fight with little to no loss in operational deployment cycles.

If the U.S. Navy is going to remain the world's preeminent naval sea power, it will have to approach future surface combatant designs with the tenets of flexibility and adaptability as integral design elements to maintain combat relevancy. Decoupled payloads from platforms, standard interfaces, planned access route, rapid reconfiguration, and growth allowance for modernization are the cornerstones of building a sustainable fleet capable of pacing the threat while seamlessly maturing with technological advances. Failure to recognize the need to shift from the traditional approach of rigid ship design to a more open and flexible

architecture will drain the defense budget and leave the U.S. Navy with a less than capable and aging fleet of warships.

A. FUTURE SURFACE COMBATANT AREAS OF STUDY LX(R)

One area of future study with regard to building flexible and adaptable ships will be the design, cost, and production of the LX(R). A recently published RAND Corporation study on the benefits of building flexible and adaptable ships highlighted LX(R) as one of only two platforms (targets) with a production cycle set to begin in the next decade whose design phase has the opportunity to capitalize on the benefits of a multi-mission, flexible, and adaptable ship design (Schank, Savitz, Munson, Perkinson, McGee, & Sollinger, 2016). LX(R) entered the preliminary design phase in 2015 and is expected to begin production in FY 2020 (Eckstein, 2015c), with projected production dates and service-life expectancy as highlighted in Figure 11 (Schank et al., 2016).



SOURCE: Based on data from Deputy Chief of Naval Operations (Integration of Capabilities and Resources) (N8), Report to Congress on the Annual Long-Range Plan for Construction of Naval Vessels for FY2014, Washington, D.C.: Office of the Chief of Naval Operations, May 2013.
 RAND RR096-5.1

Figure 11. Targets for Potential Modular/Flexible Ship Design.
 Source: Rand (2016).

The U.S. Navy has the opportunity to take the lessons learned from the flexible and adaptable build of the San Antonio class and apply them to the design of the future amphibious dock ship, LX(R). Eckstein (2015c) noted that by capitalizing on the hull form of LPD-17, LX(R) will be able to reduce cost and risk by designing a ship on an already proven hull form and propulsion system (Eckstein, 2015c). This substantial cost reduction allows the ship design approach to focus on needed combat systems and technological advances while simultaneously increasing modular aspects of the design. By examining the final engineering and redesign costs of LPD-28, a comprehensive analysis can be conducted to determine the cost-saving benefits of building larger ships with weight and space reserved for future technological advances in comparison with the final cost production of the LX(R).

B. INFLUENCING TECHNOLOGICAL TRENDS IN FUTURE FLEXIBLE AND ADAPTABLE DESIGN

The 2016 RAND Corporation study titled “Designing Adaptable Ships” focused on the need for the U.S. Navy to design modular and flexible ships capable of evolving to meet unknown adversaries in the future. The study highlighted the importance of building future surface combatants with flexible mission bays, additional power and cooling, extra space and volume, accessible equipment, and variable crew space in order for the ship to remain relevant over the course of its service life (Schank et al., 2016). The authors advocate that future ship designs may need to incur higher initial outlays to support bigger vessels that provide the “additional volume to change interface boundaries; increase the number of personnel; and add power/ cooling, and/or bandwidth as needed” (Schank et al., 2016).

To achieve a fleet of sustainable flexible and adaptable ships, the authors anticipated “four major technological trends that would likely influence naval operations over the coming decades” (Schank et al., 2016). By acknowledging these trends, the U.S. Navy can build a multi-mission fleet with reserved weight, space, and power to ultimately integrate advanced technologies that allow a

surface combatant to rapidly transform to meet emerging needs. The four expected trends are:

- The increasing use and effectiveness of off-board unmanned systems
- Growing abilities to use the electromagnetic spectrum as a weapon
- Enhanced capabilities for long-range targeting
- The increasingly networked nature of the battlespace (Schank et al., 2016)

C. FUTURE AREAS OF STUDY OUTSIDE OF SURFACE COMBATANTS

Modularity is not limited to the design of surface combatants. One future case study would involve the lack of multi-mission flexibility in Sikorsky's CH-53K heavy lift helicopter design. According to Defense Industry (2017), the CH-53E Super Stallion is the U.S. Marines' current heavy lift platform, but it is rapidly aging and comes with an estimated \$20,000 per flight hour cost ratio (Defense Industry, 2017).

The U.S. Navy also flies an aging variant of the H-53, the MH-53E Sea Dragon, capable of heavy lift and Airborne Mine Countermeasures (AMCM). The major modular difference between the MH-53E variant and the CH-53E variant is the installation of an additional hydraulic system to facilitate the AMCM mission. The current CH-53K design did not incorporate the additional hydraulic system to make the platform capable of both heavy lift and AMCM.

Priced at \$131 million apiece, the U.S. Marine Corps is set to buy 200 heavy lift helicopters (Schogol, 2017). If an Engineering Change Plan (ECP) been developed in the early design phase to incorporate the additional AMCM hydraulic system at an additional up-front cost, final purchase price and long-term maintenance and sustainment costs could have been significantly reduced. With a rapidly aging MH-53E fleet, the new CH-53K would have provided the Navy the opportunity to consider the future purchase of about 40–45 aircraft to replace the existing MH-53E. Additionally, with unknown and emerging worldwide

threats, a multi-mission aircraft has greater international sales appeal. This case study could utilize cost data for the existing design plans for the CH-53K and use Real Options Valuation and Monte Carlo simulation to determine the long-term cost savings if weight and space had been reserved for future installation of the additional AMCM hydraulic system. A comparative study would highlight the reduced costs in designing for future capabilities up front as compared to expensive re-design and retrofit after final production has begun.

D. FINAL RECOMMENDATIONS

Modularity in a flexible and adaptable design drives innovation and competition, allowing the U.S. Navy to develop the world's most sophisticated fleet of surface combatants. Flexible and adaptable ships allow any navy to do more with less through rapid reconfiguration, standard interfaces, and decoupled payloads. With cross-platform commonality, long-term maintenance costs are driven down and surface combatants can reach service-life expectancy while retaining combat relevancy. To achieve a flexible and adaptable fleet of surface combatants, the U.S. Navy needs to incorporate the theories of Real Options Valuation, Knowledge Value Added and Integrated Risk Management to assist in future design decisions. Through the use of Monte Carlo simulation and portfolio optimization, the U.S. Navy can begin a design process that will allow a future surface combatant to affordably transform over its service life, remain combat relevant, and stay within the targeted life cycle maintenance budget.

This thesis highlighted two case studies where flexibility and adaptability in the design of a surface combatant were vital to the warship's production and its ability to remain operationally relevant. The first case study highlighted the advantage of using modular missile payloads on LCS. Modularized weapons payloads prevent long and extensive yard periods when yielding new payloads, and this plug-and-play environment allowed LCS to continually meet the operational deployment cycle while technologically maturing. LPD-17 represents the U.S. Navy's first attempt at a larger, more sophisticated flexible and

adaptable ship. Moving forward, LPD-28 can serve as the bridge for the future development of LX(R), ensuring the U.S. Navy designs the most technologically advanced and capable platform, while simultaneously reducing cost and risk. If done correctly, the design of LX(R) could potentially build a platform capable of self-defense and power projection ashore without the assistance of an escort. The ability to transit independent of an escort reduces the total number of ships in inventory, allowing future funds to be reallocated to other platforms. In conclusion, the U.S. Navy must adopt a new approach to ship design, moving away from traditional rigid design and into a realm of flexible and adaptable ships that can keep pace with evolving threats and rapidly adapt to future unknown adversaries.

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