Flexibility in Early Stage Design of US Navy Ships: An Analysis of Options

by

Jonathan Page

B.S., Systems Engineering, US Naval Academy, 2002

Submitted to the Engineering Systems Division and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Engineering and Management
and
Naval Engineer

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Abstract

This thesis explores design options for naval vessels and provides a framework for analyzing their benefit to the Navy. Future demands on Navy warships, such as new or changing missions and capabilities, are unknowns at the time of the ship's design. Therefore, ships often require costly engineering changes throughout their service life. These are expensive both fiscally – because the Navy pays for engineering and installation work – and operationally – because either a warship cannot carry out a desired mission need or is carrying out a mission for which it was not initially designed. One method of addressing uncertainty in capital assets is by imbedding flexibilities in their architecture.

The thesis offers early stage design suggestions on flexibilities for naval platforms to incorporate pre-planned repeats of the platform with new or different missions. A conceptual platform created – the SCAMP – includes each of these suggestions in its architecture. Then, the thesis uses an analysis framework similar to real options to evaluate the value of including these expansion options in early stage design versus traditional design methods and their products. The analysis uses a version of the MIT Cost Model for early stage ship design to determine acquisition and life cycle costs. The model was modified to support this analysis by allowing a simulation of possible mission changes with their severity distributed stochastically over a realistic time horizon. Subsequently, the model calculates these effects on life cycle cost.

The most important result is the value of the framework for evaluating these managerial options. This framework can be extended to the subsystem level or to the system-of-systems level. In this application, the model predicts that, on average, a flexible platform should not only cost less to build, but also reduce modernization costs by 9% per ship over its life cycle. Therefore, counter-intuitively, building a less-capable ship with the flexibility to expand capabilities or switch missions actually provides greater expected utility during its service life.

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From Naval Sea Systems Command, Dr. Norbert Doerry, Technical Director of the Technology Group, and Dr. Phil Koenig, Director of Industrial and Economic Analysis Division, also provided valuable sounding boards and support throughout the thesis-writing process. This document would not have been possible without their time, interest, background, experience, and knowledge.

Biographical Note

Jonathan Page is an active duty Lieutenant in the US Navy. His previous education includes a Bachelor’s degree in Systems Engineering from the US Naval Academy.

Upon graduating from the Naval Academy, Jon was commissioned as an Ensign and entered the Surface Warfare Officer community. He served onboard the USS Stethem (DDG 63), a guided-missile destroyer. As the Communications Officer, Jon led twenty Information Systems Technicians. His division was responsible for all on- and off-ship communications across the frequency spectrum, including the shipboard Local Area Network (LAN) and controlled material system.

After earning his Surface Warfare qualification, Jon transferred to the Engineering Duty Officer (EDO) community. He reported to Southwest Regional Maintenance Center, a repair facility responsible for the maintenance of over 40 ships. Jon managed $10M, 6-month projects for four ships’ Phased Maintenance Availabilities, overseeing cost, schedule, and performance of contractors and in-house Navy repair shops completing ship maintenance. He also led two Lean events and consulted on several others to earn his Lean Green Belt under the Naval Sea Systems Command’s qualifying procedures.

Upon completion of his graduate studies, Jon will report to the DDG 1000 program office in Washington, DC to lead the systems integration efforts.

Table of Contents

Table of Figures

List of Tables

1.0 Introduction

Over the past fifteen years, the Navy's Total Obligation Authority (TOA) and acquisition costs have more than doubled and its ship maintenance budgets have almost tripled, but the overall operating budget for ships has increased less than 50% (U.S. Navy 2010). Especially in light of the United States' recent economic woes, Federal and Department of Defense (DoD) budgets cannot continue to grow at these rates and maintain the current levels of capability for the armed forces. Further exacerbating this fiscal situation is the trend of the technology required to keep ahead of potential adversaries; platforms and weapon systems are only getting more complex with time, and, naturally, are more expensive. These circumstances prompted the ideas for this thesis and their timeliness and value.

The primary motivation behind this investigation is to hypothesize and test various design considerations for naval ships that can save the US Navy money and help shrink or maintain the current budget. There are, of course, operational measures that can be taken after delivery of the ship to help reduce the budget, including: operating at slower speeds to cut down on fuel consumption, attacking logistics trails and the plethora of uncommon components throughout the various naval platforms, using simulations and online trainers instead of steaming hours, and crew-size-related initiatives currently taking place. These are reasonable measures to take for post-delivery platforms, and can reduce the operating budget for ships. However, these measures are taken after delivery of the ship to the fleet, a time when the Navy is burdened with the ship delivered and any design or mission changes are more expensive.

This thesis proposes that flexible architectures can be implemented starting in the early stage design of a vessel and conveyed through construction and delivery, providing unknown or unrealized capabilities to the operators and maintainers of the vessel through its entire life cycle. Flexible architectures will make it easier for operators and maintainers to capitalize on changing missions and requirements instead of assuming an additional burden – either operationally or fiscally. These architectures and embedded options will become more valuable the more a system or subsystem changes throughout the lifecycle (within certain reasonable design and mission-change constraints).

This flexible approach is advantageous because the uses of combatant type ships tend to digress from the original intent of the platforms, especially later in their service life. The purpose of a ship originates in the Initial Capabilities Document (ICD), which is developed in the early stages of a ship's life – years before construction begins. However, the operational environment the ship will support inevitably changes after that document is written, after the design finishes, after construction finishes, and certainly after 15 or 20 years of service. A quick means of making this point begins by assuming the average life of a ship to be 30 years. Within that timeframe, the Navy has added or changed several missions, including: Ballistic Missile Defense (BMD), strike capabilities (with the Tomahawk Missile, for instance), and several new Information, Surveillance and Reconnaissance (ISR) missions. How many more needs will be added or changed to the Navy's ever-growing mission profile over the next 30 years? Even now, one can see a growing influence on design to add capabilities for launching and recovering Unmanned Aerial Vehicles (UAV), Unmanned Surface Vehicles (USV), and Unmanned Undersea Vehicles (UUV). Ships designed and built more than a decade ago have insufficient architecture for adding these additional capabilities without a significant amount of engineering work and ship modification.

1.1 Thesis Outline

Analyzing options in warships first requires background information to better understand the environment in which warships are designed. Chapter Two describes the current Navy design practices, including current 'flexibilities' the Navy builds into their platforms. Then, it discusses reasons why those practices may not be recognized as options and introduces better ways to think about incorporation of flexibility in future designs. Chapter Three then presents the analysis framework; describing its typical aspects and its roots in Net Present Value (NPV) and financial options and the general mechanics of options valuation. The chapter also reveals why this analysis requires a new framework: one based on ROA but also fundamentally different.

Then, Chapter Four presents the analysis of early stage design decisions in the options framework. First, it recommends characteristics for an example platform that is designed with changing missions in mind, and then it suggests how to adapt to them either through modified repeat designs or through embedded modules. The documentation for the design of the platform

– called the SCAMP – resides in the 2N program offices at MIT, and is available upon request. Second, the chapter explains the modified MIT Cost Model for early stage ship design that is used for evaluating these options against the inflexible baseline ship. Next, the chapter presents the results: in all cases where a flexible platform is expected to provide value over an inflexible one, the Navy benefits both operationally (increased capability) and fiscally (less money spent on modernization of the platform), on average. Finally, an analysis tests the robustness and sensitivity of the model and framework by performing a full factorial (2^6) design of experiments that changes the inputs and assumptions of the model.

Chapter five summarizes the entire process, provides insights gained, and offers areas of further study to help transition this method to being the state-of-the-practice for US Navy shipbuilding programs.

2.0 Background

This chapter provides a foundation of the Navy processes and current state of the practice for Naval ship design. This background intends to give an understanding and appreciation for the complexities of the ship acquisition process and the transition of the design into a program of record that eventually lets a contract for construction. Further, this information provides the context in which flexibility offers part of the solution to the budget difficulties already revealed. This discussion starts with the complexities of the cost of a ship, and what, precisely, that entails. Then, after discussing the general design process and timeline for US Navy shipbuilding, the chapter reveals the current instances of flexibility designed into the architecture of vessels. Subsequently, it offers some insight on why these may not necessarily be seen as options and how the ship design community can better recognize them.

2.1 Costs of Naval Ships

Discussing the costs of a naval vessel is not a straightforward proposition, because there are several ways to describe the cost of a ship. Most often, people think of the cost of the ship as its value, akin to the value of any other asset that a company in another industry would track for balance sheet and depreciation purposes. This cost or value usually associates to the Shipbuilding and Conversion (SCN) dollars spent on a specific vessel. For example, for FY11, the Navy requested $3.4B for two Virginia class submarines, which, when added to the $1.9B already spent on advance procurement activities, brings those two submarines to an acquisition cost of about $2.7B each (U.S. Navy 2010). However, a ship uses several other appropriations categories over its lifecycle, so this $2.7B does not capture the total cost to bring a Virginia class submarine into the Fleet and operate it for 30 years.

Even before the acquisition of a ship, the Navy spends some Research, Development, Test and Evaluation (RDT&E) money to develop early designs and subsystems that may go into the platform. In many cases, the Navy spends this money concurrently with ship construction costs. Further, after ship construction and delivery, the vessel incurs Operations and Maintenance (O&MN) costs through its service life. Some vessels even incur Military Construction (MILCON) costs if support facilities specific to that vessel need to be built. The Navy Center for

Cost Analysis (NCCA) developed a graphic that shows the various costs associated with a warship, shown as Figure 1. Note that Figure 1 is a categorical listing, and not necessarily a temporal listing (i.e. a program does not incur Sailaway costs, and then acquisition costs, etc). Conveniently, NCCA also provides a sample temporal cost graph, included as Figure 2.

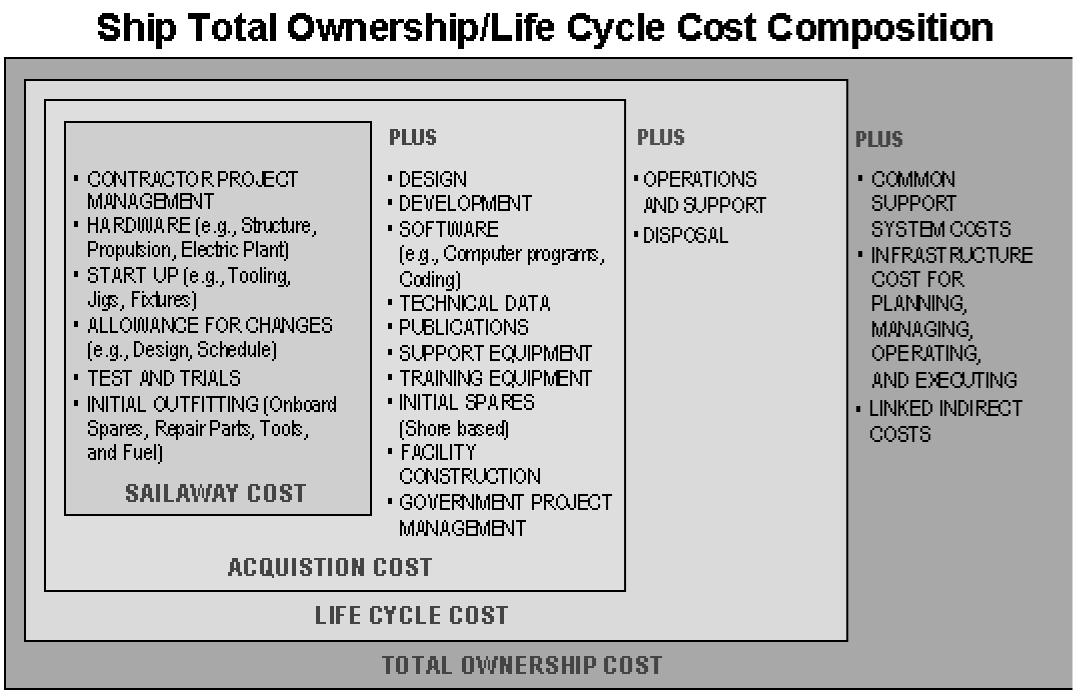

Figure 1: Example Categorical Ship's Life Cycle Cost (U.S. Navy 2010)

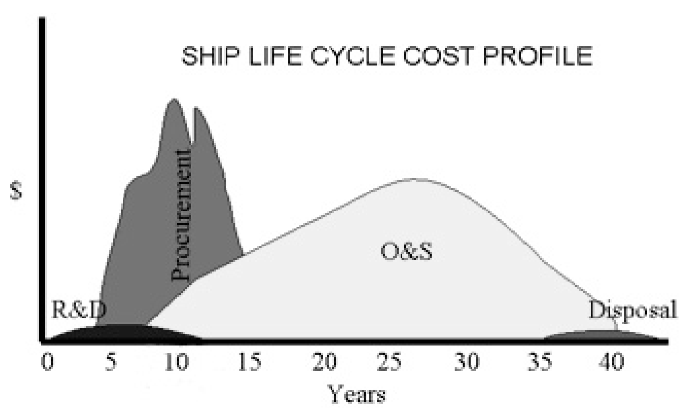

Figure 2: Example Temporal Ship's Life Cycle Cost (U.S. Navy 2010)

To be clear, the costs shown on these graphs are aggregates of different appropriations. This is an important distinction because appropriations – the money the Navy can spend each year as enacted into law by Congress – are publicly available information. Alternately, the costs that generate the aggregations above are For Official Use Only (FOUO). For instance, the Procurement Cost in Figure 2 is “the total of all funds programmed to be available for obligation for procurement for the program (Title 10 U.S.C 2432).” This means that Procurement includes not just the SCN appropriation, but the Other Procurement (OPN) and Weapons Procurement (WPN) appropriations, as well. This is similar to the Sailaway Cost depicted in Figure 1. Further, there is a Program Acquisition Cost that includes RDT&E, as well as MILCON appropriations specific to the class of vessel. For a typical ship program, the Procurement Cost is about 95% of the Program Acquisition Cost (U.S. Department of Defense 2010). The Program Acquisition Cost is similar to the Acquisition Cost of Figure 1. Similarly, the Operations and Support cost of Figure 2 includes Military Personnel (MPN) appropriations for manning the vessels in addition to the costs of fuel, repair parts, maintenance, modernization, and other typical O&MN costs.

The basic appearance of Figure 2 shows that for a single vessel, the Navy spends more money in Operations and Support (O&S) than in procurement. One reaches this conclusion by “eyeballing” the areas under the respective curves for those costs, which would represent the total cost for that category over the life of the ship. Data obtained from the FOUO sources confirms this premise, as summarized in Table 1. The latest available Selected Acquisition Report (SAR) for a given vessel provides the Program Acquisition Costs, which Table 1 first normalizes then summarizes. For example, a SAR from 1987 provided the most current data for the Oliver Hazard Perry class frigate, while a SAR from 1991 had the most recent data for the LSD 49 class (U.S. Department of Defense 2010). Additionally, the calculations converted all costs for each category in the table to $FY09 in order to compare costs in similar terms (Hirama 2004). The table does not display values for the DDG, CG, and LPD 17 classes, but each of these classes should produce the same results by the end of service life.

Table 1: Average Costs per Ship in a Class[1]

Ship Class	Avg. Program Acquisition Cost	Avg. O&S	Avg. Own-ship Maintenance	Avg. Intermediate Maintenance	Avg. Depot Maintenance	Avg. HW Modifications	Avg. Age of Ship in Class (Years)	Designed Age of Ship (years)
FFG	100%	133.6%	9.7%	3.9%	16.3%	14.0%	25	25
LSD 41	100%	147.5%	5.8%	4.3%	30.1%	11.1%	21	25
LSD 49	100%	139.4%	5.2%	5.6%	25.2%	7.8%	13	25
LHD	100%	124.1%	3.5%	2.0%	17.8%	8.7%	14	25
LHA	100%	129.7%	3.1%	2.3%	25.7%	16.1%	30	30
CVN 68	100%	203.3%	5.0%	1.2%	62.1%	16.0%	35	50
CVN 69	100%	287.9%	6.5%	1.1%	109.9%	28.6%	33	50

Table 1 focuses on the areas that are the obvious and quantifiable outcomes of design decisions: maintenance and modernization. As mentioned above, military manning of platforms is also an outcome of design decisions, but is less quantifiable over the life of the ship because manning decisions after delivery of the ship are made independently from any existing or future design decisions, and are closely correlated to recruiting practices of the Navy in general. As an example, the DDG 51 class of destroyers is typically manned to 120% of the design level for officers, because the Navy over-recruits for the junior ranks in order to ensure enough officers are in the pipeline to fill the senior ranks after attrition. Therefore, Table 1 purposely omits manpower costs. Table 1 also omits support costs (training and other support) and operating material costs (fuel and other consumables) for similar reasons – because once the Navy delivers the ship to the operators, its actual usage (fuel consumption, in particular) is largely out of the control of the designers.

Figures 3 and 4 depict an alternate picture of costs: a breakdown of several appropriation types instead of a categorical aggregation of several appropriations. This is the publicly available information that often misleads the casual reporter or observer into thinking that the cost of a warship is simply the sum of the SCN appropriation, ignoring other appropriation types used to build the ship. All of this data came from the budget book for each year, so all numbers are in then-year dollars, not referenced to a baseline year. The full table of these budget items is seen in Appendix B.

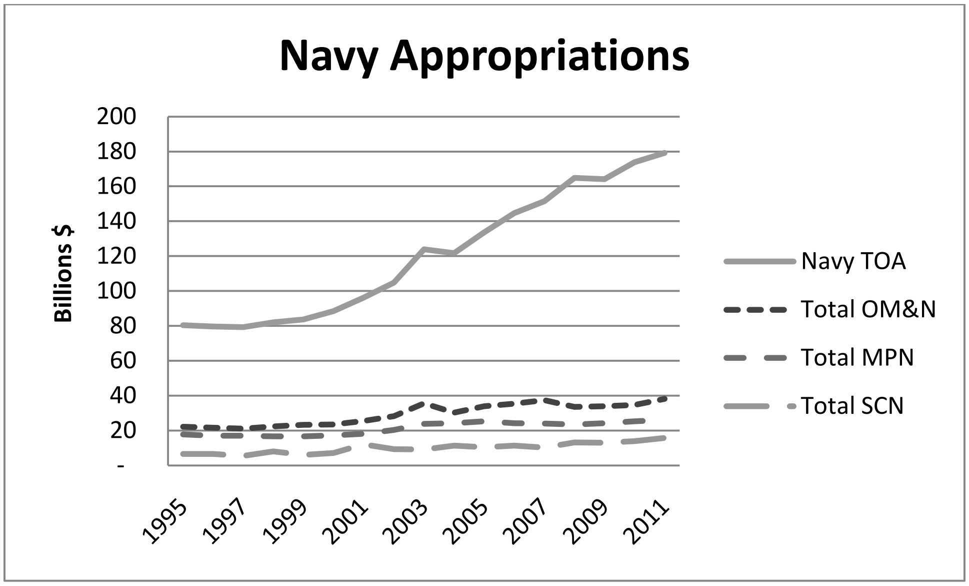

Figure 3: Absolute Values of Some Categories of Navy Appropriations (U.S. Navy 2010)

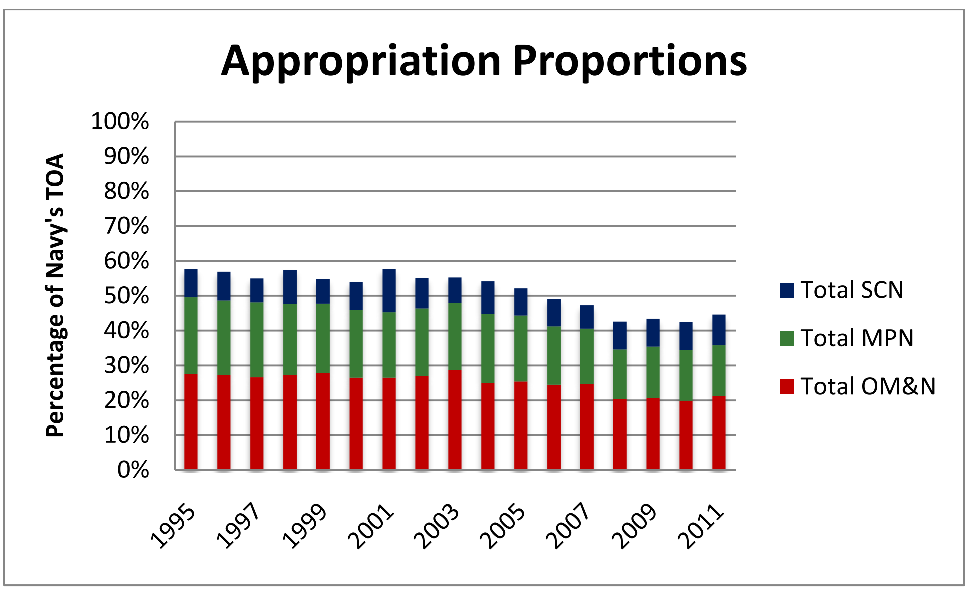

Figure 4: Relative Values of Some Categories of Navy Appropriations (U.S. Navy 2010)

Figures 3 and 4 only present three of the appropriations categories. As Figure 4 relates, these three categories make up between 50% and 60% of the Navy's budget. The other 40% to 50%

includes funding for the Marine Corps[2], the Reserve contingent of the Navy and Marine Corps[3], WPN, OPN, MILCON, Aircraft Procurement (APN), RDT&E, and many others. This data is also aggregate in nature; each budget book provides further categorization of each appropriation, e.g., OM&N money can be broken down into: 1) air operations, 2) ship operations, 3) combat operations/support, 4) weapons support, 5) mobilization, 6) training and recruiting, and 7) admin/service-wide support. However, a comparison of an individual ship's acquisition cost to its operating costs is difficult to determine based on publicly available information.

Therefore, discussing the cost of a ship requires careful consideration and specificity. A direct correlation between the funding categories of Figures 1 and 2 and the appropriation types of Figures 3 and 4 does not exist. More specifically, SCN money can fund some of the categories in Sailaway cost, acquisition cost, and even life cycle cost and Total Ownership Cost (TOC) – and similar arguments apply to the other appropriation types. Additionally, the procurement cost in Figure 2 is not strictly SCN appropriations, nor is the O&S part of the curve strictly O&MN appropriations. The fact that appropriations are publicly available but do not reveal the full costs of a specific platform or class of ships (as in Figures 1 and 2) makes it more difficult to choose a category within a ship's life cycle to save money or avoid cost. Additionally, correctly identifying, labeling, and categorizing any potential cost savings/avoidance becomes more difficult because it could be tied to any of several different appropriations types, and perhaps more than one at the same time.

These are important distinctions to make when trying to reduce or maintain the Navy's budget, because one must decide which appropriation (O&MN, SCN, etc.) or category (R&D, Procurement, etc.) to address and correctly identify the need to address those costs. This thesis proposes changes in early stage design with the goal of affecting modernization costs (funded with Procurement-type appropriations) during the O&S phase of the vessels service life.

In recent years, the Assistant Secretary of the Navy for Research Development and Acquisition and the Commander of Naval Sea Systems Command began several initiatives to reduce the TOC of each warship. Many of them try to reduce the most publicly mentioned cost: the acquisition cost. However, many of the initiatives – especially those outlined by Stackley and

McCoy (2009) – do not account well for the fluid nature of ship acquisitions and operations and the ever-changing requirements before and during a ship's service life. Therefore, incorporating flexibility in the design stage and options analysis can fortify and bolster cost initiatives currently in place.

2.2 Current Navy Acquisition Process

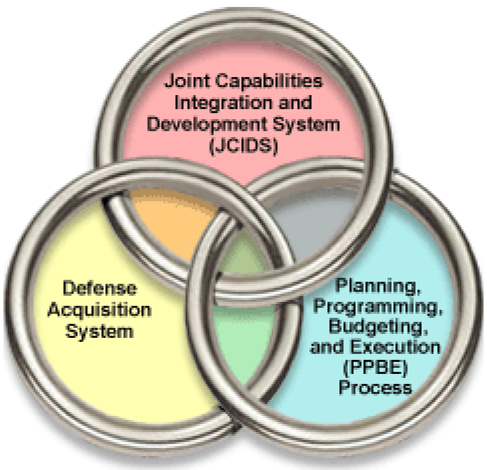

Figure 5: DoD Decision Support Systems (U.S. Department of Defense 2011)

The ship design process operates within the Defense Acquisition Process. Therefore, other activities initiate the program of record and the ship design process. Figure 5 shows the three high-level decision support systems that complement each other and provide an integrated approach to planning, acquiring, and budgeting: the Joint Capabilities Integration and Development System (JCIDS), the Defense Acquisition System, and the Planning, Programming, Budgeting, and Execution (PPBE) process (U.S. Department of Defense 2011). The JCIDS process assesses and resolves gaps in joint military warfighting capabilities. Even if the Navy identifies a mission-need gap in its current profile of warships and aircraft, closing that gap requires approval via JCIDS, not just from within the Department of the Navy. The Defense Acquisition System manages the acquisition of both weapon systems and information systems for the DoD. Strict discipline and accountability are the hallmarks of this process. This system provides guidance for the systems engineering process that takes place with every platform, and decentralizes as much of the control and reporting as possible. Lastly, the PPBE process determines how the DoD allocates the resources required to carry out the other processes. This final process is the check and balance to the other processes that recognizes resource constraints and balances those among different programs. Defense Acquisition University (DAU) generates and updates a chart that depicts the interplay of the different processes with each other in a roughly chronological sense, which is included as Appendix C.

This thesis is particularly interested in the Defense Acquisition System. This is the process in which ship design and systems engineering occur, so it is the main focus. For the purposes of this thesis, two assumptions from here forward are: 1) a capability gap has been identified and approved for material resolution through the JCIDS process, and 2) the PPBE process has identified no resource shortfalls and has assigned appropriate resources to the program. With these assumptions, we can focus exclusively on the system of interest: the Defense Acquisition System, summarized in Figure 6.

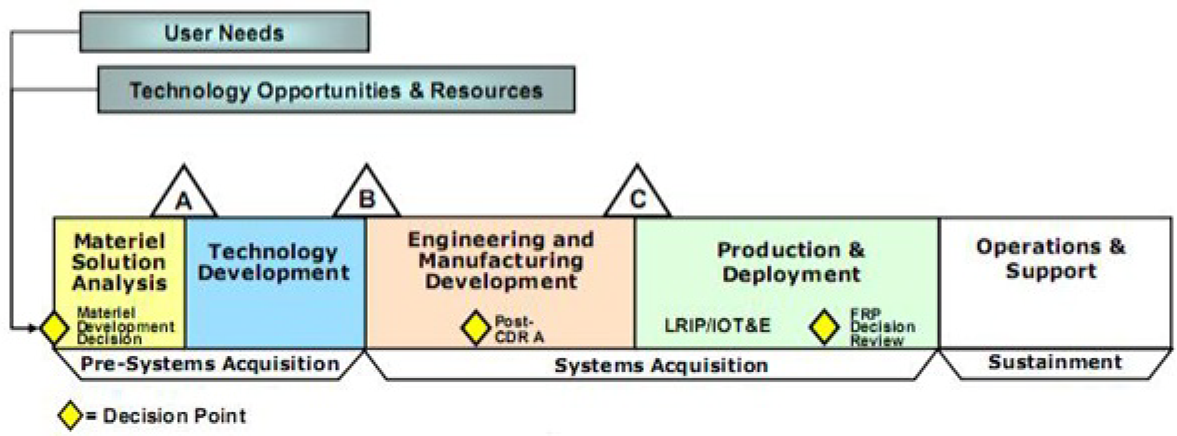

Figure 6: Defense Acquisition System Lifecycle Framework View (U.S. Department of Defense 2008)

The entrance point to the Acquisition System is the Material Development Decision (MDD); this Decision means JCIDS determined that not only is there a capability gap the Navy can solve, but that a material solution is the only way to fulfill the need (as opposed to a change in doctrine or diplomacy, for instance). An Initial Capabilities Document (ICD), Analysis of Alternatives (AoA) Study Plan, and other documentation accompany the MDD and serve as guidance to the rest of this phase of development, called Material Solution Analysis Phase. During this phase, the now-formed-and-funded program office investigates alternative material solutions and recommends one of them based on criteria provided in the ICD and AoA Study Plan. As part of this recommendation, the program office creates a Preliminary System Specification, Systems Engineering Plan, Test and Evaluation Strategy, Safety Analysis, and a plethora of other documents. The Milestone Decision Authority (MDA) reviews and approves each of them for Milestone A. The sponsoring Department typically obtains RDT&E appropriations to fund the work and products of this phase. Once the program meets the exit criteria and the MDA approves the program offices' plans, the program enters the Technology Development Phase.

The Technology Development Phase reduces technology risk and determines the appropriate set of technologies to integrate into the full system (U.S. Department of Defense 2008). This phase uses the outputs from the Material Solution Analysis Phase to refine the selected material concept. The program office procures various system and subsystem prototypes in this phase in order to adequately demonstrate critical technologies before entering the next phase. This phase culminates in the Milestone B decision. After demonstrating critical technologies and refining user requirements, the program office develops the System Performance Specification, Source Selection Plan, the overall Acquisition Strategy, the Capabilities Development Document, a Cost/Manpower Estimate, and several other reports and documents for the MDA. The sponsoring Department continues to pay for the work and documentation of this phase, typically with RDT&E money. Approval by the MDA moves the program from the Technology Development Phase to the Engineering and Manufacturing Development Phase.

The Engineering and Manufacturing Development Phase begins at Milestone B, and is normally the initiation of an acquisition program (program of record). The purpose of this phase is to develop a system or an incremental capability for an existing system (U.S. Department of Defense 2008). The program office and support personnel complete full system integration, develop a manufacturing process, establish logistics requirements, implement Human Systems Integration, and undertake numerous other tasks to ready the platform for manufacturing and deployment. The Critical Design Review happens in the middle of this phase. Integrated prototypes and production representative articles demonstrate manufacturability and successful attainment of the Key Performance Parameters outlined in the Capabilities Development Document. Successful completion of the products, documentation, and business case in this phase leads to the Milestone C decision by the MDA. In large part, RDT&E appropriations still fund all the work products in this phase, although, for the case of ships, SCN appropriations may fund some of the work. Once the MDA approves the work completed in the Engineering and Manufacturing Development Phase at Milestone C, the program enters the Production and Deployment Phase.

The Production and Deployment Phase manufactures and delivers the platform to the operators. Systems may begin with Low Rate Initial Production runs to produce articles that undergo extensive testing in the field in order to resolve any last bugs and demonstrate production articles in a live environment. After satisfaction of the test criteria, the MDA provides a Full Rate Production decision that moves the program forward and allows it to produce the full number of articles as planned in the Acquisition Strategy. In shipbuilding, most platforms do not undergo Low Rate Initial Production, instead producing the first ship of the class as a Production Representative Article, and the MDA decides to go to Full Rate Production at the Milestone C decision point, which is after delivery of the first ship of the class (U.S. Department of Defense 2010). In this phase, a program office transitions off of RDT&E appropriations into procurement-type appropriations, i.e., WPN, OPN, or SCN as appropriate. This phase naturally transitions to the Operations and Support Phase upon delivery and the funding naturally transitions from procurement-type appropriations to O&MN appropriations.

On average, a shipbuilding program office exists for almost six years before it is an official program of record, and takes another six years to deliver the first ship of the class, while the Milestone C decision for full rate production is two years after that delivery (U.S. Department of Defense 2010). Table 2 summarizes the average time frames for the data available.

Table 2: Shipbuilding Program Timelines (U.S. Department of Defense 2010)[4]

Ship Class	Milestone 0/MDD	Milestone I/A	Milestone II/B	Delivery	Milestone III/C
DDG 51	May 1978	Jun 1981	Dec 1983	Apr 1991	Oct 1986
DDG 1000	Jan 1995	Jan 1998	Mar 2005	Jul 2011	Mar 2014
LCS	Feb 2003	May 2004	Jan 2007	Jan 2007	Dec 2010
LPD 17	Nov 1990	Jan 1993	Jun 1996	May 2005	Sep 2009
SSN 774	Aug 1992	Aug 1994	Jun 1995	Oct 2004	Sep 2008
Average Total Time (years)		2.33	5.66	12.08	14.08

These data show that ship acquisition is a long and arduous process. In addition to these timelines, the ships themselves have a service life in excess of 20 years, some as long as 40 years. Therefore, there is ample opportunity for technological obsolescence of any equipment selected or technology during the first fourteen years of the ship life cycle and for decades afterwards, as well. Mission needs are likely to change after conceptualization, creating the need to meet new operational requirements before disposal of the platform.

Program offices try several methods to overcome the difficulty of obsolescence and changing requirements. For instance, the Ship to Shore Connector (SSC) program recently utilized set-based design which allows the delay of decisions until the design space for a given component is reduced. The Navy also directs that allowances are made for certain “known unknowns.” In other words, the Navy practices the use of design margins and service life allowances for certain aspects of the ship that are known to have a distribution of outcomes since high-fidelity information is not always available in early stage design. These margins and allowances offer one form of flexibility.

2.3 Current Navy Design Process

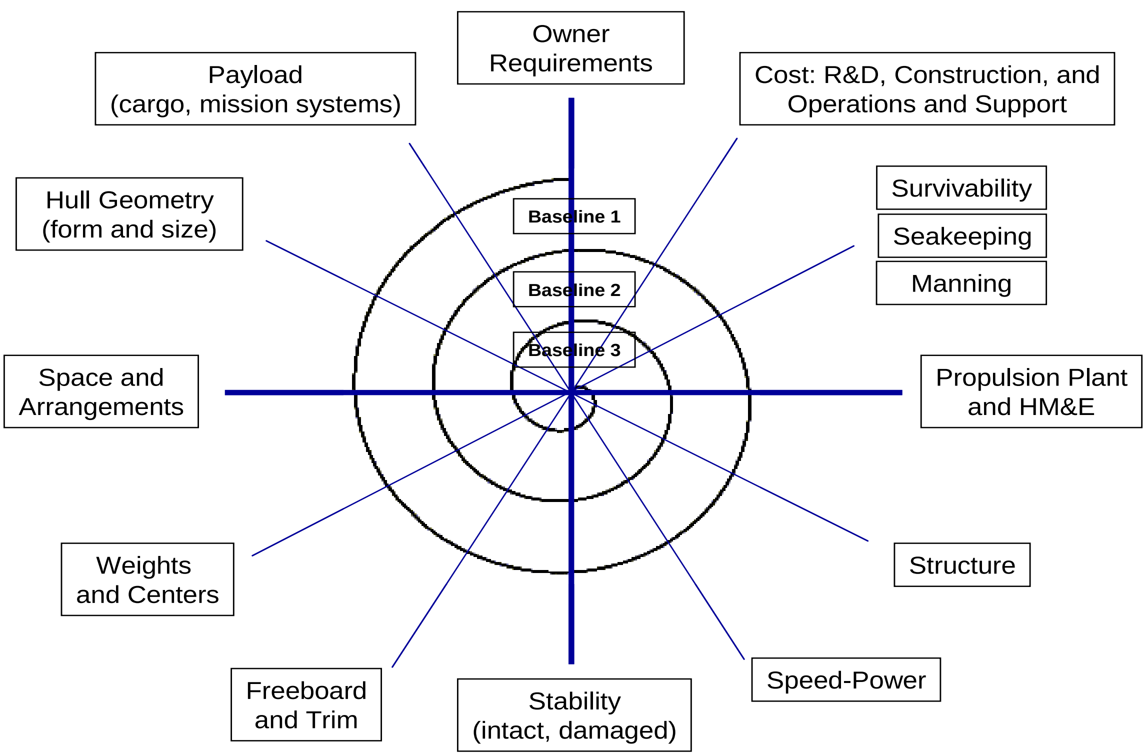

Figure 7: The Design Spiral (P. A. Gale 2003)

The typical naval design process follows the design spiral, depicted in Figure 7. The design progresses along in a rather linear fashion, assessing each discipline in sequence, e.g., payload, then hull geometry, then space and arrangements, etc. Each subsequent loop through the spiral adds fidelity to the design until it finally converges to a satisfactory point design. Ship design follows this iterative approach because, so far, ship design has proven far too complex to be described by a finite set of equations which can be solved directly. Instead, naval architects and other engineers make educated guesses as to the final hull dimensions, weights, electrical demands, etc., and then refine the initial estimates as better information becomes available from customers, vendors, or other engineers (P. A. Gale 2003). Therefore, design decisions in the infancy of a platform's life have implications well into the service life of the platform, because subsequent passes through the design spiral only refine the design as opposed to drastically changing certain parameters. The entire process can take several – perhaps dozens of – iterations through this spiral, although Figure 7 depicts three baselines to represent the three basic phases of the acquisition process before delivery of a platform.

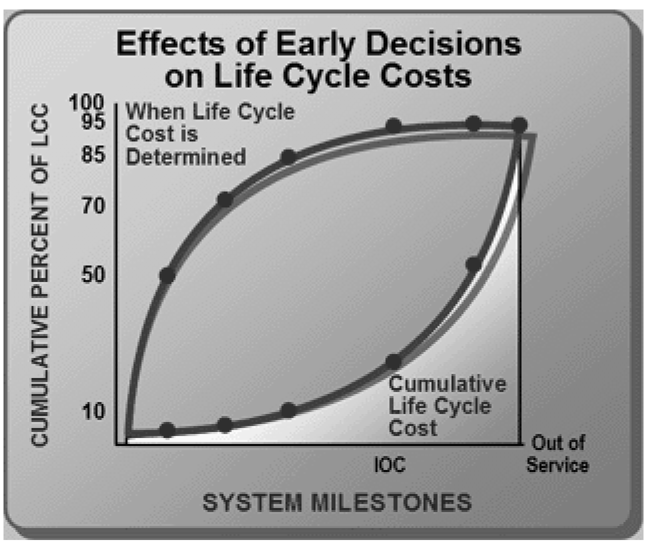

Figure 8: Effects of Early Decisions on Life Cycle Costs (U.S. Department of Defense 2011)

Because most major design decisions are made in the infancy of a platform's life, program managers must carefully consider the implications of those decisions. Pictures such as Figure 8 proliferate throughout basic Defense Acquisition educational courses, especially those on logistics or test and evaluation. The message is that decisions made early in a design's life effectively lock those portions of the design and also those portions of the cost so that managers lose any flexibility to affect the cost of the platform later in its service life. The goal, then, is to find a way to move the upper curve of "cost determined" towards the lower curve of "cumulative cost" so that the two curves match more closely.

The US Navy implements policy to account for the crude nature of estimates early in the design stage. Specifically, the two most important design criteria that must be met throughout the design and build processes involve the mass properties of the ship. The first criterion is that the ship must *float*, meaning weight must equal buoyancy. The second criterion is that the ship must float *upright*. To greatly simplify the method of establishing stability, the height of the center of gravity (KG) in relation to the height of the center of buoyancy (KB) determines the general stability of the vessel. Accordingly, the Navy enacts policy that dictates design margins for each stage of the process in order to ensure its platforms always meet these two criteria, or at least do not breach the criteria. Essentially, they are an insurance policy against the unknown mass properties of the vessel and its subsystems during the design and build phases of the life cycle. They protect against the circumstance of adding weight high on the ship, which makes the vessel more unstable. Tables 3 and 4 summarize these criteria. These tables only present the total margins, although the referenced instruction categorizes these margins into the Preliminary and Contract Design Margin, the Detail Design and Building Margin, the Contract Modification Margin, and the Government-Furnished Material Margin. All the data in the table represent the Percentage Displacement of the Light Ship Condition[5] that ought to be added for estimating purposes.

Table 3: Acquisition Margin Ranges for Studies (U.S. Navy 2001)

	Mean	Mean + 1 Std. Dev.
Total Acquisition Weight Margin	6.0%	17.5%
Total Acquisition KG (Height of the Center of Gravity Above the Keel)[6] Margin	4.8%	14.5%

Table 4: Service Life Allowance Values (U.S. Navy 2001)[7]

Ship Type	Weight Percent [%]	KG [meters (feet)]
Combatant	10.0	0.30 (1.0)
Carrier	7.5	0.76 (2.5)
Large Deck Amphibious Vessel	7.5	0.76 (2.5)
Other Amphibious Vessels	5.0	0.30 (1.0)
Auxiliary	5.0	0.15 (0.5)
Special Ships and Craft	5.0	0.15 (0.5)

Further, designers also implement margins and service life allowances for electric loads. Historically, the Navy projects a 1% growth in electric load per year for the first 2/3 of the ship's life cycle and no growth for the remaining 1/3 of its life[8]. Additionally, a 1.0 tons-per-square-inch stress margin is widely used in combatant ship design, and Naval engineers and other system designers may also apply margins to the speed and powering, spaces and accommodations, and HVAC systems onboard (Hockberger and Leopold 1981). All these margins tend to add weight and take away space and volume from the vessel. Trends in these directions tend to increase acquisition costs of a vessel.

2.4 Execution of Options

Exercising options should involve three basic steps: recognizing an opportunity, analyzing the value of that opportunity, and executing the option when appropriate. The Navy is very good at executing options, but could improve its practices of recognizing and analyzing opportunities at the outset of a program instead of when a decision is imminent. All business case analyses include the Time Value of Money (TVM) (U.S. Navy 2004), but few, if any, include an analysis of options. Because the analysis of Naval programs do not explicitly value these inherent options, these analyses potentially undervalue their programs. Further, analyses available for public consumption do a poor job of balancing the intricacies of fiscal value versus operational value, if they address such issues at all. Most program managers make decisions with the mindset that constraints are handed down to them from previous program managers. Their focus is on working within those constraints and validating the program and its cost to Congress right now, with little or no value explicitly given to managerial options in the future. Further, the

Navy incorporates margins and allowances because of the mindset that designing a warship is too complicated a task and must be done iteratively (P. A. Gale 2003). As an alternate approach, the designers could think of these margins and allowances as options imbedded in the architecture of the ship that give future program managers the right, but not the obligation, to install unknown capabilities for some cost in the future. Chapter Four proposes some characteristics of such a vessel – one that is designed with pre-planned modified repeats of the platform – after Chapter Three discusses a framework for how to evaluate the value of such a platform.

3.0 Analysis Framework for Real Options and Design Flexibility

With better context of US Navy design practices now established, this chapter reviews Real Options Analysis (ROA) principles and provides a framework for evaluating the fiscal and operational value of a warship. The chapter gives account of ROA's roots in NPV analysis, specifies how ROA is different, and communicates what advantage is gained. The chapter also introduces the concepts of options *in* projects versus options *on* projects. The former relates to flexibilities consciously imbedded in the architecture of a design while the latter relates to the execution of decisions by a manger. The chapter reviews the general categories of options *on* capital projects, introduces options *in* capital projects, and offers potential Navy applications as food-for-thought.

3.1 Options *On* and Options *In* Capital Projects

There are a few common classifications of options *on* capital projects defined by the flexibility they provide to the manager. An option to expand (e.g., production rates, purchase quantities, levels of a garage, square footage of a production facility) is one possibility. The option to contract (e.g., production rates, purchase quantities) is another. A deferral option is another type that means a manager can delay the start of a project or delay the start of a phase of a project. Complimentary to that option is the option to extend a project or a phase of a project. Similarly, managers and organizations usually have the option to abandon a project and potentially sell any assets for a salvage value. The option to switch – such as switching from one manufacturing plant to another, or opening and closing mines – is an interesting option. Of course, there are also compound options, or options on options. For example, many real assets are designed, then engineered, and finally built. One would not exercise an option to build if one did not exercise the option to complete the engineering of the design. But, one could abandon the project before or during engineering without ever proceeding forward to the build phase. Thus, this sequence is a compound option because the option to build is contingent on exercising the option to engineer the product. Additionally, rainbow options are categorized as options with multiple sources of uncertainty. Lastly and perhaps most realistically, is the compound rainbow option, which has multiple decisions contingent on previous decisions as well as multiple sources of uncertainty. This final option category fits equally well for research and development efforts, exploration and production of natural resources, or creating new products for the market (Copeland and Antikarov 2003).

Complimentary to options *on* projects are options *in* them. Options *in* projects are flexibilities and designs consciously created within the architecture of the technical system to provide exploits for mangers to execute when appropriate (de Neufville and Wang 2006). Therefore, options *in* a project set the stage for options *on* the project, ideally. Options *in* a project recognize the volatility of potential outcomes of the project and proactively imbed exploitable opportunities. Contrarily, options *on* a project reactively address changing situations. For instance, many components of desktop and laptop computers attach modularly to the rest of the system. Today, if a user desires a larger hard drive or more memory, he can replace the component instead of the entire computer because the manufacturer built in these options. Modularity is one form of flexibility that can be designed into the architecture of a system to provide options – to designers, engineers, manufacturers, and end-users alike. One can imagine the original designers of these systems recognizing the uncertainty around the volume of information that would be internally stored in the future and including this option to accommodate that uncertainty. So, the designers put an option *in* computers so that consumers could execute an option *on* it.

3.2 Net Present Value

NPV analysis is a type of economic analysis used commonly by enterprises to determine if a project (or family of projects) will increase the value of the firm. The method typically uses an accounting-style balance sheet that compares discounted investments over the life of the project to discounted expenditures. If the discounted investments and expenditures are less than the discounted revenues, the net present value is greater than zero and the general rule is to proceed with the project. In most cases, the initial investment is well known, but the cash flows are only projections based on assumptions of demand, pricing, and other factors. The selection of the appropriate discount rate is also critical to the analysis, since it determines how much more valuable a dollar is today than at some time in the future.

A simple example of a NPV calculation follows in Table 5. It assumes an initial cost of $100, but this number could easily represent thousands or millions of dollars. This cost is negative because one spends money on the investment, so it is a net out-flow of money. Next, in years one through five, the example assumes the project earns $25 dollars each year, and has a value of $2 in the last year for salvage. The net cash flows are simply the sums of all the cash in-flows and out-flows by period. Then, the discount factor[9] takes those cash flows and represents them in present value terms, to account for the time value of money. Each of these present values of the net cash flows then sums to reveal the NPV.

Table 5: Example Net Present Value Calculation (r=15%)[10]

Year	0	1	2	3	4	5
Initial Cost	$(100.00)					
Net Cash In-flow		$ 25.00	$ 25.00	$ 25.00	$ 25.00	$ 25.00
Salvage Value						$ 2.00
Net Cash Flow	$(100.00)	$ 25.00	$ 25.00	$ 25.00	$ 25.00	$ 27.00
Discount Factor	1.000	0.870	0.756	0.658	0.572	0.497
Present Value	$(100.00)	$ 21.74	$ 18.90	$ 16.44	$ 14.29	$ 13.42
Net Present Value	$ (15.20)					

This simple example illustrates a scenario where NPV analysis decides not to move the project forward, because the NPV is less than zero: the firm would lose money on this project. A manager may wonder what can be done to make the project feasible. If the discount rate decreases such that the discount rate is lowered from 15% to something less than 8.44%, the NPV becomes positive and the project seems attractive. This new value is the Internal Rate of Return: the maximum value the discount rate can assume to give the project a NPV>0. Table 5 easily expands to include more financial considerations, such as: more out-flows (e.g., operations and maintenance costs), more in-flows (e.g., external investment in the firm, different price points within a portfolio of investments), taxes, depreciation, and others. No matter the complexity and fidelity of the balance sheet used, though, the basic principles remain: the analysis appropriately discounts each cash flow and sums it over the service life to determine the fiscal attractiveness of the project.

NPV analysis is static by nature. It assumes: 1) the discount rate remains the same through the life of the project, and is not affected by corporate or world events; 2) demand and cash flows do not change; and 3) managers take no actions to affect the outcome, either positive or negative. These are generally poor assumptions, and create challenges for this type of analysis. The assumption that managers take no action over the life of the product is especially relevant to any analysis, because these actions are most easily controlled or changed (de Neufville and Scholtes 2011). A manager who does not recognize the ability to postpone, expand, extend, contract, or abandon a project midstream is truly lacking. Even smarter is the manager who builds these options into the architecture of their facilities, products, and/or contracts to give themselves these options. But, NPV analysis is inadequate for such managers.

3.3 Real Options Analysis

ROA is the practice of applying financial options (e.g., calls, puts, futures, forwards) to real assets. This analysis is different than NPV because it recognizes the dynamic nature of commerce and industry and the fact that managers often make decisions affecting life cycle costs beyond the initial decision to purchase an asset. While NPV accounts for the time value of money, it forces assumptions about demand, pricing, market conditions, and other aspects of the decision that <u>cannot</u> be known up front. Conversely, ROA recognizes the potential volatility within those assumptions and seeks to assign value to those volatilities as much as possible. ROA determines this by recognizing the decisions that can be made to capitalize on them or protect an enterprise from them. In other words, ROA recognizes that managers inherently retain the flexibility to make good decisions and their ability to make better decisions increases with time as more information becomes available (de Neufville and Scholtes 2011). This means there is an opportunity cost of investing right now; and while NPV analysis only looks at whether or not to invest right now, ROA allows a manger to weigh the option of investing later. Options represent the manager's *right* to make and exercise a decision without the *obligation* to do so.

In typical applications, ROA is especially valuable when the NPV is close to zero, because the options more accurately value the project. If a project's NPV is very negative, though, options and flexibility most likely cannot provide enough value to support a decision to undertake the project. Similarly, if a project has a high NPV, the extra value of options, although real, may not be necessary for the decision analysis to undertake the project. This causes an interesting dilemma for a ROA of warships, since ROA has both income and outlays, but the Navy has no source of income from its warships. Thus, in a pure NPV analysis, a warship has a very large negative value (several billion dollars per ship), which makes ROA seem unnecessary. However, the life of a warship is full of potential options (both *in* and *on*), from conception, through design and engineering, into construction and even during operation. There is an option to extend the life of the ship or decommission the vessel, and even an option after a decommissioning regarding whether the Navy should scuttle the ship, use it for a live-fire exercise, or mothball it for later use. Thus, it is practical to develop methods to recognize, insert, and evaluate the plethora of options available throughout the life of a ship with the goal of better utilizing taxpayer's money.

3.4 Alternate Analysis for Real Options

Unlike NPV and ROA, valuation of options *in* a project follows no set format or formula. Although its roots lie in NPV with the consideration of the present value of all cash flows, it evaluates decisions using any of several different methods appropriate for the application. The important properties in any given option-valuation framework are recognizing/identifying the volatility encompassing the problem and the managerial decision in response to that volatility. Often, the problem contains multiple sources of uncertainty and many different responses to a given situation at a given moment in time. Frequently used ROA frameworks include: modifications to existing accounting balance sheets to include sources of uncertainty and decision rules for flexibility (often involving Monte Carlo analysis), binomial lattices with weighted probabilities of possible outcomes, or other methods similar to financial options pricing and decision strategies (Dixit and Pindyck 1994) (Mun 2006). These frameworks do not support evaluation of the value of a project in non-economic terms, which is especially helpful for government projects with no revenue. Therefore, valuation of options *in* a project requires alternate frameworks to adequately address needs, costs, and capabilities.

Valuation of non-economic aspects of a project (e.g. public well-being, security, happiness) requires careful consideration of the inputs and parameters of the analysis. Which aspect to measure and how to measure it are the most important considerations, followed closely by the identification and classification of volatility. Next, framework choice presents a challenge because most of the typical analysis types (using balance sheets and Monte Carlo simulation or binomial lattices) tend not to support non-economic analysis well. For instance, one can imagine the difficulty in attempting to model the inflow and outflow of security or happiness over time in a model similar to Table 5. Externalities and volatilities affecting these particular aspects have a chance to outweigh the rest of the modeled mechanics. For example, a project to build a public park could increase happiness of citizens, but be outweighed by the occurrence of a natural disaster. Thus, the importance of specificity in inputs, parameters, volatilities, outputs, and expectations of the model is paramount. In output terms, the preceding model for building a public park should measure relative happiness of citizens as opposed to absolute happiness for such a limited decision analysis.

3.5 Potential Applications for Options *In* Navy Platforms

All Navy programs inherently contain and execute options *on* their paltforms, despite the lack of recognition and analysis required to fully exploit them. For instance, as part of their 2011 budget submission, the Navy proposed abandoning the CG(X) program due to its unaffordable costs. Prior to this cancelation, the Navy deferred the purchase of the first ship of the class from FY11 to FY17. Now, instead, the Navy proposes switching to an improved version of the Arleigh Burke (DDG 51) class destroyer, to be called the Flight III version. The Arleigh Burke program itself expanded capabilities in the mid-1990's from Flight I to Flight II and now Flight IIA when adding a helicopter hanger in front of the flight deck – among numerous other upgrades to the platform. Further, the program extended to purchase five additional platforms before potentially expanding further into Flight III. On the other hand, the Zumwalt (DDG 1000) program contracted from twelve vessels to seven and is now building three.

Other examples of options executed *on* ship designs abound throughout all programs. For instance, towards the end of the service life of the vessel, the Navy has several options related to how to abandon a platform. Some of these options are conclusive, such as selling the platform to a foreign nation, using the vessel for a live-fire exercise, or sending it to a scrap yard to recapture the metal of the hull. However, some of the options are reversible, such as laying up the vessel as inoperative, but reserving the right to re-activate the vessel in the future. Alternately, the

Navy always has the option to continue operation of the vessel, and can reverse this decision at any time. However, even though the Navy executes these options *on* the platform, it is not necessarily because they first designed the option *in* to the platform. Options analysis provides a good framework for evaluating all of these options concurrently based on currently known information.

As a last example, compound rainbow option evaluation elegantly represents the entire life cycle of any platform. As outlined in Chapter Two, the life cycle of a vessel encompasses several phases, and each of them is contingent on the previous phase. The Navy will not dispose of a vessel they have not built, and they will not build a vessel that has not been designed, and they will not design a ship that is not approved from the JCIDS process. Further, the life cycle of the vessel contains both *global* uncertainties, e.g. the amount of capability needed, the technologies that can answer those needs, and/or the state of the world, and *local* uncertainties at a moment in time, e.g. budget constraints, technology constraints, regulations, and/or laws.

Because a ship's life cycle is analogous to a compound rainbow option, flexible designs and architectures are necessary to acknowledge and manage the uncertain future of the platforms. Ship designers find this task difficult because they are tasked to design to a point solution that recognizes current or near-term threats, without much consideration for longer-term needs of the platform. Two of the more egregious examples of this are the USS Chicago (CA 136)[11] and USS Midway (CV 41)[12]. Even the Spruance (DD 963) class, which the Navy designed with modularity in mind, experienced modernization and maintenance costs above and beyond those predicted and, subsequently, the Navy decommissioned all members of the class early and instead built the Arleigh Burke (DDG 51) class. Similarly, the Arleigh Burke class of destroyers has undergone two major design revisions and technology upgrades since its program's inception, with a third in progress. Amphibious ships also experience problems with changing missions, as the Tarawa (LHA 1) class demonstrates[13]. Thus, the value of flexibility in design reveals itself more with each example included, and the samples above are by no means exhaustive. If these ship designs incorporated flexible architectures – options *in* the design – then these major changes could have been less costly.

Of course, successful implementation of a flexible design requires more thought than a typical, "tight" point design like those mentioned above. Fortunately, several existing projects aid in the development of flexible designs. For instance, the implementation of the Navy's Open Architecture (OA) strategy helps with modernization of combat systems equipment and forces programs to look at the business cases for OA (Young 2004). A program in NAVSEA called Architectures, Interfaces and Modular Systems (AIMS) developed a physical modular open system called Flexible Technology that is being tested on both carriers and combatants right now (DeVries, Levine and Mish Jr 2010) as well as a standard process for designing successfully modular ships (Cheung, et al. 2010). With these ideas and others in mind, the next chapter presents a notional modular platform and evaluates its fiscal and operational value.

4.0 Designs, Framework, and Analysis

This thesis develops a unique model to demonstrate the value of flexibility to the Navy by comparing two platforms: one flexible and one inflexible. Each of the vessels has an associated choice model that determines the manner in which capability is added to its respective platform. The basis for the model is the MIT Cost Model for early stage ship design,[14] which is primarily intended for construction costs and is based on a destroyer-like platform. The new model simplifies designer input, modifies the O&S cost estimation section to match the costs of the Arleigh Burke (DDG 51) class (U.S. Navy 2010), and adds a Capability Simulator that calculates the capability and cost of that capability over the service life of the two platforms analyzed. Lastly, it runs a Monte Carlo experiment which repeats the Capability Simulator 1000 times.

The purpose of this chapter is to lead the reader through the process of setting up the comparison framework, report the results, and reveal the robustness and sensitivity of the model. First, it introduces each of the platforms used for comparison and their general characteristics. Then, it conveys the choice models that each of the respective platforms is locked into because of its inherent characteristics as used for the analysis. Next, the chapter reveals the set-up of the model and the assumptions necessary to proceed. Finally, it defines a baseline comparison for the assumptions and discusses the results of the model, including an evaluation of the robustness and sensitivities of the model.

4.1 Inflexible Platform

The analysis uses the Arleigh Burke (DDG 51) as the baseline inflexible platform. The Navy acquires the DDG as a multi-mission platform, able to simultaneously perform anti-air, anti-surface, sub-surface, amphibious, and other missions as part of a carrier strike group or amphibious readiness group (U.S. Department of Defense 2010). This makes the DDG a highly capable (in today's measures) but volume-limited platform: that is, the platform has no additional space for new or different missions that arise, and typically existing mission capabilities must be replaced or degraded to accommodate changes. A recent example of this is the adaptation of the DDG platform to meet the new BMD mission. Although the platform performs the new BMD mission, it can only do so by degrading other capabilities. In addition to these design considerations, the DDG is a good baseline platform because cost and capability information is readily available in unclassified sources, including the original MIT Cost Model.

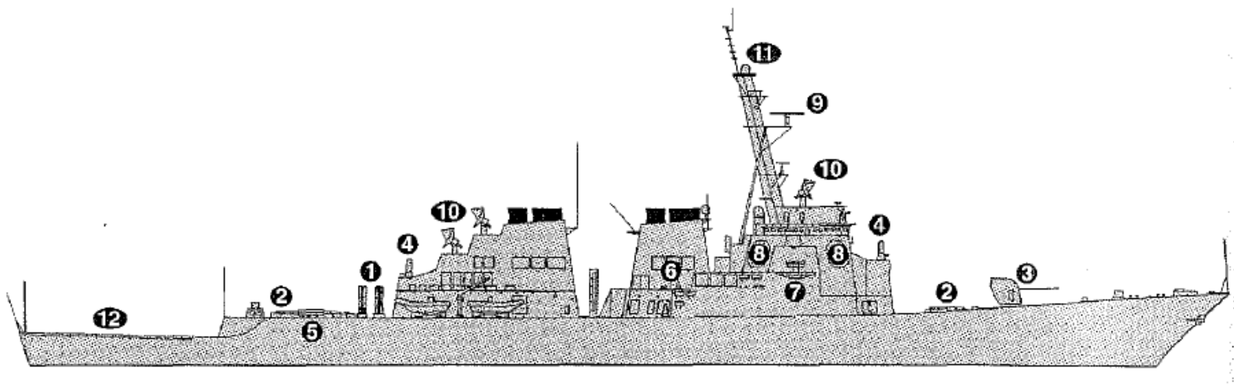

Figure 9: Profile View of DDG (Jane's 2007)

Figure 9 shows the above-water profile view of the DDG, revealing the longitudinal locations of several systems. The highlighted elements of its combat capability include (from fore to aft): Mk-45 dual purpose gun (3), 29-cell vertical launch system (2), Mk-16 Phalanx Close-In Weapon System (4), SPY-1D 3-D air search radar (8), SLQ-32 electronic countermeasures (7), two quadruple Harpoon launchers (1), 61-cell vertical launch system (2), Mk-32 triple torpedo tubes (5), and a helicopter landing platform (12). Figure 9 displays neither the SQS-53C bow-mounted SONAR nor the SQR-19 passive Tactical Towed Array SONAR. The platform also has the AEGIS weapon system that integrates all the combat components in a federated architecture, providing the operators with a combined tactical picture from all onboard and off-ship sensors (via secure communications channels).

The DDG has several performance characteristics important to the evaluation as well. It displaces almost 9,000 long tons fully loaded, and has a length of 505 feet, a beam of 66 feet, and a depth of 32 feet. Four General Electric LM2500 gas turbines – with a combined power generation of almost 80 MW – drive the two shafts that transfer power to the controllable pitch propellers to propel the ship at over 31 knots. The ship’s range is 4,400 nautical miles at its endurance speed of 20 knots. The design complement is 346 personnel, 22 of them officers. It has over 7,000 square meters of arrange-able area and over 30,000 cubic meters of volume in its hull and superstructure.

4.2 Flexible Platform Characteristics

One large difficulty with options *in* projects lies in the myriad of design variables and parameters present for possible evaluation of options (de Neufville and Wang 2006). The design of a flexible combatant platform must address the uncertainties associated with missions and mission requirements over the service life of the vessel; the Navy should design for variation instead of specification, as de Neufville and Scholtes (2011) reveal in their work. Therefore, the vessel used for this portion of the analysis gives careful consideration to typical changes that take place in a modified repeat design. Conveniently, these design aspects affect modernization of the existing vessel, not just modified repeats of the design. This study employs a simple case study to develop high-level considerations for modified repeat designs.

Three examples provide a good sense of the changes that take place during a modified repeat design effort. Interestingly, the first case study is the DDG 51 class, with its three variants. While this study uses the DDG 51 as its “inflexible” platform, it acknowledges that the platform has undergone several iterations in design since program inception. Therefore, studying these changes reveals design aspects a flexible platform should consider for low-cost modified repeats, and is in no way meant to imply the design is flexible. The Navy has executed modified repeats of the DDG 51 class because it was available at the time, and it was still cheaper to modify the existing platform than to create an entirely new design. The DDG 51 class currently has three versions in operation; with a third repeat design in process with the cancellation of the CG(X) program (O'Rourke 2010). Each subsequent design of the class incorporated new capabilities as technology allowed (e.g., AEGIS updates, satellite communications, upgraded Mk 45 gun, etc.), took other capabilities away (notably the Harpoon launchers, the SQR-19 towed arrays, and the Mk 16 weapon system), and in the most recent active version extended the hull longitudinally and added a helicopter hangar. Consequently, newer ships of the class changed in their space arrangements, compartment layouts, and installed equipment. The Hull, Mechanical, and Electrical (HM&E) systems among the different flights of the class are essentially identical. This is likely to change with the planned Flight III version of the class; since some of the combat upgrades may require more power, the Navy is investigating alternate power generation architectures like hybrid or Integrated Power Systems (IPS) (Ewing 2010).

The second example is the Ticonderoga (CG 47) class cruiser, which is a modified repeat of the Spruance (DD 963) class destroyer. The hull form, propulsion systems, and some of the combat subsystems were the same. However, the CG 47 incorporated the AEGIS combat system, including the SPY-1A radar. Consequently, it made large changes internally in space arrangements, compartment layouts, and power generation.

The final example of a modified repeat design is the dock landing ship class. The Whidbey Island (LSD 41) class is a modified repeat of the LSD 36 class that now supports diesel propulsion instead of steam and embarks two additional Landing Craft Air Cushions (LCACs). The Navy modified the class further to create a cargo variant, the Harpers Ferry (LSD 49) class. The cargo variant scaled back to only two LCACs, but added almost 1000 m^3 of palletized cargo storage forward of vehicle parking in the well deck (U.S. Naval Institute 2005). It also has greater air conditioning capacity and a cargo elevator, but only one heavy-lift crane. Each of these changes also precipitated changes in the general arrangements of the spaces and equipment on the vessel.

These examples reveal important design considerations for modified repeats and flexible architectures in general. The CG 47 case exhibits the need to consider power requirements for increasingly power-dense combat systems. If one is to design a ship for pre-planned modified repeats, one must evaluate all potential future power loads. Power distribution is equally important, although not specifically mentioned in any of the case studies. Each of the cases implies the importance of structures. In each case, mass properties distribute differently from one version of the design to the next. Intelligent design of the hull and support structure is significant to a successful flexible design so that structural considerations do not hinder potential capability upgrades. Each case also explicitly recognizes the importance of arrangements. Arrangements are perhaps the strongest consideration necessary for flexibility and for pre-planned repeats of a design. Indeed, a designer's job is simple if the capability/equipment removed for a repeat vessel has the same properties (e.g., space, volume, density, required service connections) as the capability/equipment added. Therefore, one of the most consequential elements of a design regarding its flexibility is the arrangements. Considerations for this aspect of the design include: the probability of a system's replacement/removal/upgrade, the placement of equipment within the ship and within a space, the method of connecting the system/equipment (e.g., bolts, welds, cables, service connections, etc), distribution of services (e.g., electrical power, cooling, HVAC), and adjacency to support equipment. One final consideration these cases imply is the planning of stability criteria and allowances for weight additions. The vertical center of gravity above the keel, the displacement of the vessel, and the metacentric height are sure to change during the vessel's service life, but the magnitude of the total change cannot be predicted well (i.e., Navy designers did not know how much weight AEGIS would add high on the ship during design of the Spruance class).

4.3 Flexible Platform

The analysis uses an early stage design concept called the Scalable, Common, Affordable, Modular Platform (SCAMP). A team of American and Hellenic Naval Officers at MIT developed this platform in 2011 as a design project starting with the idea of reducing acquisition cost by decoupling combat systems from HM&E. The Director of the Naval Engineering (2N) Program is able to provide full documentation of the vessel, including electronic design files and optimization routines. The team generated this idea from the fact that government furnished equipment – primarily in electronics and ordnance categories – accounts for over 50% of the acquisition cost of AEGIS ships (Parker 2010) (U.S. Navy 2010). Because of the method with which the team implemented this decoupling, they also designed several flexible measures into the architecture of their proposed platform (Brege, Page and Sarris 2011). The SCAMP aims to accomplish this through modularity, standard interfaces, use of fleet common components, and new design concepts in arrangements like cabling and piping "highways." The SCAMP can carry out the mission profiles of both the DDG and Ticonderoga (CG 47) class cruiser while incorporating enough flexibility to take on new or different mission requirements. Since it was designed with changing mission profiles in mind, it accommodates modified repeats of its design quite well. The project successfully created a baseline vessel that scales longitudinally into four other potential variants – each one meeting all standard design criteria (e.g., strength, seakeeping, powering) (Brege, Page and Sarris 2011). This analysis uses the 5-module variant, with characteristics similar to the latest ships of the DDG class.

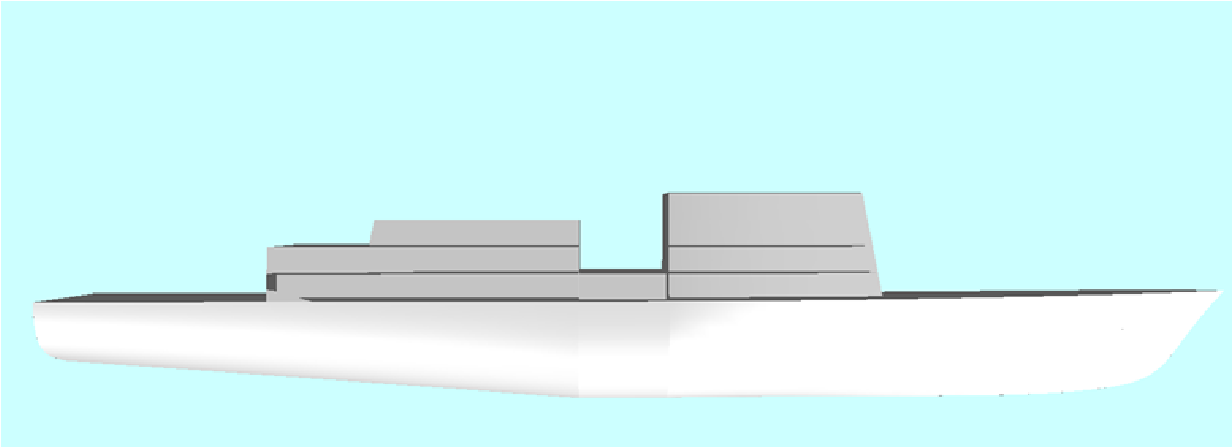

Figure 10: Profile View of The SCAMP

Figure 10 shows the profile view of the SCAMP. This does not reveal any of the combat systems; however, the mission profile of the SCAMP originates with those of the DDG 51 and CG 47, so the capabilities of the platforms match closely. The project team consciously chose not to include VLS cells, the SPY radar, or the associated equipment that helps operate those systems (Brege, Page and Sarris 2011). Instead, the platform allocates space amidships for modules and associated equipment for those capabilities. Figure 10 shows the smallest variant of the SCAMP, containing only one module space (the gap between the forward and aft superstructure). The SCAMP also has space and volume allocated on the forecastle[15] for another module, to which the team assigned a Mk-45 5” gun module for all baseline variants. The team designed the modules such that a 64-cell VLS fits within the dimensions of one module space. Further, the design allocates the space and volume adjacent to the modules for other equipment associated with the module (e.g., combat systems processors, extra berthing for personnel that accompany the mission module, etc.). The size of a module also accommodates a SPY-1F (arrays and equipment), or the arrays of the SPY-1D variant (with equipment in adjacent spaces).

The SCAMP has a much different mechanical and electrical setup than the DDG 51: it uses an IPS vice the traditional power system, which uses mechanically-driven propulsion and generates electricity separately. The incorporation of IPS offers several advantages for a platform like SCAMP, including: supporting high power (>4 MW) missions, reducing the number of prime movers, improving prime mover efficiency, providing flexibility for general arrangements, improving ship producibility, improving zonal survivability, and facilitating new technology integration like fuel cells (Doerry and Fireman 2006). Further, the approach to developing SCAMP's hull form is different. The team generated the hull using a Multi-Objective Genetic Algorithm that maximized internal hull volume while minimizing the estimated horsepower to move the hull 20 knots. Therefore, the internal area is over 11,000 m^2 and the internal volume is almost 36,000 m^3, but the hull form requires only 8.5 MW of propulsion power to sustain 20 knots, or about 40 MW to sustain 30 knots. The ship has 60 MW of installed power with the capability to expand to 120 MW or more, which should meet current and future (through end of service life) combat systems needs.

The SCAMP incorporates internal arrangement practices that support changing the capabilities of the ship. First, the design designates each of the spaces adjacent to the module spaces to support equipment for their respective modules and includes installation of FlexTech architecture, which allows the supporting equipment to be installed in a modular, open, nature as well (DeVries, Levine and Mish Jr 2010). Combat Information Central – the hub of combat systems control – also uses FlexTech architecture to accommodate potential frequent changes of the equipment. The two main spaces border the module spaces as well. This allows quicker access to the main spaces for equipment change out, repair, or upgrades through a hull cut or special door that allows direct access to the main spaces. This can provide significant time savings for rigging during maintenance and modernization periods of this vessel. Further, the mid-body section that houses the module spaces also has cabling and piping service "highways," which can simplify construction of different variants of the vessel because only the length changes; other design aspects are identical between module sections. Finally, as much as possible, the SCAMP incorporates the other flexible ship design characteristics from the preceding section. For instance, the SCAMP has an arrangement with a common galley for the messdecks and wardroom, uses common interfaces for service connections to all spaces, and places high-turnover equipment as close to a door or hatch as possible.

Table 6 summarizes some of these key characteristics of the two platforms for this comparison.

Table 6: Platform Comparison Summary

Key Performance Parameter	DDG 51	SCAMP (5-module)
LOA [m]	154	175
Beam [m]	20	20
Draft [m]	9.4	5.58
Full Load Displacement [MT]	9,042	8,915
VCG Service Life Allowance [m]	0.256	
Weight Service Life Allowance [MT]	1,218	
Internal Arrange-able Space [m^2]	~7,000	~11,000
Internal Volume [m^3]	~30,000	~36,000
Installed Propulsion Power [MW][16]	78	10
Installed Electrical Power [MW]	7.5	60
Propulsion Type	Mechanical	IPS

4.4 Choice Model

The real options analysis presented here models the results of the choices a manager makes over the life of a vessel. The analysis assumes the manager has only one choice model, which is dictated by the vessel in his charge. The choice model determines the rules the manager must follow when installing new capability on his respective platform.

The choice model for the inflexible platform (Choice Model A) reflects the current methods of installing new capabilities on these ships. Specifically, the analysis models a higher initial desired capability as the manager attempts to reach a point design, predicting how much capability is needed until the middle of the ship's service life. This choice model spends R&D money every year, and uses some procurement funding (OPN or WPN) installing small amounts of capability year by year. Then, near the ship's mid-life, the manager spends another significant amount of money to install the capability he predicts is needed until the end of service life. The model registers further R&D and procurement funding through the rest of the ship's service life at levels matching the first half of its life (N. Doerry 2011). The model does not account for the federal statute that stops modernization efforts 5 years prior to the vessel's scheduled decommissioning.

The choice model for the flexible platform (Choice Model B) uses the same R&D and procurement assumptions of the inflexible model. However, this choice model takes the mid-life modernization budget of the inflexible platform and distributes it evenly over the entire service life (N. Doerry 2011). In this way, the model overall assumes the flexible and inflexible platforms have the same budget over their life cycles instead of yearly, although this will not always be the case. This means in a case when the needed capability is always higher than the capability that can be achieved by either platform, each platform spends exactly the same research and installation budget. This budget normalization removes fiscal concerns as a variable in the comparison and allows for comparison of installed capability under constant budget terms. This choice model also only looks at the current capability gap, as opposed to a predicted capability need at some time in the future, and only installs the capability if needed now. This aspect of the model allows the assessment of the value of agile responses to capability needs versus using the predictive method of Choice Model A.

4.5 Service Life Cost and Capability Simulation

The model originates from the MIT Cost Model for early stage design that is taught and used in Course 2N (formerly 13A), the Naval Engineering program. That model uses parametrics and cost estimating relationships based on mass properties of the ship to calculate construction costs, acquisition costs, and operation costs. It is an adequate starting point for this analysis since it is roughly calibrated to a destroyer-type ship. This analysis first simplifies the model, and then rebuilds it with new analysis capabilities. The model does this in order to satisfy the basic criteria set forth for this type of analysis by de Neufville, Scholtes, and Wang (2006): 1) standard spreadsheet procedures familiar to many, 2) data available from public sources, and 3) intuitive graphics to explain the results.

First, the state of the old model necessitates simplification. The old model was a conglomeration of two separate, previous models: one for construction and acquisition costs, and one for life cycle costs. The method of conjoining these models into a holistic view of the costs of a ship was suboptimal and cumbersome to the user. Therefore, the new model consolidates all inputs and separates them categorically. It also adds notes, commentary, and data sources to allow future users to better understand what the inputs are, what they mean, and where the data originates. Figure 11 provides a screenshot of the input to the model to clarify these improvements.

Description	Variable Shorth	Value	Units	Source	Comments
Weights					
SWBS Group 100 Weight	SWBS_100	2843	LT	Designer Input	
SWBS Group 200 Weight	SWBS_200	721	LT	Designer Input	
SWBS Group 300 Weight	SWBS_300	425	LT	Designer Input	
SWBS Group 400 Weight	SWBS_400	400	LT	Designer Input	
SWBS Group 500 Weight	SWBS_500	808	LT	Designer Input	
SWBS Group 600 Weight	SWBS_600	538	LT	Designer Input	
SWBS Group 700 Weight	SWBS_700	331	LT	Designer Input	
Weight Margin	MARGIN	514	LT	Designer Input	
Loads	LOADS	1550	LT	Designer Input	
Production Assumptions					
Assumed Profit	PROFIT	10.00%	%		Will vary by contract, 15% seems pretty conservative.
Learning Curve	LEARNCURVE	95.00%	%	2005 Cost Estimating I	Section 5, Pages 98-100
Number of Ships in Class	CLASS_SIZE	71	dmnl	Designer Input	
Production Rate	P_RATE	0.5	ships/year	Designer Input	
Crew					
Officer Crew Size	OFFICERS	29	person	Designer Input	
CPO Crew Size	CPOS	24	person	Designer Input	
Enlisted Crew Size	ENLISTED	294	person	Designer Input	
Average Officer Pay	OPAY	102488	$/person	VAMOSC (more fideli	These are direct costs only, base pay, allowances, and special pay. This does not include indirect costs
Average CPO Pay	CPOPAY		$/person	VAMOSC (more fideli	like base housing, education assistance, commisary, family support services, medical, professional
Average Enlisted Pay	EPAY	64219	$/person	VAMOSC (more fideli	training, VA benefits, recruiting, or child care and educational services.
Miscellaneous for Life Cycle Cost					
Base Year	BASE_YEAR	2010	year	Designer Input	Should match base year of CERs and inflation indices. I chose this year because this was the last year with data availabe at the time of this analysis.
Average Inflation Rate	INFLATION	1.70%	%	https://www.ncca.na	2005 Cost Estimating Handbook, Section 5 page 101, lots of references to Global Insight
Discount Rate	DISCOUNT	2.30%	%	http://www.whiteho	Please note that this should depend on the service life of the ship and that the real, not nominal, rate is used.
Post-Shakedown Availab	PSACF	5.00%	$/$	Designer Input	Percentage of Construction Cost, incurred in year of IOC (assumed).
Ship Service Life	SERVICE_LIFE	30	years	Designer Input	

Figure 11: Sample of Simplification of Model Inputs

The model does not change the deterministic procurement cost calculations. Instead, for increased visibility and understanding, it changes the number of vessel costs calculated. The previous models allowed users to designate which vessel costs to display; for instance, the first and the last vessel, or the first and the 10^{th} vessel of the class. Now, the model always calculates the cost of the first (or lead) vessel, the average vessel (based on learning curve (Ostwald 1992)), and the final vessel of the class. The calculations use several cost-reducing assumptions unique to the SCAMP. These include, but are not limited to: reduced electronics costs because of equipment selection; lower ordnance costs due to the exclusion of certain combat systems; reduced planning and engineering costs because of the efficiency and commonality of the designs between several variants of the SCAMP; and increased learning curve effects due to a simple design and assumed levels of automation (Brege, Page and Sarris 2011) (U.S. Navy 2004). The deterministic portion also calculates notional O&S costs of the vessel. However, the calculations now use linear regressions derived from the class averages for DDG 51 for each of 5 categories: manpower, operations, maintenance, support, and modernization (U.S. Navy 2010). Previously, the O&S costs were simply a ratio of the lead ship construction cost. Therefore, the new method adds some fidelity to the model and allows changing of specific items within O&S costs, e.g., manpower reductions due to automation on the vessel reduce the respective manpower costs. All of these costs sum to give the estimated life cycle cost. The output of the model summarizes these calculations to allow the user to see lead ship, average ship, final ship, and class budgets, as appropriate.

Next, the new model expands beyond current abilities by incorporating a comparative analysis of capabilities and costs between the inflexible and flexible platforms. This is the basic function of the Capability Simulator: to compare the two ships – flexible and inflexible – using the appropriate choice models for capability expansion. To accomplish this, the model simulates capabilities and their costs on a yearly basis through the entire service life of the ships. The capability simulation follows a Markov process, where no memory is kept of the capability previously achieved. Instead, it uses the current capability achieved and a distribution of capability desired to determine the capability goal for the next time increment. At each time increment, the model records several parameters that aid the analysis of the alternatives:

1. The Year.
2. The projected required capability for Choice Model A.
3. The actual desired/required capability of a US Navy vessel at that moment in time.
4. The capability achieved using Choice Model A.
5. The capability achieved using Choice Model B.
6. The gap between capability desired and that achieved.

7. The cost ceiling at each moment in time.
8. The money spent to purchase capability at each moment in time.
9. The cost for that capability.

Finally, this part of the model feeds a Monte Carlo simulation that runs the Capability Simulator 1000 times, records selected results, and calculates new ones. The Monte Carlo process uses 1000 runs because the standard error of the mean for that number of runs is within 4%, and in most cases is less than one half of one percent. The general results of the model do not change on subsequent runs, further validating this selection.

Most of the recorded results are snapshots of the final year of the vessels' service lives. These reveal whether Choice Model A or Choice Model B achieves better iso-performance characteristics[17]. Other recorded results average over the vessels' lifetimes and represent how well the choice models perform throughout, not just at the end of service life. The new results produced during the Monte Carlo simulation runs are counts of how often:

1. Choice Model A over-predicts needed capability.
2. The inflexible platform has too much capability at end of service life.
3. The flexible platform has too much capability at end of service life.
4. The flexible platform spends less money than the inflexible one.
5. The average capability delta is less on the flexible platform.
6. The final capability delta is less on the flexible platform.

Throughout the model, Overall Measure of Effectiveness (OMOE) is the surrogate that represents capability, as derived through an Analytical Hierarchy Process (AHP). This process is a type of multi-attribute decision making model that simplifies the decision making process by transforming multi-dimensional decision problems down to a single criterion – OMOE (Whitcomb 1998). AHP is the method of choice for several reasons. First, it allows the use of hierarchy, as opposed to all measured attributes being directly weighted against each other, making it preferable to a simple weighted sum method. Second, AHP allows subjective information to be effectively included in the decision process, making it better than the hierarchical weighted sum method. Last, since the model develops OMOE from existing platforms, there is no reason to include risk profiles or uncertainty of the performance of the platforms for the criteria used, precluding the use of the multi-attribute utility method. Table 7 displays the Measures of Performance that encompass the Measures of Effectiveness that define the OMOE for this study.

Table 7: Measures of Effectiveness and Measures of Performance for OMOE

Measure of Effectiveness	Measure of Performance	Example Criteria
Perform Primary Missions	Undersea Warfare	SONARs, helicopters
	Surface Warfare	Guns, surface radars
	Air Warfare	Air radars, SAMs
	Mine Warfare	Magnetic signature control
	Naval Surface Fire Support	Gun range, firing rate
	Strike Warfare	Number of launch cells, type of missile
	Ballistic Missile Defense	Full, degraded, no capability
	Unknown/Future Capability	
Perform Secondary Missions	Communications	Data bandwidth, # voice channels
	Command and Control	Secure data channels, links
	Mobility/Manning	Surrogate for level of automation
	Non-combat Operations	Refuel aircraft in flight
	Unknown/Future Capability	
Seaframe	Speed	Faster is better
	Endurance	Farther is better
	Survivability	Collective Protection System, flooding
	Seakeeping	Roll period, static/dynamic stability
	Service Life Allowances	More is better

The AHP assigns weights both to the Measures of Performance, dictating how they affect the Measures of Effectiveness, and to the Measures of Effectiveness, dictating their affect on the OMOE. Pairwise comparisons determine the appropriate weights for each of the measures. Appendix D displays these pairwise comparisons and the resulting weights. The AHP process produces an OMOE for six different ships: USS Spruance (DD 963), USS Arleigh Burke (DDG

51), USS Mahan (DDG 72), USS Oscar Austin (DDG 79), USS Zumwalt (DDG 1000), and the unnamed DDG 116. The analysis uses these ships because they are all destroyers, and thus show the trend of capabilities built into these types of ships over time. Also, the analysis uses the capabilities of these ships as they were built; it does not account for any subsequent modernization that took place on the vessel, e.g. vertical launch cells on the USS Spruance or BMD on the USS Arleigh Burke. The AHP projects values for DDG 116 and DDG 1000, since those platforms are not built yet[18]. The process produces OMOEs normalized to the year 2010, meaning that the AHP evaluates each platform's capabilities based on current mission needs, not the needs of the vessel at the time it was built. This method seems initially unfair to the classes of ships that were built over 30 years ago, but this fact is part of the point of this thesis: if the Navy still operated those ships today they would be severely lacking in capability. Therefore, this method is a more accurate and appropriate measure of the trends of capability over time. Table 8 summarizes the results of the process and includes two other important data points: the year the ship was ordered and its cost.

The ship costs for this analysis also use several assumptions. First, the cost of the DD 963 uses an average cost for the first 16 ships of that class. The first Selected Acquisition Report[19] (SAR) available is from 1973, at which time the Navy had already ordered several ships, including 5 ships in 1970 alone. Therefore, it seems reasonable to use this average number because ordering this many ships at once helps to decrease the normally higher cost of the lead ship. Second, the cost of DDG 51 is from the March 1986 SAR, which is before the Navy ordered the DDG 52. Thus, this number represents the cost to get just the lead platform operational, before spreading the R&D costs over several platforms. Third, the costs for DDG 72 assume that the construction costs are the same as those for DDG 51 (in $FY10). This is because the Navy ordered 5 ships at once with the DDG-72 and there was 20 ships worth of learning curve by that time as well, and those two factors represent a $950M discount from what the cost would have been if it were the first ship of the class. A more reasonable assumption for this analysis is that the first 20 ships were never built and the class started at DDG 72 instead of DDG 51. Further, the costs for this ship assume that the R&D spent includes all R&D spent from program inception until 1992. Thus, to accurately create R&D costs for DDG 72, the process assumes that DDG 51 through DDG 71 are "deferred" but that all R&D continues to take place to develop the DDG 72. The costs for DDG 79 and DDG 116 make these same two assumptions. The costs for DDG 1000 assume that since the Navy ordered the first two ships of the class at the same time, the lead ship costs are the average of those two ships, as reported on the March 2007 SAR. The cost reductions from this strategy are unlikely as extensive as they were on DD 963, but no publicly available data exists that breaks out the construction costs of these vessels separately.

Table 8: Summary of Ship Data

Ship	Year Ordered	Lead Ship Cost ($FY10)	OMOE
DD 963	1970	383,900,000	0.254187
DDG 51	1985	3,059,100,000	0.498814
DDG 72	1992	3,870,400,000	0.525362
DDG 79	1994	4,152,900,000	0.552360
DDG 1000	2008	5,621,300,000	0.637538
DDG 116	2016	6,367,100,000	0.642358

This data develops trends that help reveal the cost of capability on naval vessels. Generally, the data show that capability gets more expensive both with time and with higher baseline capabilities. They also show that both lead ship costs (in constant $FY10) and the desired capabilities of destroyers continue to grow with time. The Capability Simulator uses regressions from Table 8 to create the values of cost and capability. Specifically, the simulator uses (see Appendix E for greater detail):

1. A regression of OMOE versus time to generate
    a. The projected desired capabilities and
    b. The distributions of capabilities for the Markov process
2. A regression of ship cost versus time to generate the budget available for the lead ship of a class in the year it is ordered
3. One of two projections for the cost of capability:
    a. A regression of cost versus OMOE[20]
    b. A regression of cost for OMOE versus time[21]

The Capability Simulator calculates several values at a yearly time increment. First, it shows what the Projected Required Capability is for the inflexible platform, as well as the actual Desired/Required Capability at that moment in time, which applies to both platforms. Next, it determines the Achieved/Afforded Capability by taking the user-designated cost-per-capability and applying a cost ceiling that includes both R&D and Procurement budgets. Then, it tracks the Capability Gap (between Desired/Required Capability and Achieved/Afforded Capability) and the amount of money spent in the current time increment.

The Capability Simulator contains six logical switches that allow the user to test different scenarios by typing a "1" or a "0" as an input that corresponds to an outcome in the Simulator. One can consider whether to:

1. Distribute the mid-life budget from Choice Model A throughout the service life of Choice Model B or whether the total budget of Choice Model B lacks this funding
2. Include the average annual R&D budget of DDG 51 in the cost ceilings of both Choice Models or not
3. Use the capability-based cost-for-capability curve ($/OMOE) or the time-based cost-for-capability curve ($/OMOE/t)
4. Use an aggressive or conservative regression for the time-based capability curve
5. Use an aggressive or conservative regression for the capability-based capability curve
6. Assume a high or low degree of variability (standard deviation) for the Desired/Required Capability and Projected Required Capability calculations

The Capability Simulator implements several rule sets to ensure the behavior of the model is realistic. First, it does not allow budget expenditures in excess of the cost ceiling. Second, if there is enough money budgeted to match the capability projected (Choice Model A) or the capability currently desired (Choice Model B), it ensures that only enough of the budget is spent to match those capabilities. Thus, the Simulator allows both Choice Models to spend only what is needed and prevents buying too much capability. However, when a platform and its Choice Model meet the desired capability, but capability desired subsequently decreases because of the volatility embedded in its calculation, the Choice Model does effectively buy too much capability because of the next rule. Third, the Simulator implements a rule that does not allow for "selling" of capability. That is, if either choice model achieves the desired capability, and then desired capability reduces (leaving the platform with "too much" capability), the Model cannot reduce the capability previously bought. Fourth, for Choice Model A, the Simulator does not allow the purchase of capability during construction, but allows that flexibility for Choice Model B. This rule attempts to simulate the concept of design lock-in, which is less necessary on the flexible platform used with Choice Model B. There is also a rule set that only allows the Simulator to run through the end of service life. This way, the user need only change the service life input and the Simulator automatically adjusts its calculations to support this change. Other rule sets implement the logical switches discussed previously that dictate which inputs the Simulator uses.

4.6 Assumptions

The set up of the Capability Simulator required several assumptions. Each is detailed below with an explanation of the rationale.

The Simulator assumes that the Navy program managers make rational decisions. These managers have the freedom to make intelligent decisions based on data available and are not encumbered by politics or other potentially irrational externalities. They follow the rule sets mentioned above and agree with the philosophy of iso-performance.

The Simulator assumes the two ships compared within have similar budgets. Thus, the mid-life upgrade budget of the DDG 51 distributes evenly throughout the service life of the flexible platform, the SCAMP. There is a logical switch to change this, but all simulation runs designate this switch such that the budget is evenly distributed. This means that if both vessels (with their respective Choice Models) are unable to achieve the Desired Capability, and consequently spend their full modernization budgets, then both vessels spend the exact same amount of money over their service life.

The Simulator incorporates inputs beyond the regressions and volatilities mentioned so far. For instance, it has an input called "cost fraction" which represents the fraction of installation cost to install capabilities during the service life versus during construction. The rationale for this input is the notion that it is more cost effective to install equipment prior to the ship's completion and launch. Submarine shipyards use a 3-5-8 rule of thumb that means if equipment installation costs 3X to install at the workbench level, it costs 5X to install when the ship is in the module or super-module phase of construction, and 8X to install once the ship is mostly assembled and launched. Thus, the model assumes that installation costs during the service life are 160% of the expense during construction. Further, the Simulator uses a variable called "flex cost fraction" that represents the relative cost of equipment installation on a flexible platform versus an inflexible platform. It balances the higher installation cost during a ship's service life using the same "3-5-8" principle. Since the SCAMP has modular spaces that facilitate easy installation and removal of equipment and incorporates smart arrangements for other equipment, the model assumes that installation costs on the SCAMP are 60% of those on the DDG 51.

Additionally, the model designates specific variability for the capability predictions of Choice Model A and the Markov process that determines capability desired during each time increment. Specifically, for the capability predictions of Choice Model A, the simulator uses variability that inserts an uncertainty band of 0.1 OMOE units around the predicted values from the OMOE versus time regression. This value represents two standard deviations based on the regression statistics, giving a 95% confidence interval of the results. Further, this allows some scenarios in which the predicted capability needed at full service life is less than that at the middle of the service life of the vessel, which is realistic and necessary. The derivation for the variability of the Markov process is different. The method dictates the variability based on desired outcomes. Specifically, the NORMDIST function in Excel solves for a value for variability which creates a 20% chance that the desired capability decreases from one year to the next. This value provides increased variability in the short term while mimicking the long term trends seen in the regression.

All values for cost and capability reference to Fiscal Year 2010. Thus, another assumption is that both the capability trends and the cost trends represented in the O&S costs and used in the regressions continue into the future. The trends account for 40 years worth of cost data, so the model uses these assumptions on cost for projections 40 years into the future. The capability measures also include 40 years of history, but have less certainty to them, particularly 40 years into the future. The certainty of the financial markets and inflation (and the costs of ships) is relatively known and predictable compared to that of technology and military capability. The world is more likely to witness step increases in military capability in the coming years with electromagnetic rail guns, free electron lasers, and upcoming detection technologies, while the global market is less likely to experience step increases in the value of all goods. Even the costs of ships, although they may experience inflation higher than other national indices, should remain more stable into the future (U.S. Congress 2010). This uncertainty in capabilities detracts from any arguments pertaining to the questionable accuracy of the AHP, because with so much uncertainty, accuracy in a capability model becomes more irrelevant.

Each of the values used in the AHP are assumptions. The Process is the best method to determine a uniform capability measure, but each of the inputs and each of the weights are the opinions of the author, and are therefore debatable. A strength of the AHP is that each of the Measures of Performance follows a fairly defined rule set, and thus all the results are consistent with that rule set. Further, the AHP weighs each of those Measures against each other, so that unless one's opinion differs *significantly* from the author's, the changes are inconsequential. For instance, if one argues that the author's assumptions for the Performance of Command and Control are off by a factor of 2 (i.e., significantly), this changes OMOE by less than 10%. Therefore, the variability the Simulator places on the OMOE predictions over time covers any uncertainty in the author's assumptions in the AHP reasonably well. A subsequent experiment tests the response of the model to this variability.

4.7 Base Case

The results of Monte Carlo simulation using the aforementioned assumptions and mechanics demonstrate the value of flexibility to the Navy. The Navy benefits both operationally and fiscally if it identifies sources of uncertainty and incorporates flexibility in the architecture of a platform to capitalize on or avoid those uncertainties, as appropriate. As the mission profile required of a surface combatant is highly uncertain through its service life, the Navy needs a platform that can adapt quickly and easily to changing mission profiles. The SCAMP may not be the best solution, but its design principles are a step in the right direction.

The deterministic procurement costs for the SCAMP are encouraging, if unsurprising. All of the changes to the deterministic portion of the cost model imply cost reductions throughout procurement. At this time, the model does not balance the projected savings from a flexible platform with the risks associated with such a platform. Brege, Page, and Sarris (2010) recommend managing the risk of the design and build process for this platform by increasing the R&D budget to fully vet the platform through extensive systems engineering, systems architecture, and program management processes. Nevertheless, the analysis shows that a vessel with flexible architecture, modular payloads, and hull optimized for construction and arrangements saves the Navy money. Table 9 shows the Program Average Unit Cost that is reported to Congress on the SAR. This data supports the deterministic results of the model; it shows the results are within 3% of the numbers reported to Congress for the DDG 51 class (U.S. Department of Defense 2010).

Table 9: Program Average Unit Cost Comparison, Model versus Actual ($M)

Platform	Base Year	Program Acquisition Cost ($Base Year)	# Ships	Program Average Unit Cost ($Base Year)
DDG 51[22] **-** as reported on SAR	1987	56,591.7	71	797.1
DDG 51[23] **-** inflation adjusted	2010	94,259.1	71	1,327.6
DDG 51 – model results	2010	96,836.0	71	1,363.9
Difference	0	2.7%	0	2.7%

By comparison, the projected cost for 71 ships with the SCAMP's design is $65,570 million, which means its average unit cost is about $920 million. Next, Table 10 compares the acquisition costs of the two platforms used in this study. Note that all of these values are results of the model, and should only be interpreted as representative of the costs of the two vessels. The amounts representing the model outputs do not match between Tables 9 and 10 because of rounding errors. Although Table 10 reports a slight increase in cost for the lead ship of the SCAMP versus the lead ship of DDG 51, on average, the Navy could save around $400 million per ship for a similar class size.

Table 10: Procurement Cost Comparison ($FY10, millions)

	Inflexible Platform (DDG 51)			Flexible Platform (SCAMP)		
	Lead	Average	Class	Lead	Average	Class
Procurement	1,700	1,260	92,280	1,380	850	62,500
R&D	1,130	50	4,550	1,530	20	3,070
Acquisition	2,830	1,310	96,830	2,910	870	65,570

Table 10 shows a flexible platform such as the SCAMP may cost a little more than a DDG 51 for the lead ship of the class. However, the architectural flexibility to change missions and the intelligent arrangements of equipment saves the Navy money with each subsequent vessel of the class ordered. Also, to be clear, the SCAMP represents a vessel with less built-in capability than the DDG 51, so these results effectively show that the Navy spends less money to get a relatively less capable ship, at least at the completion of the acquisition phase. However, the SCAMP does meet the requirements of a combatant vessel, but does so in an un-optimized and less-integrated manner. Specifically, a strike warfare capability is not integrated in the baseline of the SCAMP, but, the cost to install strike capability modularly is less than the $400 million cost savings represented in Table 10, so the Navy can still meet all requirements for less money. The Capability Simulator and Monte Carlo analysis provide interesting results for the capability and cost of the two platforms after acquisition and prior to disposal.

The results of the Monte Carlo analysis demonstrate cost avoidance and improved capability-matching for a flexible platform. Figure 12 shows the cumulative distribution functions (CDF) of the various capability measures tracked in the Capability Simulator by the Monte Carlo analysis, as de Neufville, Scholtes, and Wang (2006) suggest. It reveals that, on average, the flexible platform achieves a higher capability at the end of service life.

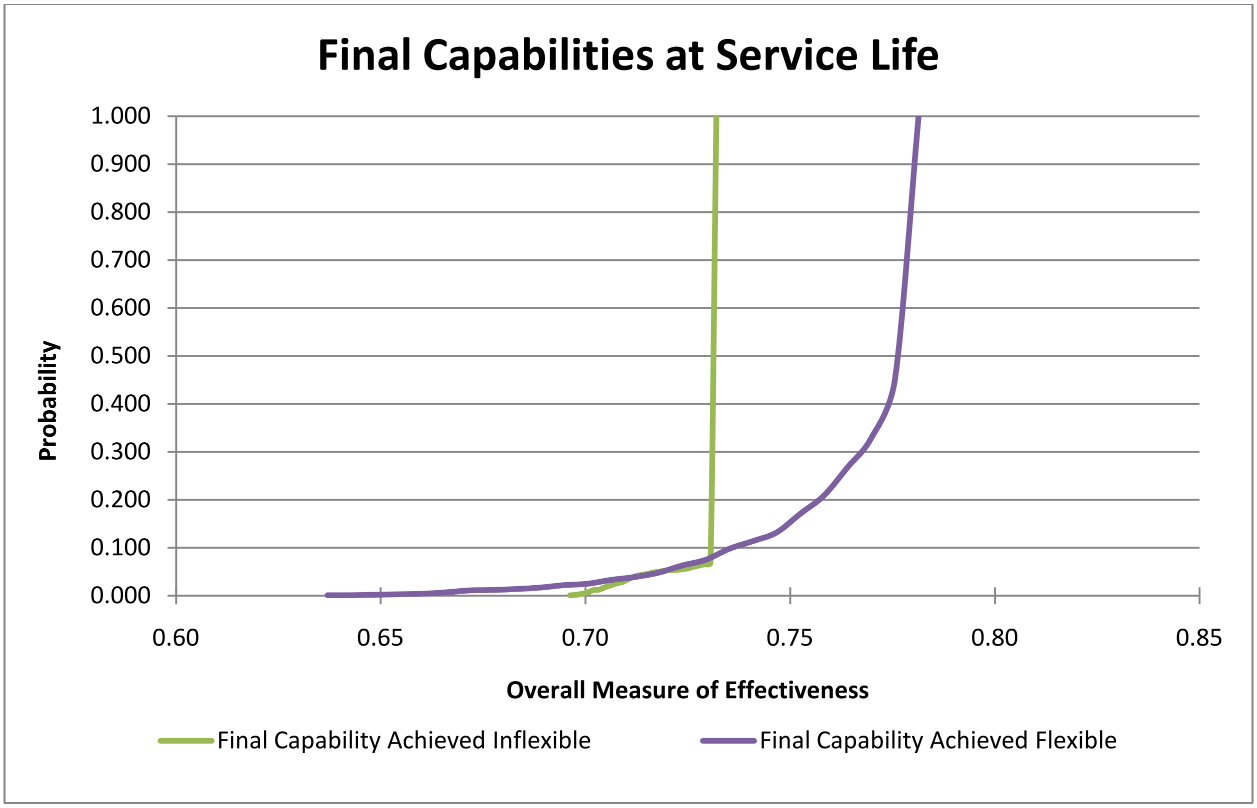

Figure 12: Cumulative Distribution Functions of Final Capabilities

To help round out the analysis, the Monte Carlo analysis provides more amplifying information. It tracks the number of times either of the platforms buys too much capability. The inflexible platform buys too much capability in 50 of the 1000 scenarios, while the flexible platform buys too much capability in 44 of the scenarios. A difference of six runs out of a thousand may seem insignificant, however, it is consistent; with each subsequent run of the Monte Carlo simulation, the flexible platform over-purchases capability in a fewer number of scenarios. Figure 13 displays the CDFs of both the average and final differences of capability for the two platforms and Choice Models.

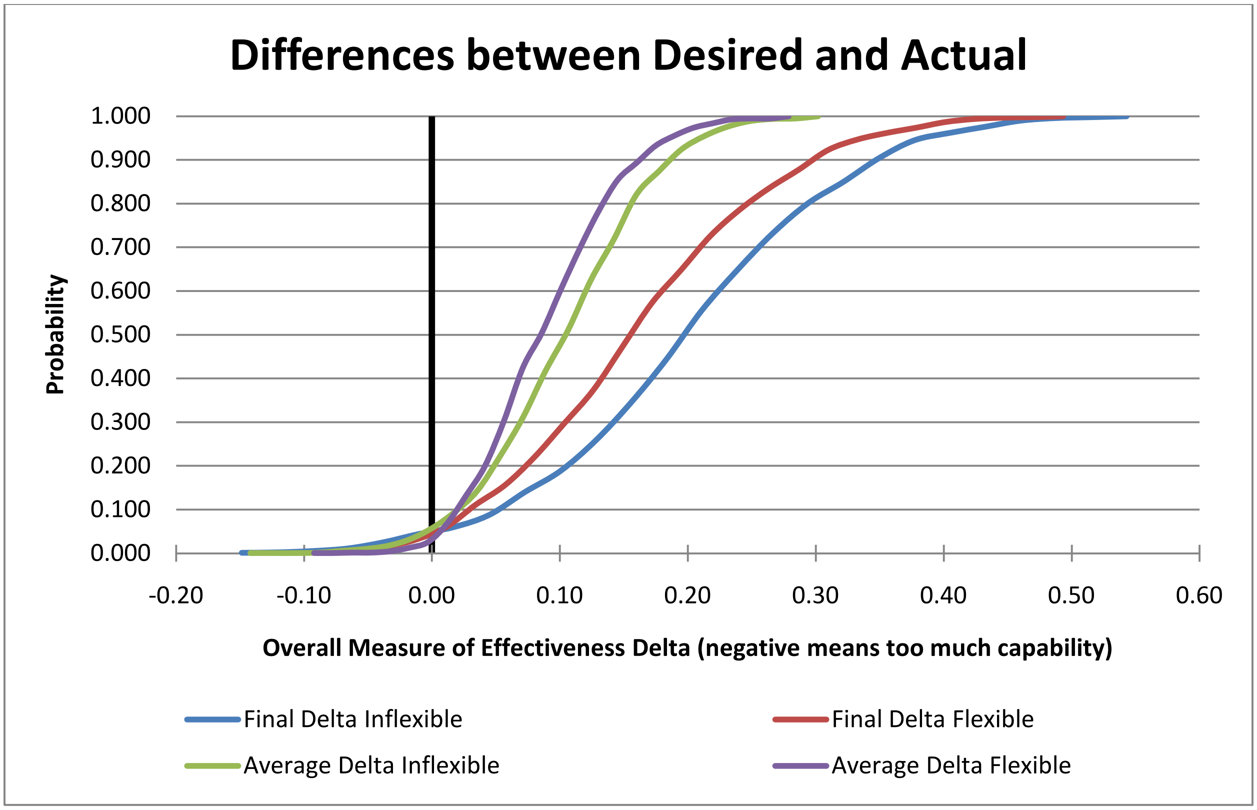

Figure 13: Cumulative Distribution Functions of Capability Gaps

Figure 13 provides additional insight on the difference between the two vessels and their Choice Models. The ideal results are the black vertical line at 0.00. Such a line represents perfect iso-performance, in which the exact amount of capability needed is achieved at all times. This is unrealistic, though, because of the assumption that capability installed on the platform cannot decrease (and certainly cannot do so without some cost). Although an ideal solution is unrealistic, the best results are still those that are closest to ideal. In both metrics, the flexible platform is closer to ideal. Another interesting result is that the ideal solution at 0.00 acts as a crossover point for the solutions, so that no matter whether the Choice Model purchases too much or too little capability, on average, the flexible platform is always closer to zero. In fact, the Monte Carlo analysis reports that this is the case in about 94% of scenarios.

The costs associated to purchase the capability on each platform provides one last data point to confirm the benefits of flexible architectures. So far, the results show that a flexible platform, on average, achieves more capability and more closely matches the desired capability throughout the vessel's service life. But, a valid question is: at what cost? Figure 14 shows the modernization costs, including both R&D expenditures to develop the systems and the installation costs to put them on the respective vessel.

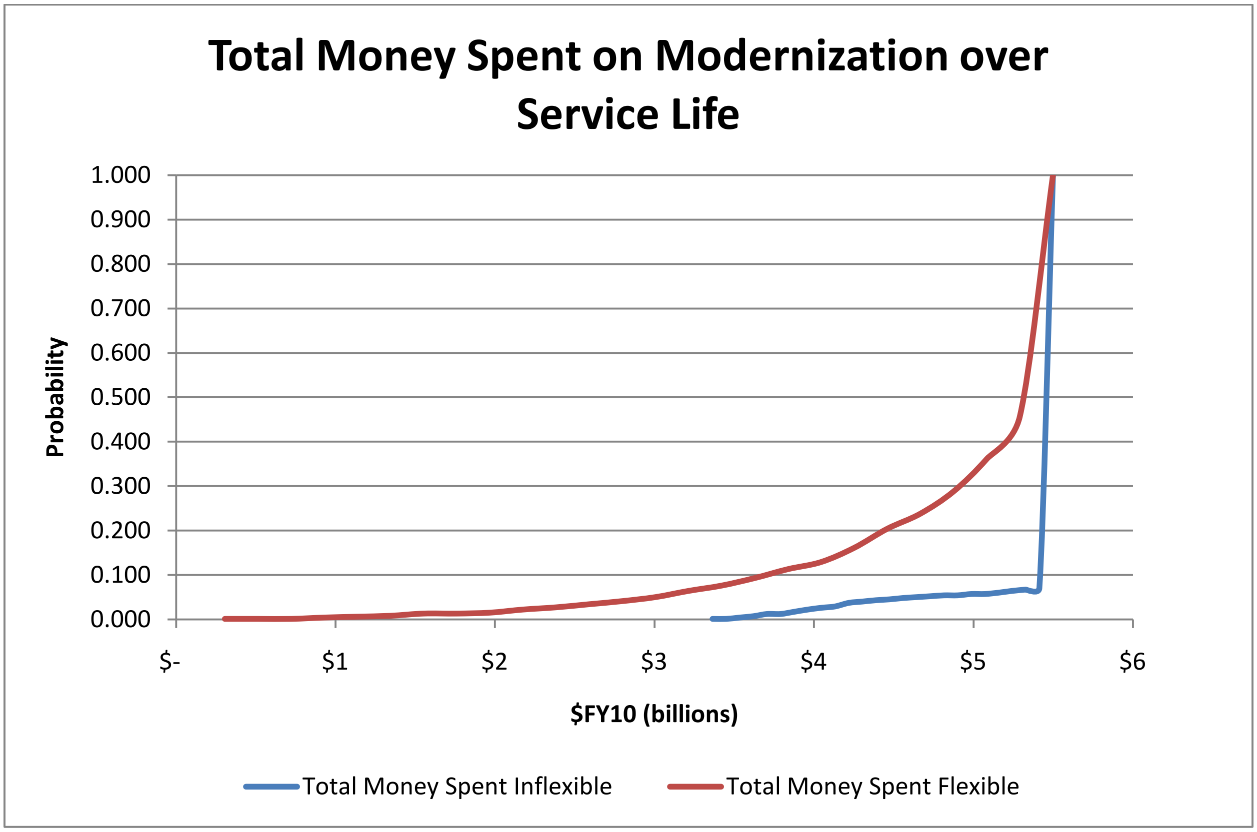

Figure 14: Cumulative Distribution Functions of Modernization Costs

Figure 14 clearly illustrates cost avoidance by using the flexible platform and its Choice Model. The raw data for Figure 14 cites that, on average, the flexible platform spends less money about half the time, and the remaining half is scenarios in which both vessels spend their maximum budget each year. Coincidentally, further analysis reveals that the flexible model spends less or equivalent money in about 94% of all scenarios, similar to its results for matching the desired capability. The interesting caveat to this result is that upon deeper investigation, the Capability Simulator reveals that in the 6% of scenarios where the inflexible platform spends less money, it is because its Choice Model predicts a small capability needed at the middle of its service life, which it quickly achieves, and therefore stops spending money. However, this is always an under-prediction of capability needed, and the inflexible platform always falls short of capability needed at the end of service life in these scenarios. So, Choice Model A spends less money in these scenarios, but at the cost of a far greater gap in capability.

Therefore, the results of the simulation show that a flexible platform achieves greater capability at the end of service life (when appropriate), is better at matching the desired capability at any moment in time, and accomplishes these feats using less money. This scenario is better by every measure, and seems too good to be true. Thus, a complete analysis requires more rigorous model testing. The results hold more credence if the model performs similarly under varying conditions and assumptions. With the additional testing, the characterization goes beyond creating a model and assumptions to support the cause of flexibility, verifying the results occur naturally because of the inherent value of flexible platforms.

4.8 Robustness/Sensitivity Check

The final analysis tests the robustness and sensitivity of the model to varying assumptions. The results – that properly designed flexibility is more valuable to the Navy than current design practices – are more powerful if this analysis shows that the model produces these results under a multitude of conditions, not just those created for the base case analysis. Therefore, to accomplish this, a final model check varied six of the main assumptions of the model. It tested these assumptions using a full factorial (2^6) design of experiments.

Although all assumptions for the model are subject to skepticism, some stand out as particularly uncertain or worthy of testing. The first assumption tested is the installation cost fraction. Quite possibly, installation costs are not 160% more during service life. Therefore, the experiment also tests a 100% cost ratio. In reality, a 100% cost ratio might be more accurate considering the model uses the aggregate costs of R&D and installation, and: 1) R&D costs are not likely to increase significantly beyond those of the acquisition phase, and 2) R&D costs are the majority of the budget. However, non-recurring engineering costs for modified repeats make a case for some value greater than 100%. Irrespective of what the true value should be for a single analysis, this new value represents an optimistic case versus the baseline case.

The second assumption tested is the fraction of cost savings that a flexible platform affords the Navy. The baseline case assumes a ratio of three to five based on the "3-5-8" rule. However, the worst case scenario is if the flexibility provides no cost savings over the standard platform. One could create a scenario in which flexibility costs more, but the scenario would be contrived, specific, and, I would argue, unlikely. Therefore, the examination tests the model with the baseline 60% of inflexible installation cost, as well as the worst case scenario, 100% of the cost.

Another assumption tested is the variability of the capability projections, both in Choice Model A (predicting half- and full- service life capabilities) and Choice Model B (the Markov process of yearly capability desired). Since this measure is also a surrogate for the accuracy of the AHP that develops OMOE, the experiment should allow this to vary quite a bit. Therefore, the experiment allows the variability to double from their baseline values.

Lastly, a critical assumption is the cost of capability. Both capability and its cost derive from regressions based upon the author's opinion of capability and the assumptions made about the cost of lead platforms. However, the simulations inevitably calculate values outside the range of data points created. While regressions are very good for interpolation, they do not work well for extrapolation (which this analysis requires). Therefore, the assumptions of the cost of capability must vary for these tests as well. The tests switch between two possible representations for the cost of capability. One representation assumes the cost of capability is time-based: the money paid for equivalent capability trends a certain way over time. The regression of cost/capability/time (Figure E-2) provides these data. Alternately, the second representation assumes that the cost of capability is based on current capabilities: the budget required to reach the next increment of capability depends on the current state of technology. The regression of cost/capability (Figure E-1) provides these data. Further, both of these representations contain their own uncertainty of outcomes. Therefore, not only do the tests check the outcome of one representation versus the other, but also incorporate conservative and aggressive scenarios within the regressions of data points.

Thus, the examination of robustness of the model and assumptions conducted 64 experiments with 1000 simulation runs each. An additional hypothesis was that some of these experiments should produce very similar results because two of the factors are dependent on a third. For instance, if an examination run uses the time-based capability, then the regression curve the model uses for the capability-based representation is moot, and the two experiment runs that only switch that curve should match very closely (within experimental error for 1000 runs, at least). The reason the full factorial is still necessary is that the initial capability afforded by the ship only depends on the cost per capability curve at this time, with no consideration given to the time-based capability curve for determining the starting point. Table 11 summarizes the six factors and their "high" and "low" values as tested in this experiment.

Table 11: Factors and Values for Design of Experiments

Factor	HIGH value	LOW value
Installation Cost Fraction	160%	100%
Flexible Cost Fraction	100%	60%
Time-based Cost Curve	Linear with DD 963 $\frac{\$}{OMOE} = 170{,}382{,}041 * YYYY - 332{,}893{,}871{,}541$	Linear w/o DD 963 $\frac{\$}{OMOE} = 113{,}811{,}860 * YYYY - 219{,}560{,}391{,}522$
Capability-based Cost Curve	Power $\frac{\$}{OMOE} = 24{,}175{,}645{,}622 * OMOE^{3.002603}$	Linear $\frac{\$}{OMOE} = 14{,}509{,}074{,}139 * OMOE - 3{,}612{,}918{,}980$
Cost Curve to Use	Capability-based	Time-based
Variability	Double	Single

The results of the robustness experiment further support the thesis that flexibility provides value to the Navy. The results from the baseline case showed that a flexible platform achieved more capability on average, and accomplished this while spending less money on average. Those results establish the benchmark for the comparison with other experiments. Appendix F includes all results of the experiment. Fifty-five of the 64 experiments provide the same results as the baseline. The four experiments reported in Table 12 result in the opposite conclusion: flexibility and Choice Model B are worse. The five experiments reported in Table 13 have marginally worse results than the baseline case. However, the patterns of these nine experiments prove that the model works realistically and is mechanically satisfactory, and that the combination of assumptions is important to the results.

Table 12: Scenarios in Which Flexibility Provides Less Value

Scenario	Installation Cost Fraction	Flexible Cost Fraction	Time-based Cost Curve	Capability-based Cost Curve	Cost Curve Used	Variability
1	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
2	HIGH	HIGH	HIGH	HIGH	HIGH	LOW
9	HIGH	HIGH	LOW	HIGH	HIGH	HIGH
10	HIGH	HIGH	LOW	HIGH	HIGH	LOW

The four experiments that produce the opposite conclusion to this thesis are scenarios in which one would expect that an inflexible platform has less value. The experiments all cost extra to install capability in their service life, gain no benefit from flexible architecture, use the capability-based cost curve, and use the higher cost curve (with the power function). Only two variables change during these four experiments. The first variable to change is the regression to use for the time-based capability curve. However, these four runs all use the capability-based curve, so the value for the time-based curve is not used. Therefore, the calculations for scenarios one and nine effectively use the same input parameters, as do two and ten. Thus, two scenarios produce opposite results, and the difference of these two scenarios is the level of variability. So, if installation costs are high, the Navy gains no benefit for flexibility, capability costs increase cubically – but are relatively cheap right now, than one expects that there are advantages to buying as much capability as possible right now and letting economies of scale dominate the assessment of value over flexibility. In fact, scenarios two and ten report that if variability is low (i.e., the capability model is relatively accurate at predicting the future), there are zero model runs where the flexible model achieves more capability, and only 9% of the runs show the flexible platform spending less money. However, another promising result of the experiments is: when switching to a higher variability (2 or 10 → 1 or 9), the flexible platform achieves more capability in about 9% (vice zero) of scenarios and spends less money in about 40% (vice 9%) of scenarios. So, even in the worst of cases, if capability is highly variable, flexibility begins to gain value.

Further, the results reveal that careful design immediately gains value. The beauty of the "flexible cost fraction" is that designers have a good deal of control over this input. They can carefully design options *in* to the platform to achieve cost-and-time efficiencies for modernization during the service life of a vessel. Accordingly, the experimental results show that if a designer can reduce future modernization costs with flexibility, then the other inputs matter much less. In fact, starting with the worst case (Scenario 2), but switching the flexible cost fraction to allow for gains from flexibility produces the best results of the 64 experiments, with over 99% of the Capability Simulator runs showing better value in flexibility. Further investigation reveals that cost-and-time gains of 85% of the inflexible installation costs (vice the baseline 60%) suffice for a platform to begin realizing the benefits of flexibility. The results in Appendix F consistently show that if all else is held equal, switching from an inflexible platform with Choice Model A to a flexible platform with Choice Model B provides more value to the Navy.

Table 13: Scenarios in Which Flexibility Provides Marginally Better Value

Scenario	Installation Cost Fraction	Flexible Cost Fraction	Time-based Cost Curve	Capability-based Cost Curve	Cost Curve Used	Variability
5	HIGH	HIGH	HIGH	LOW	HIGH	HIGH
6	HIGH	HIGH	HIGH	LOW	HIGH	LOW
8	HIGH	HIGH	HIGH	LOW	LOW	LOW
13	HIGH	HIGH	LOW	LOW	HIGH	HIGH
14	HIGH	HIGH	LOW	LOW	HIGH	LOW

The experiments that produce marginal results also follow a pattern: they are similar to the runs that produced the opposite thesis, but use the less-aggressive linear curve for capability instead of the cubic curve. These results support the thesis indirectly by showing that inflexible platforms exhibit smaller preference if the cost for capability is not increasing exponentially for both platform types because economies of scale begin decreasing their dominance in the value assessment. Further, each of these scenarios report the flexible platform achieving a lower final capability, but also show the inflexible platform buying too much capability in over a quarter of the scenario runs. Thus, although the flexible vessel achieves a lower overall final capability, on average, it still manages to better match the desired capability, on average.

The experiments provide other interesting patterns and insight. One insight is that the pattern of buying capability as needed instead of predicting several years out and buying in advance causes over-purchases of capability in 12% fewer scenarios, on average. Such a Choice Model is not easy to execute under the PPBE process, but provides great value. Another insight is that the results are sensitive to the fraction of cost of installing capability during the service life versus during acquisition; favoring the lower cost fraction. This makes sense since cheaper modernization during a vessel's service life allows both platforms to purchase more capability, and meeting iso-performance metrics becomes easier. The value of flexibility becomes less prominent as a result. Lastly, an important observation is that with the exception of the four scenarios that support the opposite of the thesis, the flexible platform requires a smaller budget in 80% of all model runs for all other scenarios, on average.

Thus, the experiment proves the model is robust enough to variation in inputs and the conclusion of the simulation and analysis is consistent: the Navy saves money, achieves higher capability, and better matches the needed capabilities at any moment in time if they properly design flexibility into the architecture of naval platforms, on average. Of course, this does not relieve one of properly considering the input factors and the uncertainties with each assumption.

4.9 Summary

A flexible architecture for combatant-type vessels that is designed for pre-planned modified repeats provides value to the Navy throughout the platform's service life. A flexible vessel provides value in the pre-delivery stage because it saves money in GFE costs, albeit by delivering a relatively less capable ship than an optimized and inflexible design that has projected needed capabilities at some point future. However, in the case presented here, the flexible platform can meet all the requirements without optimizing or integrating expensive combat systems into the baseline. The lack of a fully optimized and integrated solution initially lowers its OMOE in respect to the optimized, integrated, but inflexible platform. For example, the platform has air self defense capability with a Close-In Weapon System and a SPS-49 3-D air search radar, and therefore meets this requirement without installing a Vertical Launch System with surface to air missiles and the SPY-1 phased array radar (Brege, Page and Sarris 2011). Further, the cost to add the strike capability to the platform is still less than providing a fully integrated and optimized ship. The cost for a single 64-cell vertical launch system and associated hardware and software to use it is about $100M, which is a factor of 4 less than the delta projected in Table 10 (U.S. Navy 2010). In fact, even the state-of-the-art Peripheral Vertical Launch System is projected to provide more cells (80 vice 64) and still cost less than the delta if the Navy desires to add this capability to the SCAMP (U.S. Navy 2010).

Despite a flexible platform starting its service life with less capability, it ends its service life with more capability, and accomplishes this with less money, on average. This happens for a few reasons. First, the model assumes the cost of capability on the flexible platform is 60% of the cost on an inflexible platform. This allows the Navy to install more capability for less money. The beauty of this assumption is that the Navy has control over its outcome. That is, the Navy controls what options it designs *in* to its platforms to allow these savings. Thus, it is even possible for the Navy to design *in* options that allow for greater savings when options are exercised *on* a flexible platform. Second, the choice model associated with a flexible platform allows the addition of capability as needed, which also means capability is not added when it is not needed. Thus, the flexible platform's choice model allows it to avoid expenditures when they are unnecessary. Lastly, the flexible platform accomplishes more with less, on average, because it does not bother to project needed capabilities into an uncertain future, but rather tries to meet the current needed capabilities. The trend of capability versus time (Figure E-3) grows steadily. That is, the Navy tends to want more capability than it currently has. Thus, when they project into an uncertain future, it is only possible to see the need for more capability. Contrarily, a manager with a flexible platform purchasing capability needed right now knows with a high degree of certainty that the platform needs no more capability than what is called for in its current mission profile and can avoid purchase of unneeded mission capabilities.

To make this point clear, another modified version of the model recorded the yearly outputs for cost and capability over both vessels' service lives for 1000 experiments. Figures 15 and 16 present the average results. Figure 15 shows that Choice Model A, on average, over-estimates the needed capability, even at mid-life and at the end of service life. Further, it shows quite clearly that the flexible platform surmounts its initial shortcoming in capability and overtakes the optimized, inflexible platform around the year of IOC (2016).

Based on the assumptions of the model, the flexible platform achieves its ultimate capability for less money, on average, as Figure 16 reports. The picture shows that not only is less money spent initially on a relatively less capable platform, but that the flexible platform also continues to spend less money over a comparative service life. Note the slight uptick in capability added to the inflexible platform around the year 2031, representing the mid-life capability upgrades.

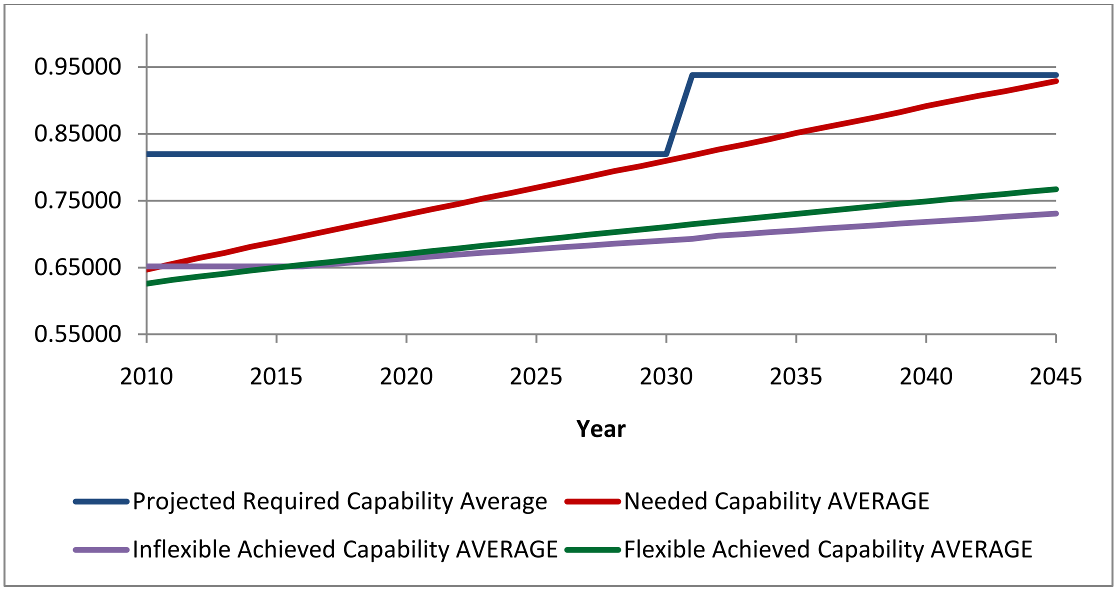

Figure 15: Capability of the Platforms over Their Service Life, On Average

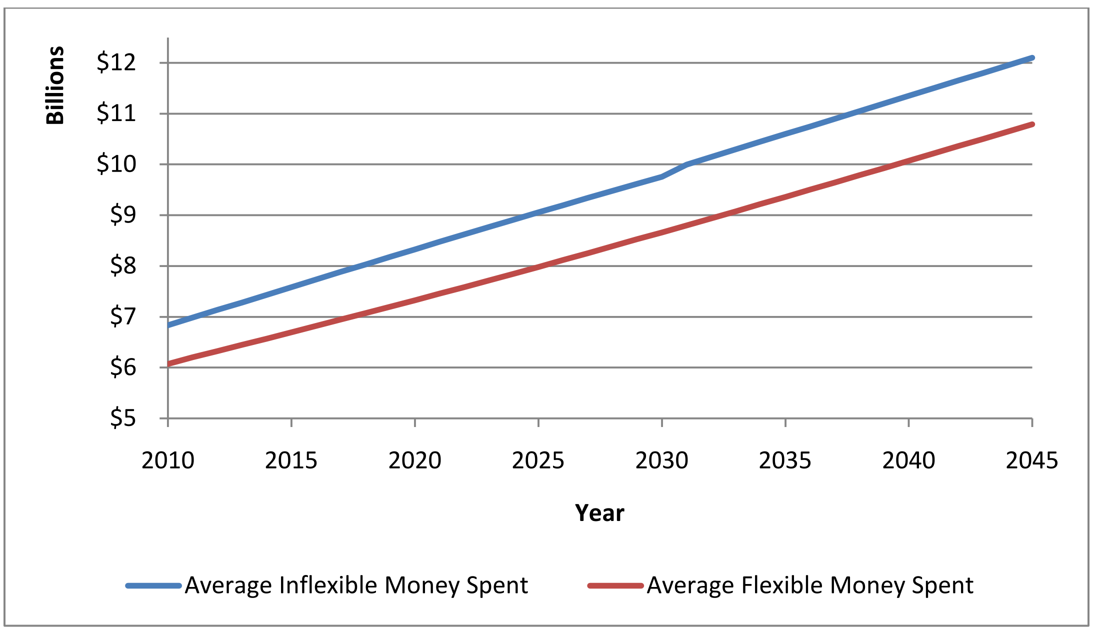

Figure 16: Cumulative Cost to Achieve Capability on Each Platform, On Average

Figure 15 appears to suggest that the design-lock aspect of the inflexible platform restricts its eventual capability, and the flexible platform therefore has an unfair advantage. However, removal of the design-lock rule does not affect the pattern of the results: the flexible platform still achieves more capability in the end of its service life. Design lock-in merely delays the inevitable time when the flexible platform overtakes the inflexible platform in capability, as Figure 17 shows.

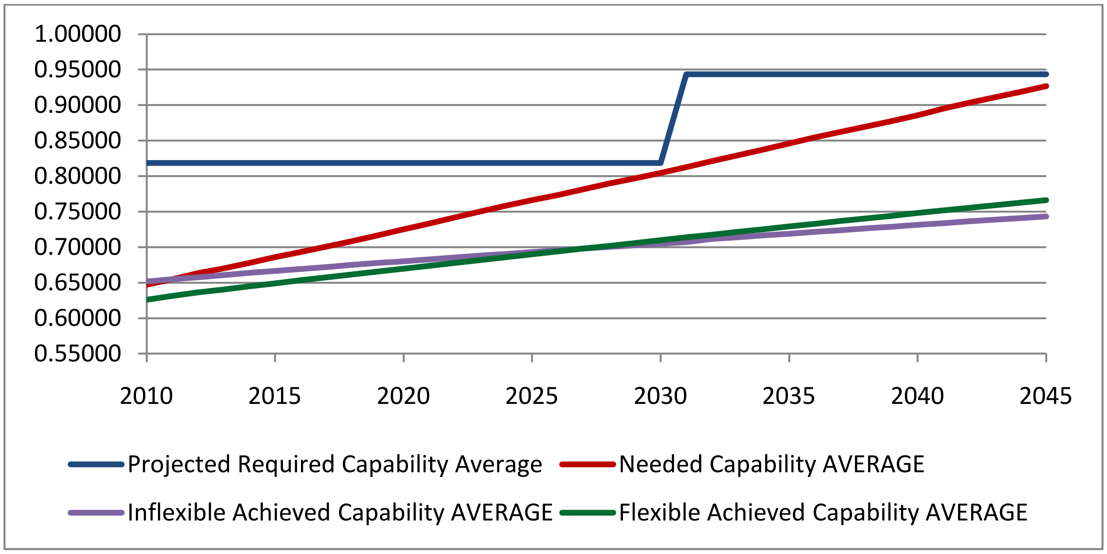

Figure 17: Capability of the Platforms over Their Service Life, On Average, with No Design Lock

The case for flexibility becomes even more apparent when considering extreme outcomes instead of the averages. In the rare scenarios when capability needs go down, the flexible platform's response is much better; managers can better protect themselves from over-purchasing capability. Further, in the scenarios when capability needs are extremely high, the flexible platform achieves higher capabilities, on average, despite spending the same amount of money as the inflexible platform; managers exploit efficiencies in the architecture better.

Thus, the selling point of the flexible platform is its agility in responding to change in an operationally and fiscally efficient manner. It starts with a lower relative capability than an optimized platform, but responds to changing needs and can surpass the inflexible design in capabilities before either of them reaches the middle of their service lives. Therefore, counter-intuitively, starting with a less capable platform provides the Navy a more capable platform in the end, and does not sacrifice mission requirements to do so. Lastly, should the Navy require the addition of entire mission sets (i.e., strike warfare), the flexible platform responds in an equally agile manner, even if one assumes installation costs are equivalent on both platforms.

5.0 Conclusions and Further Work

In the face of uncertainty, the Navy could realize improved matching of operational capability and decreased fiscal burden through the conscious design of flexible architectures. The process is straightforward, but difficult because it requires a change in thinking. First, the Navy must identify the sources of uncertainty in a given platform design. In the case of destroyer-type platforms, I argue that one of the greatest sources of uncertainty is in the mission requirements. A designer must conceive flexible strategies that capitalize on events developing favorably, protect when events develop unfavorably, or both. In this case, the strategy is a scalable modular platform with carefully designed interfaces, architectures, and arrangements that provides an expansion option through cost-effective addition of capability as needed. This type of vessel also provides a contraction option if capability needs decrease, but this option *on* the platform is not evaluated here. An important note is that the Choice Model associated with the flexible platform is as important as the platform itself. If the Navy were to build a platform like the SCAMP, but continue current modernization practices, the full benefit of such a vessel would never be realized.

An important fact is that flexibility is always more valuable with uncertainty. In all cases in which the Navy designs enough flexibility in to realize cost benefits, the value of this flexibility increases with increases in variability of the inputs. The converse is also true, if the future state is more certain, flexibility has less value. The simulation reveals four cases that exhibit this exact behavior. These are important implications for naval architects, and provide the basis for the first step of the flexible design process: identifying the sources of uncertainty. Flexibility is only valuable if it addresses an underlying uncertainty appropriately.

The robustness of the results to variations in input parameters helps establish the validity of the framework. The model avoids traditional NPV or ROA analysis because the Navy has no source of income. Therefore, it develops a new capability-based framework that compares two platforms with respective Choice Models simultaneously. The results of this type of model prove the usefulness of the approach. With this approach, the Navy can identify trade-offs between cost and capability and test different assumptions related to these desires. The model also displays the risk of the assumptions and outcomes, since part of the output is a cumulative distribution function. Thus, a manager knows the result "on average," but also literally sees the variation in the outputs, as well.

The robustness of the model does not relieve managers of their duty to establish the appropriate inputs and their variations. Although the model performs well despite wide variations on assumptions, the actual value of flexibility above and beyond that of a standard naval vessel still depends on them. Based on this model's assumptions, the SCAMP is cheaper to produce and cheaper to modernize. However, this may not be the case for all flexible platforms or systems. There may be scenarios where the value of flexibility is less than the cost it takes to develop that flexibility, which leads to the conclusion: do not go forth with the project when the investment exceeds the benefit. One of the most important assumptions to understand for the framework presented is the cost of capability: in general, changes in the cost-of-capability assumptions produced the least consistent support for the value of flexibility, whereas changes in the other assumptions produced predictable results that supported the thesis.

The evaluation framework presented is useful for other options evaluations, as well. This scenario demonstrated the value of expansion options such as pre-planned modified repeats and modernization of Navy platforms. Extending the model by adding contracting options analysis is straightforward: simply change the rule set that does not allow a decrease in capability. However, the actual behavior of the rule set and how it makes decisions may not be as easy as its implementation. Similarly, the framework accommodates the inclusion of abandonment and other options easily. The option this framework should ultimately model for this application is the switching option, in which the Navy switches to a new mission profile for the platform through use of its modules or otherwise.

Of course, modeling a vessel and a Choice Model are easier than implementation. Designing options *in* a flexible platform like the SCAMP requires active interplay among a disciplined systems engineering approach, a creative systems architecture process, and steadfast project management for success. Further, the Choice Model updates capability every year, a practice that is difficult under the PPBE process, which projects budgets several years into the future.

Future work may benefit from implementation of decision rules that account for the PPBE process and timelines.

Other work omitted in this study would add fidelity and/or insight to the results. For example, the simulation only reproduces average modernization and R&D budgets. However, the suggested architectural design likely affects maintenance practices and costs, as well. Modeling the effects designs have on maintenance costs and efficiencies certainly would add both fidelity and valuable insight to the results presented here. Further, the design likely affects operation and manning costs, which were not modeled. And, a class of ships may have even greater gains in cost savings than a single ship due to supply chain efficiencies for common components, for instance. Another small aspect that would add realism to the analysis is if no capability is bought starting at service life minus five years. Congressional mandate dictates that the Navy cannot add capability to a platform within 5 years of when they dispose of it. This point would alter the results of the simulation runs marginally, but would not alter the ultimate conclusion. Last, the model currently uses the data regressions to ascertain the initial cost ceilings for each platform instead of using the actual deterministic procurement cost calculations. Using the deterministic costs would add elegance to the model, and would alter the results since both platforms exhibit budget-limited behavior (if they were not budget limited, they would both easily buy as much capability as predicted or needed). Ultimately, the cost of capability differs from construction to service life, and accounting for this fact in the first year versus subsequent years deserves implementation after further study.

Additionally, altering the model to incorporate larger step changes in capability on the flexible platform would provide more realism. The modular nature of the SCAMP allows for immediate increase in capability. These increases could be much larger than those currently modeled. Additionally, in the past, the Navy has completely changed the warfare areas a given platform is required to accomplish. For example, due to unforeseen circumstances, the Navy decided that Oliver Hazard Perry class frigates no longer needed much of their air warfare capability, and subsequently removed their surface-to-air missiles and launchers. The current model does not simulate a representatively large decrease in a platform’s overall capability. Larger step changes

– either positive or negative – are likely to make the case for flexible platforms stronger, since these platforms respond to changes more aptly and cost effectively.

Further, this model assumes that all increases in capability cost the same, and thus uses an average value for the cost of capability. In reality, the Navy requires specific capabilities of their platforms, and different capabilities naturally have different development and installation costs. Further analysis of this phenomenon could develop knowledge of which technologies and capabilities perform well in the SCAMP model and can be added and removed modularly, and which ones are better suited to baseline installation. For example, a quick thought experiment suggests that SONAR systems are not well suited to frequent upgrades due to their customary placement forward and low in the vessel, so traditional design practices are more appropriate for those systems. This type of knowledge could help inform design decisions for ship-wide arrangements and interfaces as well.

The Navy could benefit from application of this type of flexibility analysis to platforms other than medium displacement surface combatants. Amphibious vessels provide an interesting platform for studying service life allowances and design margins. Analysis of design options intended to prevent the scenarios on the LHAs[13] and the USS Midway[12], whose service life allowances did not account for growth in the weight embarked cargo and platforms, could alter future amphibious designs to account for these types of changes. Additionally, submarine designs are typically tight in order to squeeze as much equipment and capability into a relatively small hull. Examination of flexible options in submersibles could open up design possibilities. Incorporating options could prevent potential rework on the Ohio Replacement program, whose value may not be determined for some time and could change drastically based on new nuclear armament treaties between the US and foreign nations.

To conclude, the Navy would realize fiscal and operational benefits by incorporating options *in* its platforms starting in early stage design. The fact is, the Navy already executes options *on* its platforms and programs, but does so without the recognition and analysis of the uncertainties. Innovative frameworks – like the one presented here that utilizes real options – provide adequate support of the value of providing options *in* designs, as well. The framework is easily extendable to provide analysis of other types of options (e.g., contraction, deferral), analysis of multiple concurrent options, analysis of more than two platforms, and analysis of subsystems and system-of-systems. Most importantly, it shows the possibility of saving taxpayer money both in acquisition and operation of a flexible platform.

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[1] All data in Table 1 that is not from a SAR is instead from Visibility and Management of Operating and Support Costs (VAMOSC). VAMOSC recorded data as of 1984. Therefore, the data for the FFG and LHA classes is incomplete, i.e. the costs reported in columns 3-7 should be even higher as a percentage of Program Acquisition Cost. Similarly, CVN-68 was commissioned in 1975 and CVN-69 was commissioned in 1977, and therefore 10 and 8 years worth of operating are costs are missing for those vessels, respectively. Also, the rows for the two carriers are for those specific vessels and do not represent the average for a class of ships, as the other rows depict. Further, please note that the costs of columns 4-7 are subsets of column 3, the Average O&S Cost, and that other subsets exist but are not reported here. The costs for Average Own-ship Maintenance (column 4) are the cost of repair parts only; these numbers do not include the cost of military personnel labor to install those parts. Contrastingly, Average Intermediate Maintenance (column 5) and Average Depot Maintenance (column 6) include parts, labor, and overhead (as applicable), with the exception of military labor used at Intermediate Maintenance Facilities (U.S. Navy 2010).

[2] The Marine Corps has similar appropriation types to the Navy, but are included as separate line items under the Navy's budget submissions.

[3] This includes personnel costs, operations and maintenance costs, and military construction for the reserves of both services.

[4] The average time in the final row represents the average time from Milestone 0/MDD to the given Milestone of the associated column. The column headers use some terms not mentioned in the preceding summary because the Acquisition System has changed several times through the years and some of the ships represented started under the old System, which, among other changes, had different titles for the milestones. The Initial Capabilities Document for LCS showed the MDD of February 2003, and the Mission Need Statement for LPD 17 showed Milestone 0 of November 1990. The original documents produced this data. The respective program offices provided reasonable estimates for all dates in the future. This table represents most currently active shipbuilding programs, with the exception of: JHSV, LHA-6, and aircraft carrier programs.

[5] The Light Ship Condition is the sum of the weights of everything installed permanently on the vessel, e.g., fuel weight, ballast water weight, ammunition, and food stores are not included in this weight.

[6] KG is the height of the vertical center of gravity of the vessel and its loads above the keel of the ship.

[7] The weight percentage is based on the predicted full load departure displacement at delivery (Naval Sea Systems Command 2001). The KG values are based on the predicted full load departure KG at delivery (Naval Sea Systems Command 2001).

[8] Khosrow Moniri, the Technical Warrant Holder for electrical systems at NAVSEA, revealed this information to the author in an e-mail on January 11th, 2011.

[9] The discount factor is the product of the discount rate applied over time. It is obtained using the equation $Discount\ Factor = \frac{1}{(1+i)^t}$ where *i* represents the discount rate per time increment and *t* represents the subsequent time increments. The case in Table 5 assumes a discount rate of 15%.

[10] Some of the numbers are slightly off due to rounding.

[11] The USS Chicago was originally built as a heavy cruiser during WWII to protect aircraft carriers and aid in shore bombardment for amphibious operations. After the Korean War, the Navy decommissioned most of the ships in her class except for four which were converted to the world's first missile cruisers during 5-year extended conversions that, among other things, replaced her entire superstructure and all her combat systems (Wikipedia 2011).

[12] The USS Midway was an aircraft carrier built at the end of WWII before the advent of jet-powered aircraft. The change to jet-powered aircraft – that were heavier than the previous propeller-powered aircraft – changed the seakeeping characteristics of the vessel to the extent that the hull required "blistering." However, the "blistering" caused its own adverse conditions which required further major modification to the hull (Gale and Ricketts 1989).

[13] The Navy designed these platforms starting in 1965, with the knowledge of the helicopters and vehicles of that era. Over the next 30 years, the USMC developed Osprey and other vehicles that are battle-hardened versus their earlier counterparts. This means more steel and more weight carried high on the vessel, just as on the aircraft carriers like USS Midway[12]. Now, because this ship class cannot fully support the future ACE, centered on the MV-22B and F-35B aircraft, and because the service life allowance margins for weight and center of gravity have been completely depleted, building more Tarawa-class LHAs would mandate undesirable trade-offs in mission weight and capability (GlobalSecurity.org 2008).

[14] The MIT Cost Model for early stage ship design is a Microsoft Excel®-based model. The calculations are appropriately parametric in nature (U.S. Navy 2004). The earliest version of the model was incorporated in Advanced Surface Ship Evaluation Tool, a computer program that quickly converges ship models based on designer inputs. That model has since been removed from the software and migrated to Excel® using cost estimating relationships approved for academia by the cost estimating code of Naval Sea Systems Command. The model is maintained and updated by students and faculty at MIT.

[15] For those unfamiliar with nautical parlance, the forecastle is the area on the main deck of the vessel forward of the main mast. In this case, the forward superstructure of the ship is a surrogate for the main mast.

[16] The SCAMP's propulsion power for the baseline is determined by the Propulsion Motors, not the installed power generation capacity (60MW). Space and volume are allocated around the motors to allow for installation of larger motors in order to achieve top speeds above 20 knots.

[17] Iso-performance characteristics are analogous to "Goldilocks" characteristics. In this case, that means the Navy desires neither too much capability at the end of service life nor too little, they want the capability to be "just right."

[18] The inclusion of these two platforms in the analysis almost warrants use of multi-attribute utility methods, since there is some uncertainty around their performance. However, the author chose not to use two decision making models for the various ships, and addresses uncertainty in a different manner sufficient for this analysis later in the chapter.

[19] SARs are congressionally mandated quarterly reports from DoD to the Congress that report the funding status of all ACAT I (big and expensive) programs, or any other programs of interest as designated by the Congress. It is important to note that Selected Acquisition Reports include all acquisition costs, not just construction. Therefore, all of the numbers reported include R&D appropriations as well as procurement appropriations, and military construction appropriations as necessary.

[20] Using this regression assumes that the cost of capability is based solely on the current capability achieved.

[21] Using this regression assumes that the cost of capability is based on the increasing costs of complex systems over time, and is decoupled from the currently-achieved technological state.

[22] (U.S. Department of Defense 2010)

[23] This data row uses an inflation factor from 1987 to 2010 of 1.6656 to make the results clear (Hirama 2004).

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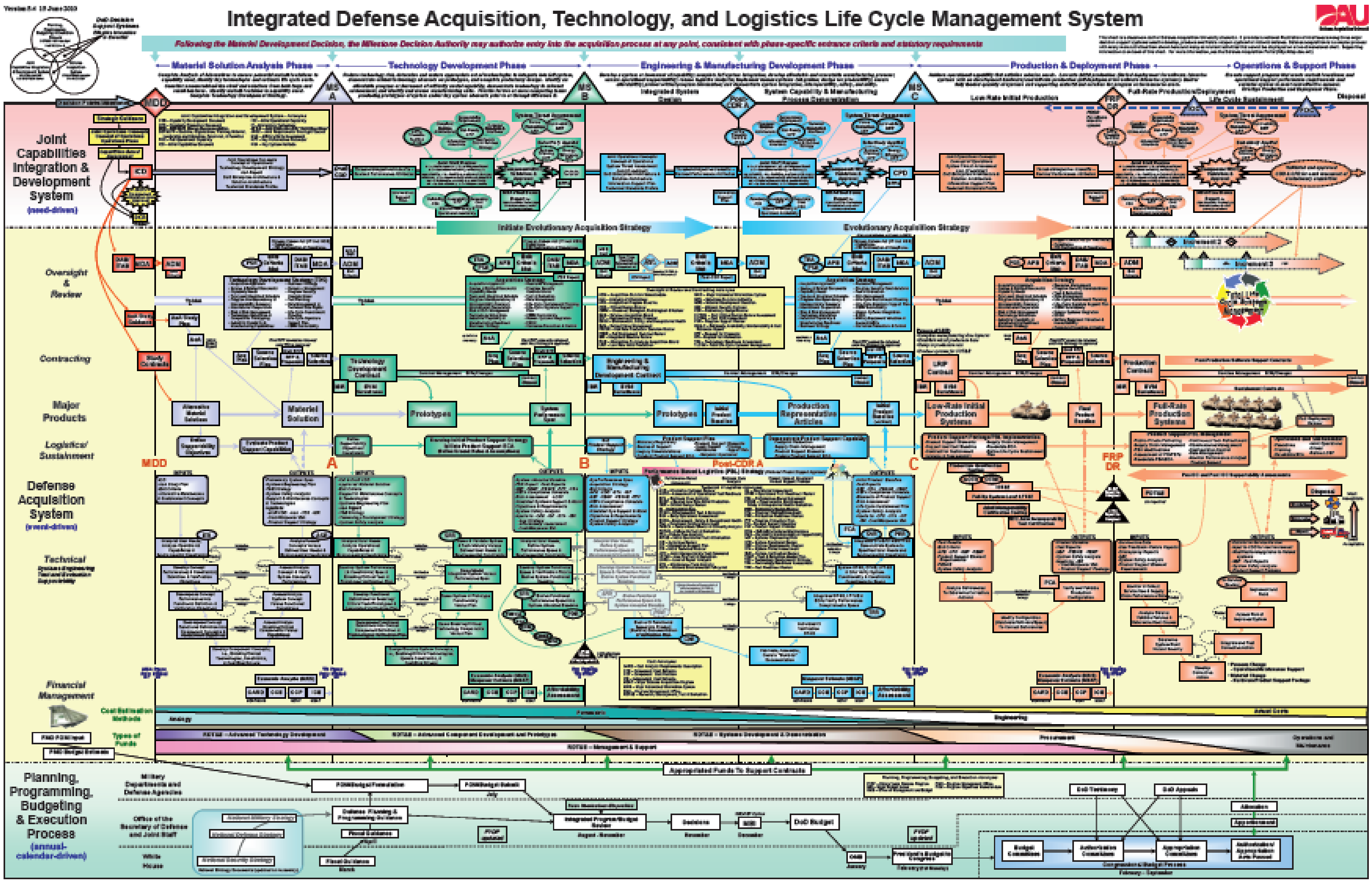
Appendix A: List of Acronyms

AHP – Analytical Hierarchy Process
AIMS – Architecture, Interfaces and Modular Systems
AoA – Analysis of Alternatives
APN – Aircraft Procurement Navy Appropriation
ASN FM&C – Assistant Secretary of the Navy for Financial Management and Comptroller
BMD – Ballistic Missile Defense
CDF – Cumulative Distribution Function
CG – Guided Missile Cruiser
CVN – Aircraft Carrier (Nuclear)
DAMIR – Defense Acquisition Management Information Retrieval
DDG – Guided Missile Destroyer
DoD – Department of Defense
FFG – Guided Missile Frigate
FOUO – For Official Use Only
FY – Fiscal Year
HM&E – Hull, Mechanical, and Electrical
HVAC – Heating, Ventilation, and Air Conditioning
ICD – Initial Capabilities Document
IPS – Integrated Power System
ISR – Information, Surveillance, and Reconnaissance
JCIDS – Joint Capabilities Integration and Development System
KB – Height of the Center of **B**uoyancy above the **K**eel
KG – Height of the Center of **G**ravity above the **K**eel
LCAC – Landing Craft Air Cushion
LCS – Littoral Combat ship
LHA – Amphibious Assault Ship
LHD – Amphibious Assault Ship
LPD – Amphibious Transport Dock
LSD – Dock Landing Ship
MDA – Milestone Decision Authority
MDD – Material Development Decision
MILCON – Military Construction Appropriation
MPN – Military Personnel Navy Appropriation
NAVSEA – Naval Sea Systems Command
NCCA – Navy Center for Cost Analysis
NPV – Net Present Value
O&MN – Operations and Maintenance Navy Appropriation
O&S – Operations and Support
OA – Open Architecture
OMOE – Overall Measure of Effectiveness
OPN – Other Procurement Navy Appropriation
ORD – Operational Requirements Document
PPBE – Planning, Programming, Budgeting and Execution
RDT&E – Research, Development, Test and Evaluation Appropriation
ROA – Real Options Analysis
SAR – Selected Acquisition Report
SCAMP – Scalable, Common, Affordable, Modular Platform
SCN – Shipbuilding and Conversion Appropriation
SONAR – Sound Navigation and Ranging
SSC – Ship to Shore Connector
TOA – Total Obligation Authority
TOC – Total Ownership Cost
TVM – Time Value of Money
UAV – Unmanned Aerial Vehicle
USV – Unmanned Surface Vehicle
USD AT&L – Undersecretary of Defense for Acquisition, technology and Logistics
UUV – Unmanned Underwater Vehicle
WPN – Weapons Procurement Navy Appropriation

Appendix B: Select Navy Budget Items [1995 - 2011(projected)]

Fiscal Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Navy TOA	80,418	79,685	79,191	81,935	83,666	88,509	96,117	104,836	123,887	121,608	133,560	144,596	151,526	164,777	164,050	173,946	179,143
Total MPN	17,752	17,099	17,032	16,686	16,655	17,188	18,042	20,281	23,820	24,216	25,294	24,119	24,047	23,422	24,146	25,289	25,951
Total OM&N	22,095	21,676	21,055	22,355	23,233	23,433	25,439	28,285	35,555	30,288	33,892	35,445	37,366	33,502	33,963	34,671	38,134
Total Ship OM&N	7,214	6,766	6,844	7,244	6,397	6,646	7,063	7,864	10,571	8,465	9,196	9,358	9,588	9,433	8,978	9,379	10,532
Total Ship Maintenance	2,207	2,816	2,913	2,808	3,375	3,785	3,819	4,870	6,721	5,069	5,404	5,127	5,109	6,205	6,306	6,409	7,374
Total SCN	6,486	6,548	5,467	8,007	5,937	7,125	11,965	9,278	9,108	11,373	10,373	11,370	10,152	13,177	13,022	13,839	15,725
(all figures in $Million)																	
Projected Baseline Only																	

Appendix C: Defense Acquisition Processes Chart



Appendix D: Pairwise Comparisons of Measures of Performance

Table D-1: Primary Mission Pairwise Comparison

Criteria		1 Undersea Warfare	2 Surface Warfare	3 Air Warfare	4 Mine Warfare	5 Naval Surface Fire Support	6 Strike Warfare	7 Ballistic Missile Defense	8 Unknown	Weights
Undersea Warfare	1	1	0.5	0.7	2	0.5	0.5	0.5	0.8	0.0816
Surface Warfare	2	2	1	1.3	4	1	1	1	1.6	0.1633
Air Warfare	3	1.5	0.8	1	3	0.8	0.8	0.8	1.2	0.1224
Mine Warfare	4	0.5	0.3	0.3	1	0.3	0.3	0.3	0.4	0.0408
Naval Surface Fire Support	5	2	1	1.3	4	1	1	1	1.6	0.1633
Strike Warfare	6	2	1	1.3	4	1	1	1	1.6	0.1633
Ballistic Missile Defense	7	2	1	1.3	4	1	1	1	1.6	0.1633
Unknown	8	1.3	0.6	0.8	2.5	0.6	0.6	0.6	1	0.1020

Table D-1 presents the final pairwise comparison the AHP uses to determine the appropriate weights for the Measures of Performance for the Primary Missions. The interpretation of each line is the same, and that of Undersea Warfare is included:

1. Is as important as itself (naturally)
2. Is half as important as surface warfare
3. Is 2/3 as important as air warfare
4. Is twice as important as mine warfare
5. Is half as important as naval surface fire support
6. Is half as important as strike warfare

7. Is half as important as ballistic missile defense
8. Is 4/5 as important as potential future (currently unknown) missions

Table D-2: Secondary Mission Pairwise Comparison

Criteria		1 Communications	2 Command and Control	3 Mobility	4 Non-Combat Operations	5 Unknown	Weights
Communications	1	1	0.5	0.8	3	0.8	0.1714
Command and Control	2	2	1	1.6	6	1.6	0.3429
Mobility	3	1.3	0.6	1	3.8	1	0.2143
Non-Combat Operations	4	0.3	0.2	0.3	1	0.3	0.0571
Unknown	5	1.3	0.6	1	3.8	1	0.2143

Table D-2 presents the final pairwise comparison the AHP uses to determine the appropriate weights for the Measures of Performance for the Secondary Missions. The interpretation of each line uses the same method as for the Primary Missions.

Table D-3: Seaframe Pairwise Comparison

Criteria		1 Speed	2 Endurance	3 Survivability	4 Draft	5 Seakeeping	6 Service Life Allowance	Weights
Speed	**1**	1	1	0.8	1.5	1.5	1	0.1765
Endurance	**2**	1	1	0.8	1.5	1.5	1	0.1765
Survivability	**3**	1.3	1.3	1	2	2	1.3	0.2353
Draft	**4**	0.7	0.7	0.5	1	1	0.7	0.1176
Seakeeping	**5**	0.7	0.7	0.5	1	1	0.7	0.1176
Service Life Allowance	**6**	1	1	0.8	1.5	1.5	1	0.1765

Table D-3 presents the final pairwise comparison the AHP uses to determine the appropriate weights for the Measures of Performance for the Seaframe. The interpretation of each line uses the same method as for the Primary Missions.

Appendix E: Cost, Capability, Time Regressions

This appendix reveals the regressions used in the Capability Simulator for both the baseline analysis and the robustness/sensitivity analysis. Figure E-1 shows the trends of cost versus capability. The simulator uses either the “Power” or the “Linear” regression line based on user input to a logical switch that chooses one or the other.

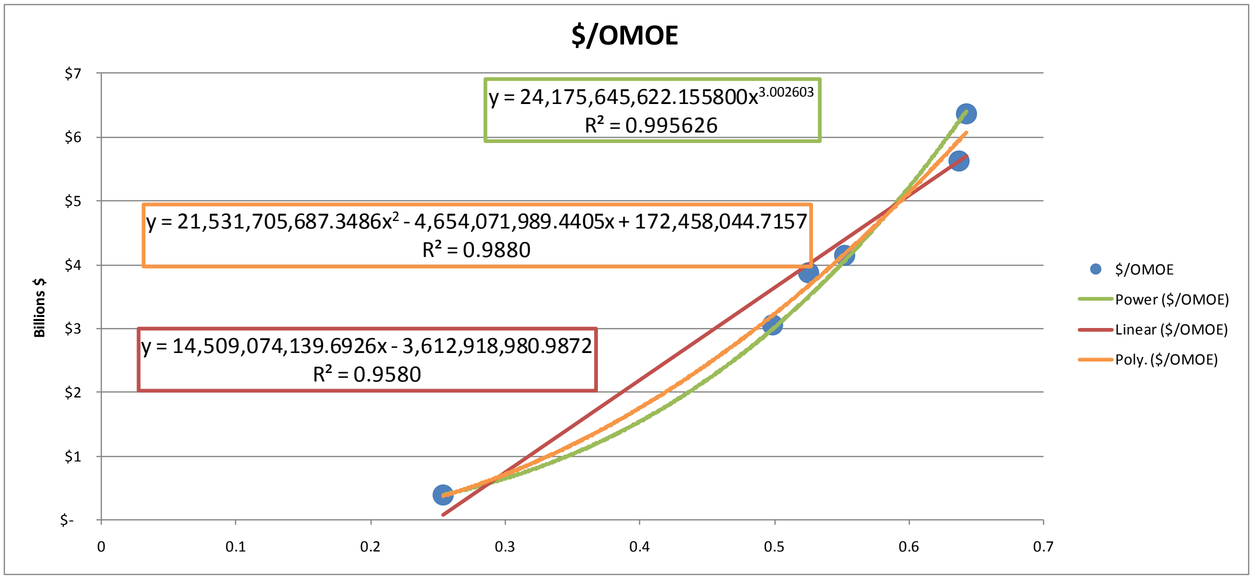


Figure E-1: Cost per Overall Measure of Effectiveness Regression

Figure E-2 reveals the other regression the Capability Simulator sometimes uses to determine the cost of capability (depending on the user’s input). Another logical switch dictates which of the two linear regressions the Capability Simulator uses in the analysis.

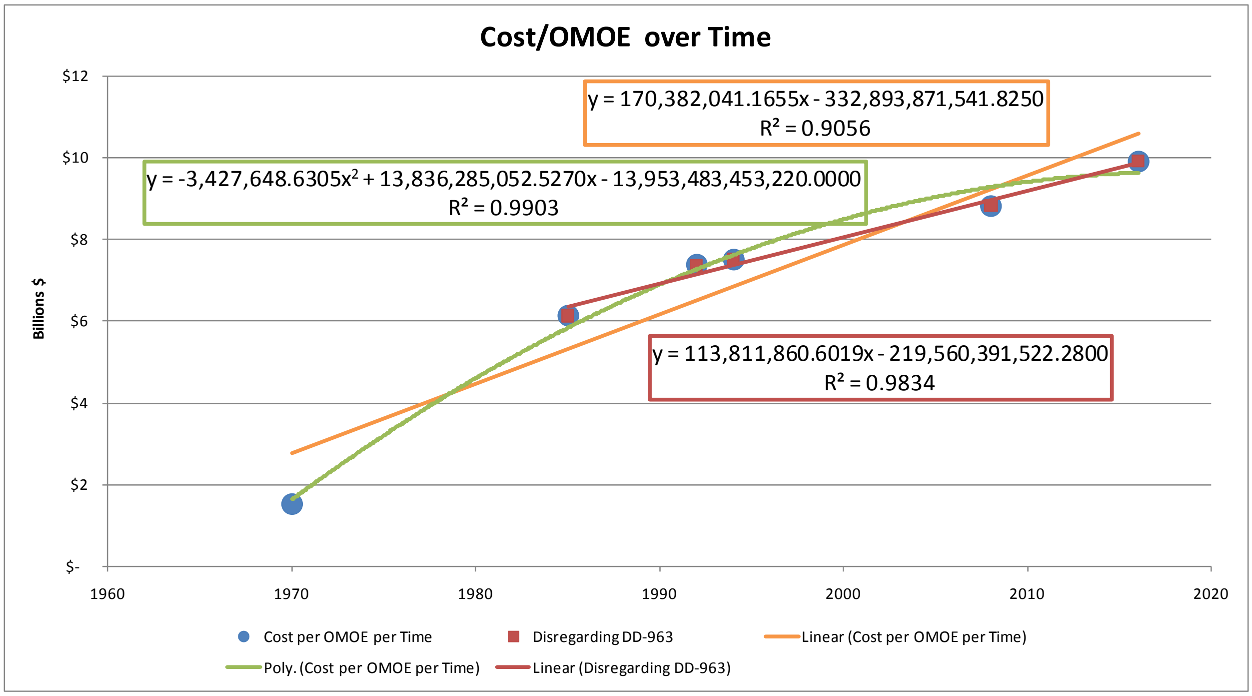


Figure E-2: Cost of Overall Measure of Effectiveness over Time Regression

Figure E-3 displays the trend of OMOE over time. The Capability Simulator uses the linear regression from this Figure and introduces uncertainty bands about its slope to determine if capability needs go up or down with time.

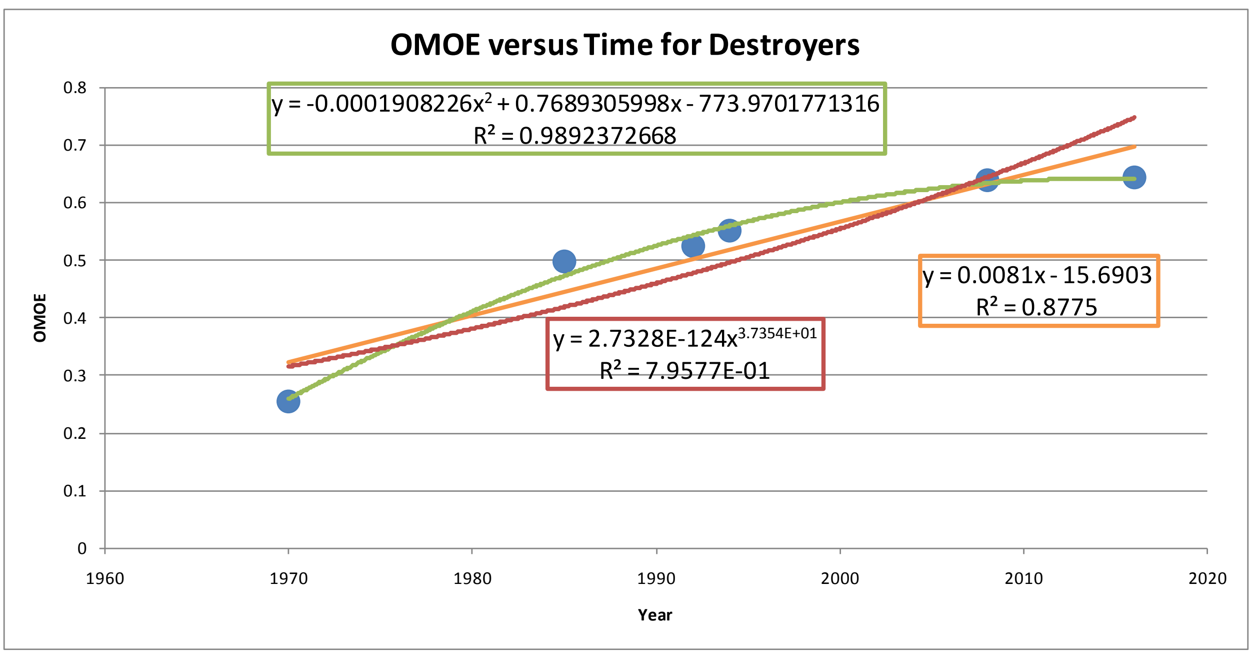


Figure E-3: Overall Measure of Effectiveness Trends versus Time for Destroyer-type Vessels

Finally, Figure E-4 reveals the trend of budgets for lead ships over time. The Capability Simulator uses the linear regression from this Figure to determine the budget ceiling the year a vessel is ordered.

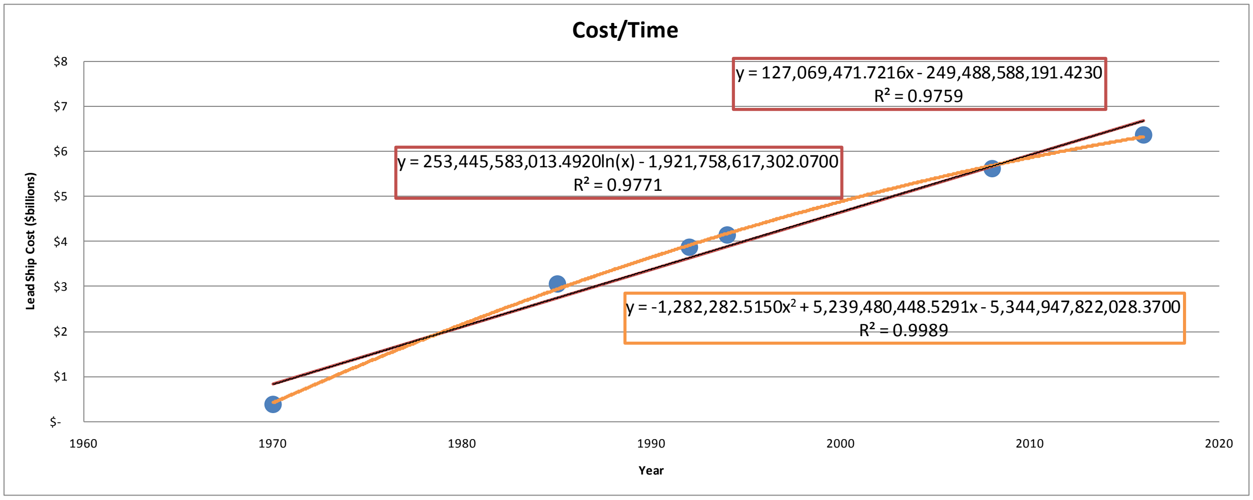


Figure E-4: Cost of Lead Ships ($FY10) versus Time

Appendix F: Robustness/Sensitivity Experiment Results

Cost Fraction	Flex Cost Fraction	$/OMOE/t	$/OMOE	CAP time-base or CAP-base	OMOE over time variability	"Similar" Runs	PROJECTED > Actual Final Cap	Inflex Final CAP too much	Flex Final CAP too much	(Total Money) Flex <= Inflex	(Average Delta) Flex < Inflex	(Final Delta) Flex < Inflex
HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	1	53.00%	4.10%	2.10%	42.60%	7.60%	9.90%
HIGH	HIGH	HIGH	HIGH	HIGH	LOW	2	56.20%	0.00%	0.00%	8.50%	0.00%	0.00%
HIGH	HIGH	HIGH	HIGH	LOW	HIGH	3	50.60%	23.90%	10.40%	61.70%	75.70%	71.60%
HIGH	HIGH	HIGH	HIGH	LOW	LOW	4	56.10%	13.90%	2.10%	77.80%	74.80%	67.90%
HIGH	HIGH	HIGH	LOW	HIGH	HIGH	5	52.90%	27.30%	9.10%	59.40%	41.80%	50.10%
HIGH	HIGH	HIGH	LOW	HIGH	LOW	6	53.40%	21.10%	1.10%	67.60%	20.80%	28.50%
HIGH	HIGH	HIGH	LOW	LOW	HIGH	3	51.20%	31.10%	12.50%	54.70%	56.40%	60.60%
HIGH	HIGH	HIGH	LOW	LOW	LOW	4	54.20%	26.90%	1.60%	64.40%	41.40%	43.80%
HIGH	HIGH	LOW	HIGH	HIGH	HIGH	1	52.20%	3.20%	2.20%	40.20%	7.40%	9.00%
HIGH	HIGH	LOW	HIGH	HIGH	LOW	2	56.30%	0.00%	0.00%	8.70%	0.00%	0.00%
HIGH	HIGH	LOW	HIGH	LOW	HIGH	7	50.50%	28.20%	12.00%	69.10%	75.70%	72.40%
HIGH	HIGH	LOW	HIGH	LOW	LOW	8	52.80%	21.80%	4.60%	82.80%	71.20%	66.10%
HIGH	HIGH	LOW	LOW	HIGH	HIGH	5	54.10%	28.30%	10.80%	59.60%	40.90%	53.50%
HIGH	HIGH	LOW	LOW	HIGH	LOW	6	55.30%	23.30%	1.70%	69.50%	22.00%	29.30%
HIGH	HIGH	LOW	LOW	LOW	HIGH	7	51.70%	33.50%	15.20%	51.70%	62.50%	67.30%
HIGH	HIGH	LOW	LOW	LOW	LOW	8	58.30%	36.80%	5.00%	61.60%	54.20%	57.20%
HIGH	LOW	HIGH	HIGH	HIGH	HIGH	9	51.10%	3.60%	3.40%	93.90%	90.00%	93.80%
HIGH	LOW	HIGH	HIGH	HIGH	LOW	10	54.80%	0.00%	0.10%	100.00%	99.70%	99.80%
HIGH	LOW	HIGH	HIGH	LOW	HIGH	11	52.00%	22.00%	27.60%	86.60%	93.30%	85.70%
HIGH	LOW	HIGH	HIGH	LOW	LOW	12	53.20%	11.80%	13.70%	99.90%	93.40%	90.00%
HIGH	LOW	HIGH	LOW	HIGH	HIGH	13	51.30%	27.70%	24.10%	70.10%	78.30%	83.90%
HIGH	LOW	HIGH	LOW	HIGH	LOW	14	56.50%	22.90%	15.10%	94.60%	72.00%	86.50%
HIGH	LOW	HIGH	LOW	LOW	HIGH	11	53.70%	30.00%	26.30%	75.50%	82.60%	84.90%
HIGH	LOW	HIGH	LOW	LOW	LOW	12	53.90%	28.20%	14.40%	96.30%	77.70%	84.70%
HIGH	LOW	LOW	HIGH	HIGH	HIGH	9	52.90%	2.60%	2.80%	55.00%	90.20%	93.40%
HIGH	LOW	LOW	HIGH	HIGH	LOW	10	55.40%	0.00%	0.00%	100.00%	98.80%	99.90%
HIGH	LOW	LOW	HIGH	LOW	HIGH	15	51.90%	27.90%	32.10%	88.40%	92.90%	87.10%
HIGH	LOW	LOW	HIGH	LOW	LOW		55.20%	22.40%	17.20%	99.70%	89.90%	87.90%
HIGH	LOW	LOW	LOW	HIGH	HIGH	13	56.60%	30.10%	25.50%	71.70%	81.20%	82.10%
HIGH	LOW	LOW	LOW	HIGH	LOW	14	55.80%	23.90%	14.80%	94.00%	73.00%	86.00%
HIGH	LOW	LOW	LOW	LOW	HIGH	15	51.80%	33.20%	32.80%	75.00%	87.30%	83.50%
HIGH	LOW	LOW	LOW	LOW	LOW		51.70%	32.60%	17.50%	96.80%	79.60%	87.70%

Cost Fractio	Flex Cost Fractior	$/OMOE/t	$/OMC	CAP time-base or CAP-base	OMOE over time variability	"Similar" Runs	PROJECTED > Actual Final Ca	Inflex Final CAP too much	Flex Final CAP too much	(Total Money) Flex <= Inflex	(Average Delta) Flex < Inflex	(Final Delta) Flex < Infl
LOW	HIGH	HIGH	HIGH	HIGH	HIGH	17	54.80%	9.10%	3.90%	51.10%	58.20%	64.90%
LOW	HIGH	HIGH	HIGH	HIGH	LOW	18	51.70%	0.30%	0.00%	100.00%	79.60%	83.00%
LOW	HIGH	HIGH	HIGH	LOW	HIGH	19	51.40%	39.70%	24.30%	66.10%	81.90%	80.50%
LOW	HIGH	HIGH	HIGH	LOW	LOW	20	54.10%	46.70%	12.70%	79.70%	75.80%	77.20%
LOW	HIGH	HIGH	LOW	HIGH	HIGH	21	55.50%	46.50%	22.80%	58.00%	72.90%	76.10%
LOW	HIGH	HIGH	LOW	HIGH	LOW	22	53.20%	45.10%	11.00%	60.50%	67.10%	78.00%
LOW	HIGH	HIGH	LOW	LOW	HIGH	19	52.10%	42.50%	24.80%	54.30%	81.10%	79.90%
LOW	HIGH	HIGH	LOW	LOW	LOW	20	53.40%	46.60%	13.80%	64.80%	79.40%	80.70%
LOW	HIGH	LOW	HIGH	HIGH	HIGH	17	51.50%	7.80%	4.30%	50.00%	57.90%	64.90%
LOW	HIGH	LOW	HIGH	HIGH	LOW	18	55.80%	0.40%	0.00%	100.00%	80.10%	83.20%
LOW	HIGH	LOW	HIGH	LOW	HIGH	23	51.20%	45.00%	32.20%	67.40%	84.70%	81.80%
LOW	HIGH	LOW	HIGH	LOW	LOW	24	55.00%	51.90%	17.00%	80.00%	75.80%	84.30%
LOW	HIGH	LOW	LOW	HIGH	HIGH	21	53.00%	42.50%	24.20%	54.80%	70.50%	78.90%
LOW	HIGH	LOW	LOW	HIGH	LOW	22	54.30%	46.20%	13.80%	60.80%	69.00%	78.30%
LOW	HIGH	LOW	LOW	LOW	HIGH	23	53.50%	47.80%	30.50%	60.10%	84.60%	79.70%
LOW	HIGH	LOW	LOW	LOW	LOW	24	54.50%	51.90%	14.80%	68.10%	82.20%	83.50%
LOW	LOW	HIGH	HIGH	HIGH	HIGH	25	52.00%	7.00%	7.40%	90.30%	92.20%	91.80%
LOW	LOW	HIGH	HIGH	HIGH	LOW	26	54.80%	0.40%	0.90%	100.00%	99.10%	99.80%
LOW	LOW	HIGH	HIGH	LOW	HIGH	27	50.70%	39.40%	39.70%	94.20%	93.20%	85.90%
LOW	LOW	HIGH	HIGH	LOW	LOW	28	51.60%	45.10%	23.60%	100.00%	84.70%	87.00%
LOW	LOW	HIGH	LOW	HIGH	HIGH	29	53.20%	42.70%	40.70%	81.90%	90.70%	85.50%
LOW	LOW	HIGH	LOW	HIGH	LOW	30	52.40%	47.00%	22.80%	99.00%	85.30%	87.80%
LOW	LOW	HIGH	LOW	LOW	HIGH	27	49.10%	41.80%	40.40%	83.50%	92.20%	87.80%
LOW	LOW	HIGH	LOW	LOW	LOW	28	53.70%	46.70%	22.90%	99.30%	89.10%	88.60%
LOW	LOW	LOW	HIGH	HIGH	HIGH	25	53.20%	30.00%	14.90%	86.30%	90.80%	90.00%
LOW	LOW	LOW	HIGH	HIGH	LOW	26	55.70%	0.20%	0.60%	100.00%	98.90%	99.50%
LOW	LOW	LOW	HIGH	LOW	HIGH	31	50.60%	44.90%	45.30%	95.20%	94.00%	87.70%
LOW	LOW	LOW	HIGH	LOW	LOW	32	54.70%	51.40%	27.30%	99.90%	86.70%	87.80%
LOW	LOW	LOW	LOW	HIGH	HIGH	29	53.40%	44.20%	40.20%	81.30%	92.70%	85.80%
LOW	LOW	LOW	LOW	HIGH	LOW	30	54.50%	46.00%	24.90%	99.00%	86.20%	89.30%
LOW	LOW	LOW	LOW	LOW	HIGH	31	52.40%	48.40%	44.30%	87.80%	93.60%	85.40%
LOW	LOW	LOW	LOW	LOW	LOW	32	51.70%	49.40%	26.10%	99.50%	87.20%	90.20%