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The Lightly Manned Autonomous Combat Capability (LMACC)

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Abstract

As technology continues to move forward and a continued emphasis is placed on construction of large ships and submarines, there is another possibility. That is to construct a third tier of small combatants that project power from the sea in contested environments and employ a "shoot first" backed by a "second salvo." These vessels would be constructed based on the lessons learned from automation of the medium unmanned surface vessel (MUSV) Sea Hunter, in which most ship functions and basic navigation would be automated. The new vessel, called Sea Fighter, would have a crew of 15 and have a single combat mission: to deliver long-range precision weapons and distribute secondary combat functions among the pack of Sea Fighters and Sea Hunters. An analysis of total ship costs is applied in a simulation and comparison to other vessels. The simulation is transportable and can be reused to help determine the best possible vessel for this task.

Introduction

Multiple recent articles have highlighted the drifting maintenance availability schedules for surface ships and submarines. The primary cause of shifting restricted availability (RAV) completions for scheduled maintenance is a stretched operational tempo (OPTEMPO) faced by the fleet. Added to this is the strain imposed on crews in multiple dimensions (rest, schools, family time), and a very dynamic global environment, producing systemic problems—with symptoms such as collisions at sea and less-than-mission-capable platforms. Indeed, the recent collisions indicate that there is a problem with humans on manned platforms understanding the complex systems that watch teams need to manage in order to operate safely in times of time-critical decision-making.

OPTEMPO-induced deficiencies and managing complexity are just a couple symptoms pointing to a need to rethink Navy force structure. Prescriptions generally adjust the fleet upward in the number of ships available to meet perceived near- and far-term global security demands, with a secondary effect of creating system slack that will enable better ship maintenance and personnel training.

However, creating a 355(+/−)-ship Navy is a task with many multiple nested decision trees—decisions that once taken will shape the configuration of the target fleet and its capabilities.

One such decision point involves the role of autonomous systems at sea. The U.S. Navy is indeed exploring air, undersea, and surface autonomy. However, there are substantial hurdles.

A CNA paper from 2017 describes the role of the three “offsets,” with the implementation of artificial intelligence and autonomy being the third offset.

> It is the economic necessity to rebalance force structure that has spurred the Department of Defense (DoD) to pursue a Third Offset strategy emphasising improved human/machine collaboration through the exploitation of autonomous, distributed, and network-enabled systems. “Third Offset is the latest in a series of offset strategies, which are driven by those numbers [and] a need to work in smarter ways,” Carr said. “It’s about how you get the most capability out of the dollars that you have. We have to stop buying fewer numbers of more expensive stuff.”

As pointed out above, there is a need to embrace the oncoming operational and technical advances in autonomy. These advances are problematic if not worked through at an operational level, with real platforms that are engaged in an increasingly diverse set of operational problems. Acquainting fleet operators with automation technology and developing concepts of operations (CONOPs) along with trust in the capabilities is extremely important. “Thus it likely will be necessary for operators and operational commanders to work with these systems more extensively and over a wider range of scenarios for such systems to become relatively predictable and acquire an appropriate degree of trust.”

Sea Hunter

The medium unmanned surface vessel (MUSV) Sea Hunter is currently undergoing testing for collision regulations (COLREG) compliance and within limited operational concepts by Surface Development Squadron ONE. This game-changing technology merged onto a long-endurance platform has produced some real shifts in perception of a surface unmanned vessel.

> However, the first step is to better understand how Sea Hunter will fit into the fleet. “Frankly, the navy has to understand the CONOPS,” Russell said. “How we would use these vehicles, understanding if a technology is viable enough, and what systems you might put on there to increase the capability of these unmanned platforms. [Those are] areas of research that we are focusing on.”

There are numerous challenges, some technical, others policy, that still need to be addressed—such as cybersecurity.

A second medium displacement unmanned surface vessel (MDUSV) has been funded, which may help create some momentum in the direction of fleet implementation. At the same time, the U.S. Navy (USN) has announced its plan to purchase a new class of warship, at a cost of $950 million per hull. Little additional information could be found on this vessel, but it is likely to be built on precepts that will be outdated by the time they are delivered, and without the advances in autonomy that are likely.

We propose considering another possibility, one that will create the technical, operational, policy, and CONOPs development opportunity in concert with the third offset and be a potential sea change for the USN of the future, while enabling the relief in OPTEMPTO and continued complex missions of manned surface vessels.

Lightly Manned Autonomous Combat Capability

Defense Advanced Research Projects Agency (DARPA) largely built the autonomous continuous trail unmanned vessel (ACTUV)—later to become MDUSV, then MUSV, and synonymous with Sea Hunter—as an experiment in autonomy. As it began to show promise, many in the USN began to rub their chins and ask, “Well, what do we use it for?” A lot of years have been spent determining what its mission set should be. There are many problems with “potential” and “possible” as determinants of capability—mainly in that they don’t exist. And there is a bridge to cross between fully manned (present) and fully unmanned (future). While we test run at these hurdles, a middle ground is needed for the United States’ response to the near peer nations and possible domination of the sea lines of communication (SLOCS) in the Pacific we are dependent on.

Lightly manned autonomous combat capability (LMACC) turns “what if” thinking on its head. It is designed to meet a CONOP and strategic mission as it is needed *now*, rather than built and then refined in a concept of operations. The LMACC has one primary mission: deliver missiles to targets ashore and afloat within the first island chain, while the “leviathan navy” waits out the first round of missile exchanges to become the second round of mission capable delivery. The cruisers, guided-missile destroyers, and aircraft carriers with nuclear propulsion will not survive the first round inside the second island chain.

In a truly distributed maritime operations, each of these vessels has the primary mission above and a secondary warfare mission unique to that platform. Anti-submarine warfare (ASW) vessels, anti-air warfare vessels, and surface warfare vessels, for example, would be distributed among the Sea Fighter, and in company with Sea Hunter vessels as sensors. A “pack” consists of four Sea Fighters and six Sea Hunters. Three packs would be employed forward and relieved on station by another three packs. This equates to 12 Sea Fighters and 18 Sea Hunters. The manned vessels would include a crew of 15 specialists, commanded by the weapons and tactics instructor. The ship would be built around the current state of autonomy, which looks after the ship’s well-being and navigates according to the rules of the road.

Sea Fighter is currently being designed at Naval Postgraduate School, employing innovative design for “hyper maneuvering” diesel electric hybrid technology, weapon and sensors, and C2 capabilities that allow it to communicate over the horizon in a satellite degraded/denied environment. Many tactics are taken from the aviation community, human systems integration, and the field of human-machine teaming.

Funding for this project was initiated under Navy Research Project funding, with N96 as its sponsor. To build this vessel (prototype) will take a stretch of the acquisition system, employing funding such as Joint Capability Technology Demonstrations, congressional plus-up, and Other Transaction Authority (OTA) procurement. Nontraditional shipyards could be employed for this 1,000-ton, fully loaded vessel of less than 200 feet.

Our first design was based on an extension of the Cyclone coastal patrol–class that has been refit using current autonomous seakeeping and mission behavior capabilities. This partially manned vessel would perform most of its mission-state behaviors (e.g., sea keeping, maneuvering, systems maintenance) and mission behaviors (e.g., surface intelligence, surveillance, and reconnaissance; patrol of sea lanes; and intelligence gathering) autonomously, while the limited crew would perform oversight, man-in-the-loop and man-on-the-loop functions, as well as providing security. This would be an experimental but also CONOP developing system, one that could point the way to future ship/human teaming designs. As a mother ship to other autonomous systems, integration and interoperability of these systems could be optimized and focused on making these systems operationally viable.

Other recent cost analysis included hauling out and refitting an FFG-7 hull. The cost was put at around $450 million if it were to be updated for communications, weapons sensors, weapons systems, and habitability. If kept to the concept of autonomy, outfitting the ship with required sensors to sense the environment for autonomy could be modeled on the lessons learned from Sea Hunter, and at a lower cost. Autonomy is not just sensing the physical environment around the vessel, extracting what is mission-relevant; it is also the sensing of systems aboard the vessel. Sea Hunter has been very important in showing that systems and maintenance-related needs required to the vessel can be implemented and controlled by autonomy for long durations.

In the end, our current configuration is a new hull design with some innovations:

- Deep keel for sea keeping and attachment of ASW pod for this variant;
- Diesel-electric hybrid power plant and possible continuous variable transmission;
- Controllable pitch propellers;
- Forward water jet bow thruster;
- Unique missile launcher with overboard discharge;
- Internal habitability gleaned from airline industry (e.g., sleeping pods from first class, with additional privacy);
- Meals taken again from airline industry for first-class passengers (e.g., small galley for coffee, heating frozen food, and prepping of dried food like rice, beans, etc.);
- Fuel bladders internal to the vessel, in addition to fuel storage, to increase range—as fuel may not be available over its 9,000-mile mission range;
- Rethinking of watch teams (e.g., section watches not required; move more to work on demand and as circumstances require);
- Sensor decision aids and emergency action messaging; and
- Extremely high frequency satellite communications, backed up by wide-area network, high-frequency internet protocol.

Literature Survey

In the *NAVSEA Cost Estimation Handbook*, Deegan (2005) provides a ready reference to “support the stewardship of our cost engineering capabilities,” while SPAR Associates (2015) “uses its system to quickly estimate ship costs based on initial design data and to provide the impact on costs of alternate design and build strategy decisions.”

Lee (2014) looked at improving the parametric method of cost estimating relationships of U.S. Navy ships. In considering recent military budget cuts, there has been a focus on determining methods to reduce the cost of Navy ships. According to Lee,

> [A] RAND National Defense Research Institute study showed many sources of cost escalation for Navy ships. Among them included characteristic complexity of modern Naval ships, which contributed to half of customer driven factors. This paper focuses on improving the current parametric cost estimating method used as referenced in NAVSEA’s Cost Estimating Handbook.

Currently, as Lee (2014) describes,

> Weight is used as the most common variable for determining cost in the parametric method because it's a consistent physical property and most readily available. Optimizing ship design based on weight may increase density and complexity because ship size is minimized.

That paper introduced "electric power density and outfit density as additional variables to the parametric cost estimating equation and will show how this can improve the early stage cost estimating relationships of Navy ships" (Lee, 2014).

From our literature survey, we found that there are four common types of cost estimating methods: "Analogy, Parametric, Engineering Build-up, and Extrapolation from Actuals" (Lee, 2014). During the very early stages of cost estimating, even before the concept refinement stage, the *analogy* cost estimating method is used. As more details emerge and more information is available for the cost estimator, a more accurate, *build-up* cost estimation is used. Toward the end of the ship's life cycle, we can *extrapolate actual* cost information, and it is no longer an estimation.

NAVSEA (2015) released instructions regarding the preparation of government cost estimates. The general methods described in the manual include the four most common methods of cost estimating: "roundtable, comparison, detailed estimating, and parametric cost estimating (cost estimate relationships)."

In his article "Budget Office Questions Navy Shipbuilding Cost Estimates," Walcott (2012) finds that the U.S. Navy is

> underestimating the cost of its proposed 30-year shipbuilding program by 19 percent, the non-partisan Congressional Budget Office said in a report. By comparison, using its own models and assumptions, CBO estimates that the cost for new-ship construction under the 2013 plan would average $20.0 billion per year, or a total of $599 billion through 2042.

In *Integrating Cost Estimating with the Ship Design Process*, Deschamps and Greenwell (2009) explain that the ship design process is an

> evolutionary process where at the conceptual design level, pre-Milestone A for Naval acquisition programs, few details are known, and the metrics used for estimating costs are based on analogous platforms and limited parametric functions. As the design process continues towards Milestone B the design begins to take shape with fewer analogies and an increasing number of parametric cost drivers. At this point, 80% of the life-cycle costs (LCC) are set and the cost risk associated with the design becomes an important piece of the overall acquisition costs. It is imperative that the methods used to estimate the cost and cost risk are tightly coupled with the design iteration process and are parametric in nature in order to support the needs of the Program Manager in terms of not only the basic design but design trade-offs.

The authors present the use and benefits of employing a set of parametric cost models during the concept and preliminary phases of ship design.

> These cost models produce quick assessments of costs and risk, for design and mission trade-off alternatives. The cost models, being parametric, can follow the evolutionary design process. At early stages of the design, when many details of the design are not yet available, the cost models automatically provide statistically-synthesized values for missing parameters. Then, as the design matures, these default values can be replaced with values developed for the design. (Deschamps & Greenwell, 2009)

In *A Practical Approach for Ship Construction Cost Estimating*, Ross (2002) states that to succeed commercially, shipyards must be able to accurately estimate costs. Cost estimating is necessary for the “bid process, change orders, and trade-off studies.” Numerous cost estimating approaches exist. They are based on extrapolations from “previously-built ships, detailed bottoms-up parametric models, and integrated physics-based analyses.” Cost estimating can be frustrating to shipyard personnel. Cost estimators may lack timely technical information and face data inconsistencies.

> Ship engineers and naval architects commonly lack feedback on the cost consequences of their technical decisions. Managers often lack information denoting the level of confidence in cost estimates upon which they must make business decisions. Finally, many approaches to cost estimating are mysterious and not formally validated (each cost estimator has his own black book), complicated (too time consuming to be of use to decision makers), or difficult to use (steep learning curve). (Ross, 2002)

This paper presents an approach that enables instant sharing of cost and technical data among ship engineers, naval architects, and cost estimators; the analysis was meant to provide confidence measures to managers.

Truver (2001) believes that estimating ship construction costs is behind the times. In one highly critical area of naval analysis, the Navy seems to be “bogged down in the early years of the last century.” The Navy’s traditional approach and methodology for estimating the construction and life-cycle costs of new ships is “out of step with the Revolution in Business Affairs.” According to Truver (2001),

> The Naval Surface Warfare Center (NSWC) is rethinking the current paradigm of ship cost estimating. Taking the lead in a joint Navy-industry initiative to reinvent the way ship costs are determined, have developed the Product Oriented Design and Construction (PODAC) Cost Model.

Additionally,

> since the end of the Cold War, naval procurement for the U.S. Navy has seen a dramatic decrease. This decrease in defense spending has placed existing programs under more scrutiny than previous years. As a result, there is less tolerance on the part of taxpayers and U.S. Congress for procurement cost growth. (Miroyannis, 2006)

The research attempts to examine the current method that the Navy conducts ship cost estimates, and it suggests changes in order to improve the confidence level and accuracy of the forecasts. An examination of how industry is conducting cost estimates was used as a comparison to the current Navy practices. Finally,

> using only a weight-based approach to ship cost estimating is insufficient. It is necessary to develop and use a model that incorporates other cost driving factors in order to develop estimates of sufficient quality at the preliminary design level. (Miroyannis, 2006)
>
> Smith (2008) updates one ship cost estimation model by
>
> combining the two existing models (the Basic Military Training School [BMTS] Cost Model and the MIT Math Model) in order to develop a program that can accurately determine both a ship’s acquisition cost as well as its life-cycle cost. Using United States Coast Guard resources, this project addressed various aspects of the ship design process which have a direct effect on the cost of building a ship. This will include, but not be limited to, the cost estimation process, determining which design decisions have the biggest impact on the ship's total cost, common pitfalls in the design process that lead to increases in cost, and lessons learned that have helped minimize the cost of a ship.
>
> Sullivan (2011) found that the

> inability to predict ship acquisition cost accurately is a great impediment to budget formulation and execution for shipbuilding programs. It also has eroded the U.S. Navy's credibility with Congress. Dramatic improvements in cost analysis tools are needed. Areas for improvement include the following:
>
> - Prediction of R&D costs based on system complexity, subsystem technology, and state of development;
> - Modeling of design and construction workforce requirements;
> - 10 Naval Ship Design and Construction;
> - Topics for the Research and Development Community;
> - Modeling the cost of design tools, including configuration, mass properties tools;
> - Product Logistics Models environment;
> - Modeling of ship integration and test costs;
> - Assessment of the costs of facilitation of prime shipbuilding contractor, principal subcontractors, and warfare system contractors;
> - Modeling of the effects of concurrent workloads from multiple contracts at all contractors facilities;
> - Assessment of cost of government warfare center participation in development and execution; and
> - Probabilistic cost analysis tools that give the range of estimates and the probability that the estimates will not be exceeded. (Sullivan, 2011)

Cost estimating tools could benefit from an approach that takes advantage of the massive computing power available today and also the availability of highly intelligent search engines. The principle should be that if cost data exist anywhere, the Navy should be able to access them. This means that the cost of any component or commodity could theoretically be queried, stored in the Navy shipbuilder cost database, and periodically updated—either from catalog information, bid pricing, or other publicly available information. The Navy should, according to Sullivan,

> adapt one or more of the commercially available search engines for this purpose and mandate its use for all shipbuilding programs. Furthermore, if shipbuilders could continue to execute the Common Parts Catalog initiative of the National Shipbuilding Research Program (NSRP), the search engines could query this catalog for component cost tabulation. (Sullivan, 2011)

Moore and White (2005) used a regression approach for estimating procurement costs:

> Cost growth in Department of Defense weapons system continues to be a scrutinized area of concern. One way to minimize unexpected cost growth is to derive better and more realistic cost estimates. In this vein, cost estimators have many analytical tools to ply. Previous research has demonstrated the use of a two-step logistic and multiple regression methodology to aid in this endeavor. We investigate and expand this methodology to cost growth in procurement dollar accounts for the Engineering and Manufacturing Development phase of DoD acquisition. We develop and present two salient statistical models for cost estimators to at least consider if not use in mitigating cost growth for existing and future government acquisition programs.

According to Brown and Neu (2008), engineering cost models must be reliable, practical, and sensitive to the cost and performance impact of producibility enhancements. A baseline surface combatant cost model was developed using a modified weight-based approach. A more flexible model will be developed in Phase 2 using automated cost estimating integrated tools (ACEIT). ACEIT is an automated architecture and framework for cost estimating. It is a government-developed tool that has been used to standardize and simplify the life-cycle cost estimating process in the government environment. Core features include a database to store technical and normalized cost data, a statistical package specifically tailored to facilitate cost estimating relationship development, and a spreadsheet that promotes structured, systematic model development and built-in government-approved inflation, learning, time phasing, and documentation, as well as sensitivity/what-if, risk, and other analysis capabilities. Our task will be to adapt this general framework for concept development to naval ship cost analysis, including producibility. Cost uncertainty aspects will be integrated with Task 2.3.

The *Joint Agency Cost Schedule Risk and Uncertainty Handbook* (Cost Assessment Data Enterprise [CADE], 2014) states that the government cost analysis community recognizes the need to

> capture the inherent uncertainty of acquisition programs into realistic cost estimates to support milestone decision process. Programmatic, cost, schedule, and technical uncertainties are present from the earliest concept exploration phase, through system development, acquisition, deployment, to operational and sustainment. Many estimating processes have focused on producing a single, discrete dollar value that in turn becomes the budget. Realistically, estimating processes develop a range of likely values, with objective and quantifiable analysis of uncertainty intrinsically embedded. The goal of this handbook is to introduce industry best practices for incorporating uncertainty into our estimates in order to provide decision makers with the information necessary to make sound, defendable investment decision.

This handbook emphasizes the need to shift away from estimates based solely on the best-guess of system and programmatic parameters and encourages the cost analyst to build models that address technical, programmatic, cost, and schedule uncertainties and view risks as interdependent, not separate, processes. The effective incorporation of risk uncertainty in cost and schedule estimates is a challenging task. This handbook is promulgated to help establish a systematic, structured, repeatable, and defendable process for delivering comprehensive estimates to government leadership to get the best possible capability with increasingly limited available resources (CADE, 2014).

Cost estimating in NAVSEA “requires accurate costs estimates as it is critical to achieving an affordable U.S. Navy shipbuilding program” (Deegan & Mondal, 2008).

> There is significant concern, both within and outside the Department of Defense, over the future affordability of the U.S. Navy’s shipbuilding programs. The increasing costs of these programs reflect a variety of factors, such as lower production quantities, increasing weapons system complexity, increasing commodity prices, and a shortage of skilled, workers in the shipbuilding industry. This article examines the challenges one faces when attempting to accurately predict future ship and weapons system costs. It also summarizes current initiatives under way within the cost engineering organization of the Naval Sea Systems Command (NAVSEA) to mitigate these challenges. Reliable cost estimates are important to maintaining a viable Navy. It is encouraging to see greater importance accorded to independent cost estimating within the DoN along with efforts to understand and use quantitative risk analysis in making cost decisions. NAVSEA cost estimators are proud to be leaders in this endeavor. (Deegan & Mondal, 2008)

Mulligan (2008) states that

> the accepted method for estimating ship construction and operating costs is due to Harry Benford, a professor of naval architecture and marine engineering at the University of Michigan, and dates from the 1960s. Benford conducted regression studies with a variety of technical and cost parameters to arrive at basic algebraic relationships among cargo capacity, ship dimensions, degree of streamlining (block coefficient), design operating speed, Admiralty coefficient, required shaft horsepower, required engine size, and ship steel weight. His approach however is based on design assumptions which have grown increasingly less applicable.

Case Application: DDG 51 FLT III Cost Model

This section details an illustration of the proposed integrated cost estimation modeling approach. As this is only an illustration, and due to a lack of proprietary data for this first phase of the analysis, the input assumptions are only high-level approximations based on publicly available information and subject-matter expert estimates. Therefore, the results generated are not to be used in any specific decision-making. Nonetheless, the approach presented is robust and valid, and with the correct input assumptions, it can be rerun to generate accurate and reliable estimates. Information and data were obtained via publicly available sources and were collected, collated, and used in an integrated risk-based cost and schedule modeling methodology. The objective of this study is to develop a comprehensive cost modeling strategy and approach and, as such, notional data were used. Specifically, we used the Arleigh Burke–class guided missile destroyer—DDG 51 Flight I, Flight II, Flight IIA, and Flight III (see Figure 1)—as a basis for the cost and schedule assumptions, but the modeling approach is extensible to any and all other ships within the U.S. Navy.

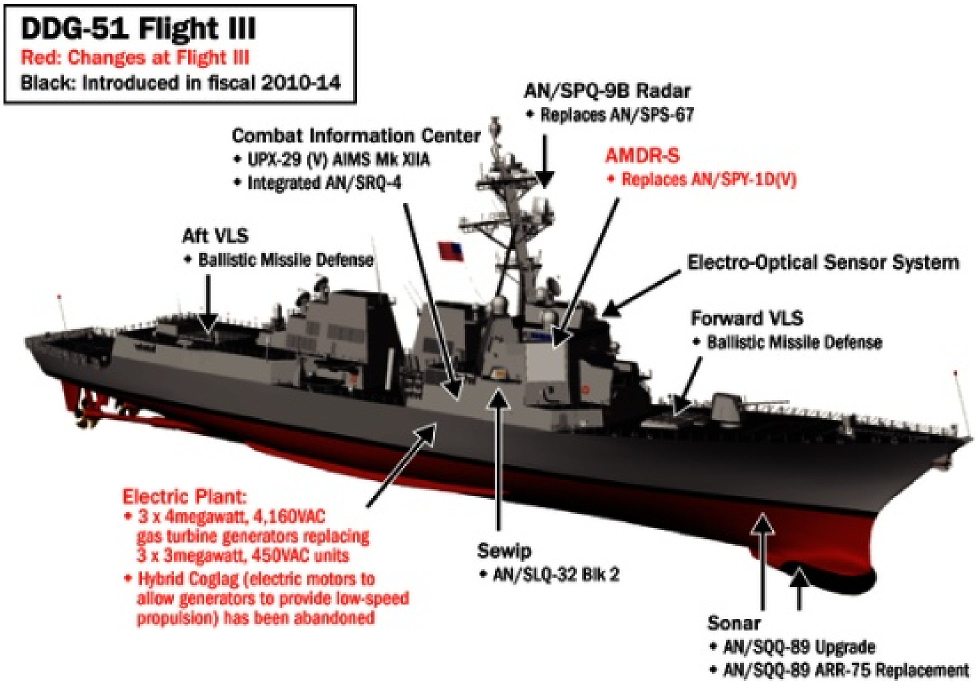
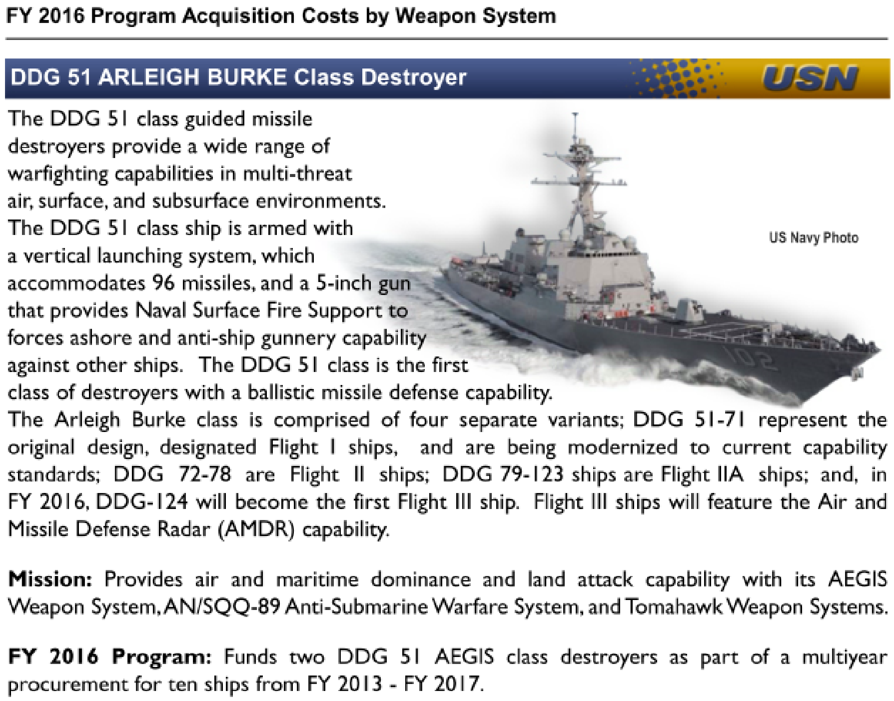


Figure 1. Overview of DDG 51 Flight III

Overview of the DDG 51 Arleigh Burke Destroyer

In the cost analysis models, we will consider the full build of the ship, with its accoutrements such as weapons systems, electrical systems, radar and electronic warfare systems, communication and navigation systems, aircraft, and other extra add-ons.

Figure 2 is a descriptive summary of the DDG 51 Arleigh Burke destroyer. The DDG 51 is a guided missile destroyer in the U.S. Navy, with a complement of up to 96 missiles and a five-inch gun for naval surface warfare. The DDG 51 has multiple variants; in the current analysis we will consider the FLT III variant. One of the reasons the DDG 51 was selected for this analysis is because sufficient information on its acquisitions process is available, since two DDG 51 Aegis destroyers have been funded in Fiscal Year (FY) 2016. These two ships are part of a 10-ship procurement between FY2013 and FY2017.



FY 2016 Program Acquisition Costs by Weapon System

DDG 51 ARLEIGH BURKE Class Destroyer

The DDG 51 class guided missile destroyers provide a wide range of warfighting capabilities in multi-threat air, surface, and subsurface environments. The DDG 51 class ship is armed with a vertical launching system, which accommodates 96 missiles, and a 5-inch gun that provides Naval Surface Fire Support to forces ashore and anti-ship gunnery capability against other ships. The DDG 51 class is the first class of destroyers with a ballistic missile defense capability. The Arleigh Burke class is comprised of four separate variants; DDG 51-71 represent the original design, designated Flight I ships, and are being modernized to current capability standards; DDG 72-78 are Flight II ships; DDG 79-123 ships are Flight IIA ships; and, in FY 2016, DDG-124 will become the first Flight III ship. Flight III ships will feature the Air and Missile Defense Radar (AMDR) capability.

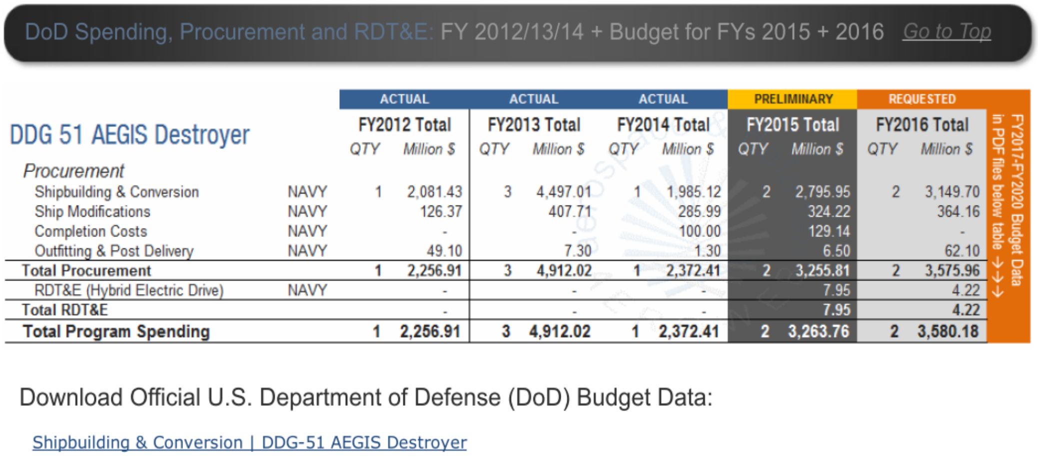
Mission: Provides air and maritime dominance and land attack capability with its AEGIS Weapon System, AN/SQQ-89 Anti-Submarine Warfare System, and Tomahawk Weapon Systems.

FY 2016 Program: Funds two DDG 51 AEGIS class destroyers as part of a multiyear procurement for ten ships from FY 2013 - FY 2017.

Figure 2. DDG 51 Specifications

DoD Spending on the Aegis Destroyer in FY2012 to FY2016

Figure 3 shows some sample acquisition budgets for DDG 51 Aegis destroyers from FY2012 through FY2016. The comprehensive DoD budget was downloaded and analyzed in the current research.



DoD Spending, Procurement and RDT&E: FY 2012/13/14 + Budget for FYs 2015 + 2016 Go to Top

DDG 51 AEGIS Destroyer		ACTUAL		ACTUAL		ACTUAL		PRELIMINARY		REQUESTED		FY2017-FY2020 Budget Data in PDF files below table →→→
		FY2012 Total		FY2013 Total		FY2014 Total		FY2015 Total		FY2016 Total		
		QTY	Million $	QTY	Million $	QTY	Million $	QTY	Million $	QTY	Million $	
Procurement												
Shipbuilding & Conversion	NAVY	1	2,081.43	3	4,497.01	1	1,985.12	2	2,795.95	2	3,149.70	
Ship Modifications	NAVY		126.37		407.71		285.99		324.22		364.16	
Completion Costs	NAVY		-		-		100.00		129.14		-	
Outfitting & Post Delivery	NAVY		49.10		7.30		1.30		6.50		62.10	
Total Procurement		1	2,256.91	3	4,912.02	1	2,372.41	2	3,255.81	2	3,575.96	
RDT&E (Hybrid Electric Drive)	NAVY		-		-		-		7.95		4.22	
Total RDT&E			-		-		-		7.95		4.22	
Total Program Spending		**1**	**2,256.91**	**3**	**4,912.02**	**1**	**2,372.41**	**2**	**3,263.76**	**2**	**3,580.18**	

Download Official U.S. Department of Defense (DoD) Budget Data:

Shipbuilding & Conversion | DDG-51 AEGIS Destroyer

Figure 3. DoD Spending and Procurement for FY2012 to FY2016

High-Level Shipbuilding Process

Figure 4 shows the high-level process flow of building ship hulls and sections.

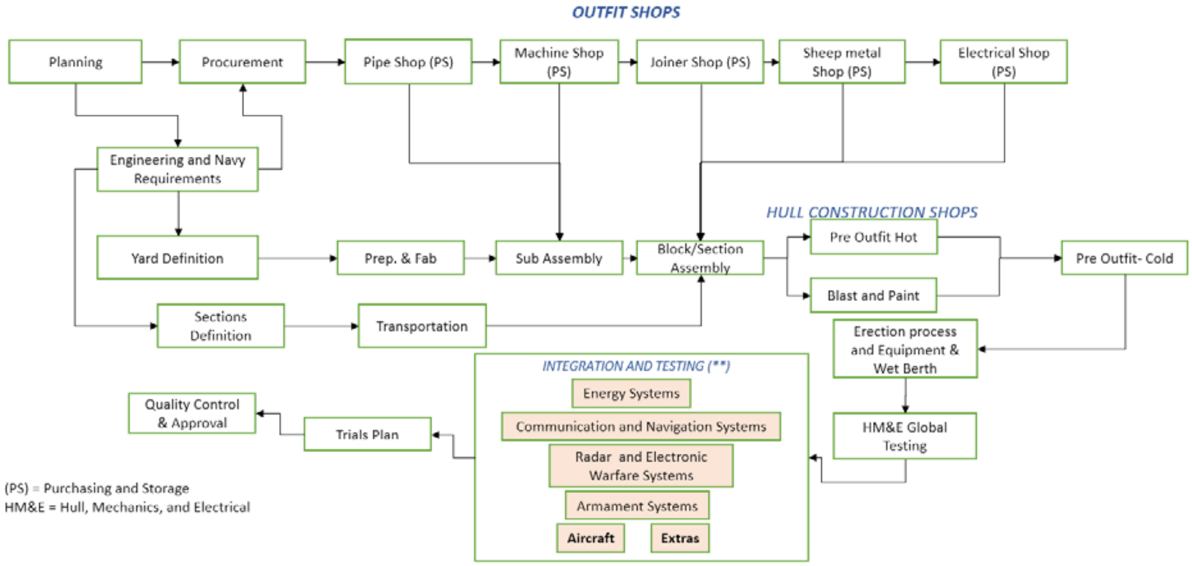


Figure 4. High-Level Process Flow (Hull and Sections)

Information, Communication, and Technology Subprocess

Figure 5 shows the ship’s subprocess for information, communication, and technology.

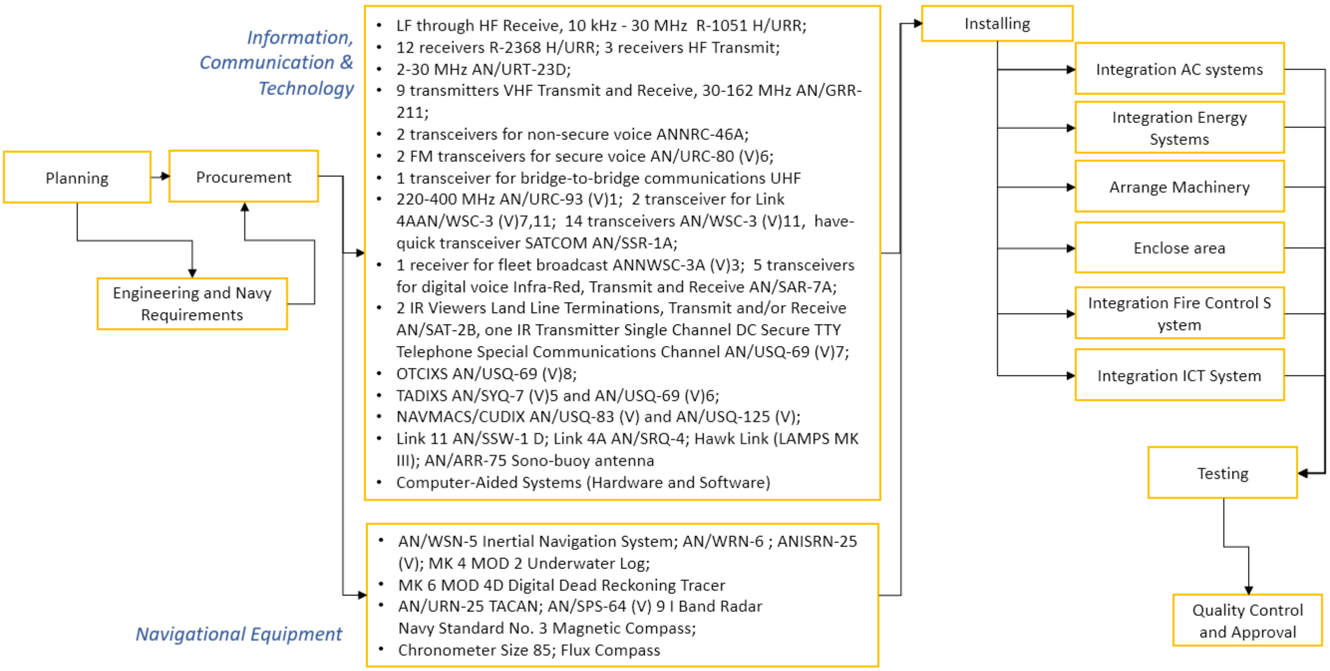


Figure 5. Subprocess for Information, Communication, and Technology

Weapons System Subprocess

Figure 6 shows the ship’s subprocess for weapons systems.

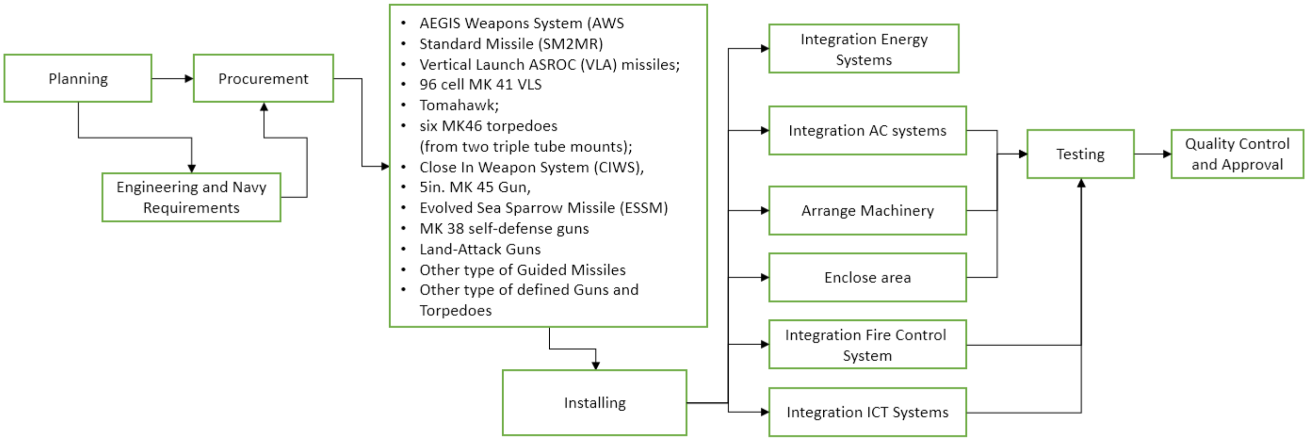
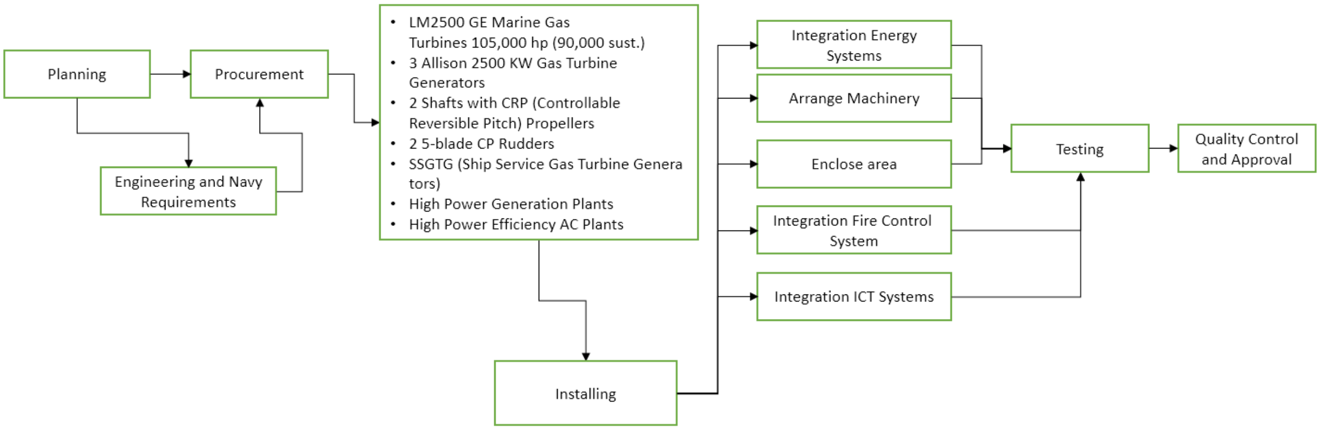


Figure 6. Subprocess for Weapons Systems

Electrical Systems Subprocess

Figure 7 shows the ship’s electrical systems subprocess.

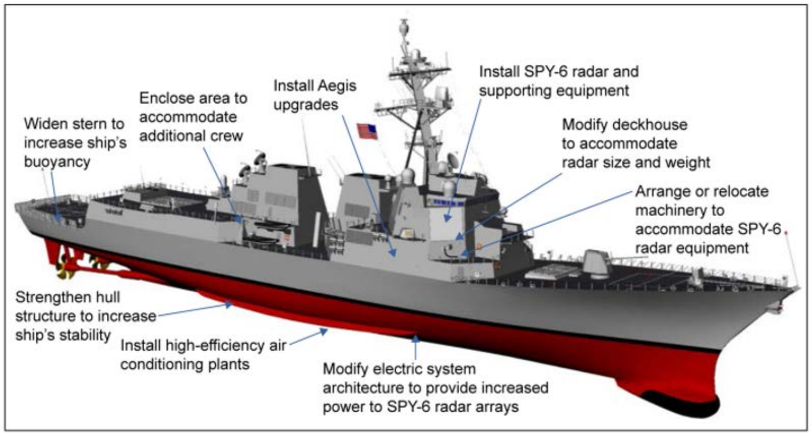


Propulsion: General Electric LM2500 gas turbines each generating 26,500 HP (19,800 kW); coupled to two shafts, each driving a five-bladed reversible controllable-pitch propeller

Figure 7. Subprocess for Electrical Systems

SPY-6 Radar System

Figure 8 shows the ship's radar subsystem's process.



Source: GAO (analysis); Navy (image and data). | GAO-16-613

ARLEIGH BURKE DESTROYERS:
Delaying Procurement of DDG 51 Flight III Ships Would Allow Time to Increase Design Knowledge
GAO-16-613: Published: Aug 4, 2016. Publicly Released: Aug 4, 2016.

What GAO Found

The Air and Missile Defense Radar (AMDR) program's SPY-6 radar is progressing largely as planned, but extensive development and testing remains. Testing of the integrated SPY-6 and full baseline Aegis combat system upgrade—beginning in late 2020—will be crucial for demonstrating readiness to deliver improved air and missile defense capabilities to the first DDG 51 Flight III ship in 2023. After a lengthy debate between the Navy and the Department of Defense's (DOD) Director of Operational Test and Evaluation, the Secretary of Defense directed the Navy to fund unmanned self-defense test ship upgrades for Flight III operational testing, but work remains to finalize a test strategy.

Figure 8. SPY-6 Radar System and Rework

DoD Extras: Electronic Warfare, Decoys, Extra Capabilities

Figure 9 shows the ship's electronic warfare, decoys, and extra capabilities subprocesses.

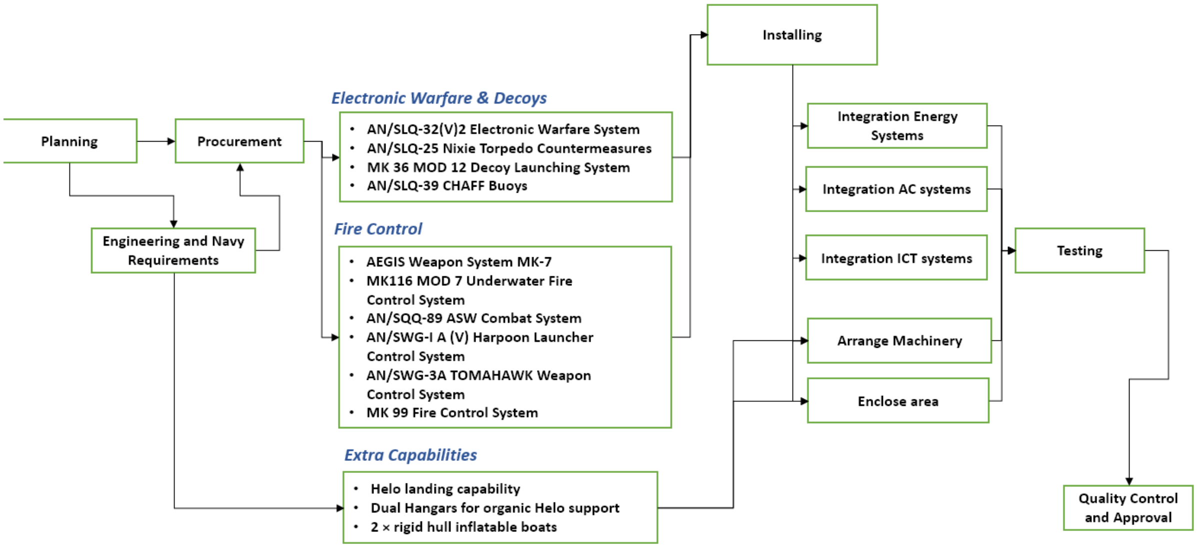


Figure 9. Subprocesses and Examples of DoD Extras

Risk-Based Schedule and Cost Process Modeling

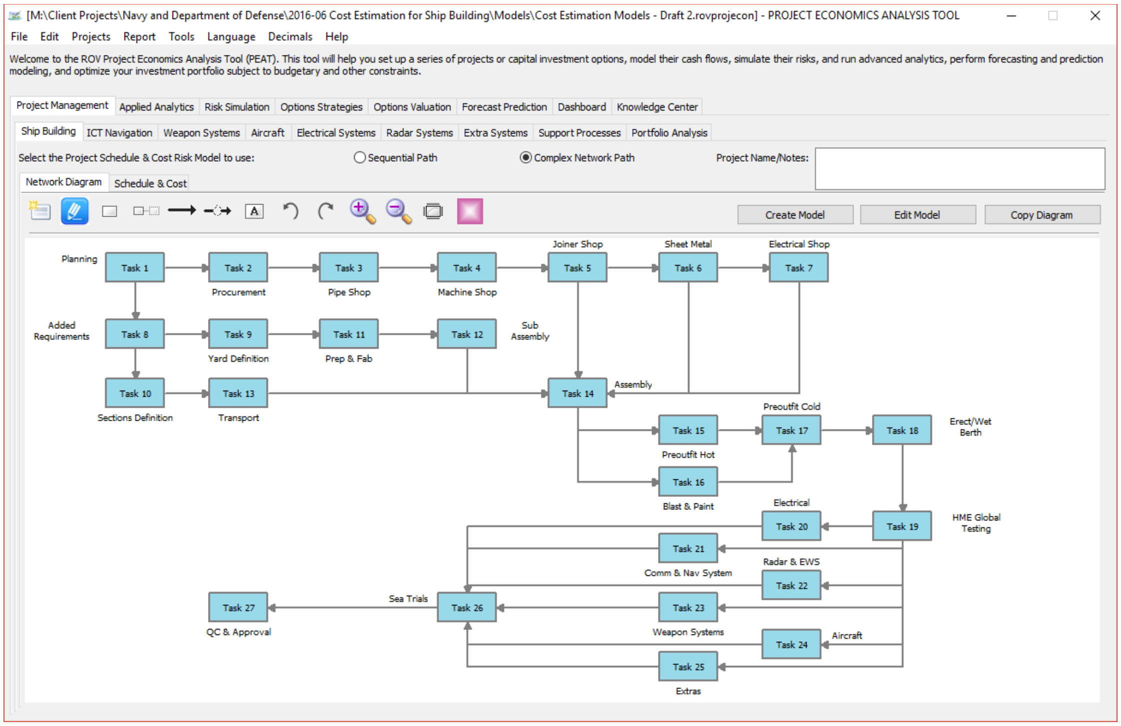
Figures 10 illustrates how the project management tasks are incorporated into the PEAT software application. The parallel development of tasks 20 to 25 is where the ship's various subsystems are incorporated into the cost and schedule analysis.

Further, Figures 11, 12, and 13 show how some of the publicly available data are collated and incorporated as assumptions into the PEAT software (see Figure 14).

Sea Hunter Analysis of Alternatives

Figure 12 illustrates the analysis of alternatives or strategic options. Based on the pricing policy on PC 14 at the Bollinger Machine Shop and Yard, we were able to extrapolate the data for 1990 to current dollar values (2020) as shown in Figure 13 for patrol coastal (PC) boats. The Monte Carlo simulated cost shows a range of $16.4 million to $32 million, with a 90% confidence interval (see Figure 14). The range depends on the number of ships, where there is a learning curve (i.e., cost reduces over the course of multiple ships). Figure 15 shows the simulated expected value of PC boats at $23.6 million. This corresponds to the estimated $20 million price tag as reported by the *Daily Mail,* stating that

> the 132ft-long (40-metre) unarmed prototype, dubbed Sea Hunter, is the naval equivalent of Google's self-driving car, designed to cruise on the ocean's surface without a crew. The ship's projected $20 million (£14.2 million) price tag and its $20,000 (£14,300) daily operating cost make it relatively inexpensive for the Navy. (Zolfagharifard, 2016)

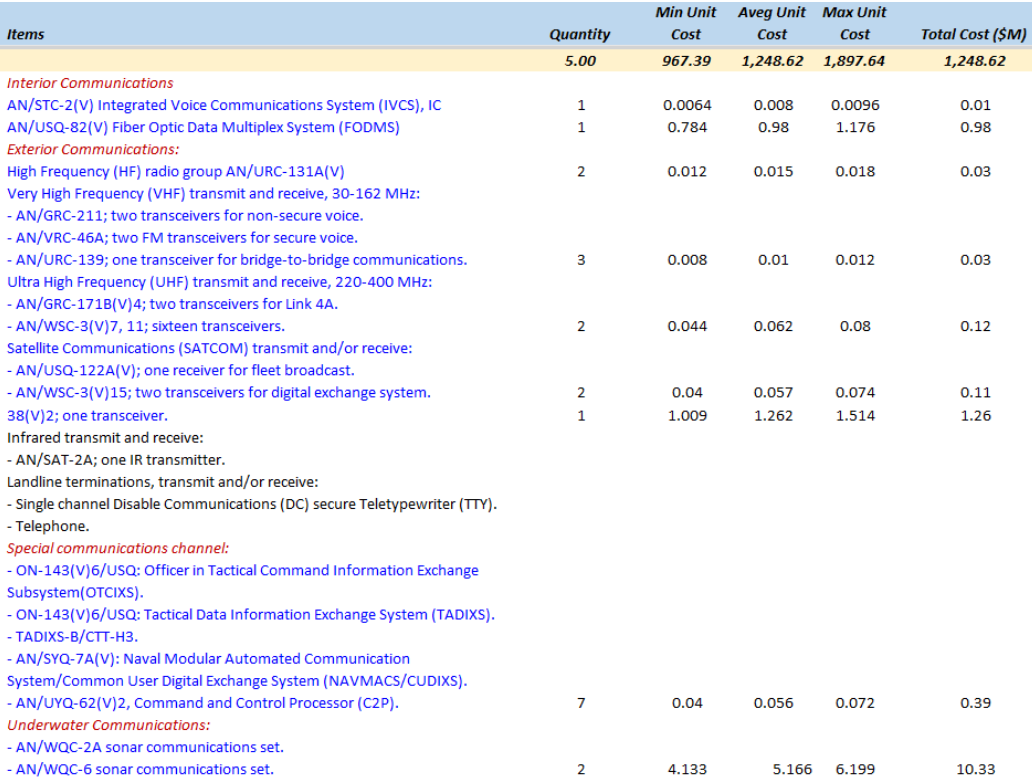

[M:\Client Projects\Navy and Department of Defense\2016-06 Cost Estimation for Ship Building\Models\Cost Estimation Models - Draft 2.rovprojecon] - PROJECT ECONOMICS ANALYSIS TOOL

Welcome to the ROV Project Economics Analysis Tool (PEAT). This tool will help you set up a series of projects or capital investment options, model their cash flows, simulate their risks, and run advanced analytics, perform forecasting and prediction modeling, and optimize your investment portfolio subject to budgetary and other constraints.

Select the Project Schedule & Cost Risk Model to use: ○ Sequential Path ● Complex Network Path

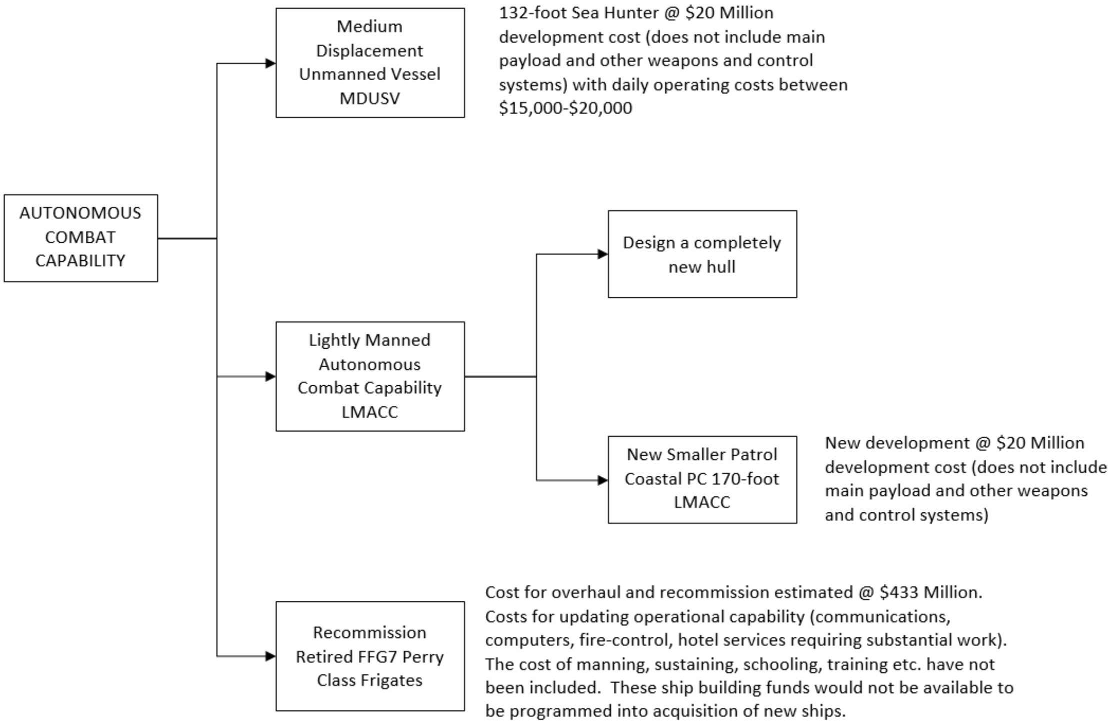
Project Name/Notes:

Figure 10. Modeling Overall Process



Items	Quantity	Min Unit Cost	Aveg Unit Cost	Max Unit Cost	Total Cost ($M)
	5.00	967.39	1,248.62	1,897.64	1,248.62
Interior Communications					
AN/STC-2(V) Integrated Voice Communications System (IVCS), IC	1	0.0064	0.008	0.0096	0.01
AN/USQ-82(V) Fiber Optic Data Multiplex System (FODMS)	1	0.784	0.98	1.176	0.98
Exterior Communications:					
High Frequency (HF) radio group AN/URC-131A(V)	2	0.012	0.015	0.018	0.03
Very High Frequency (VHF) transmit and receive, 30-162 MHz:					
- AN/GRC-211; two transceivers for non-secure voice.					
- AN/VRC-46A; two FM transceivers for secure voice.					
- AN/URC-139; one transceiver for bridge-to-bridge communications.	3	0.008	0.01	0.012	0.03
Ultra High Frequency (UHF) transmit and receive, 220-400 MHz:					
- AN/GRC-171B(V)4; two transceivers for Link 4A.					
- AN/WSC-3(V)7, 11; sixteen transceivers.	2	0.044	0.062	0.08	0.12
Satellite Communications (SATCOM) transmit and/or receive:					
- AN/USQ-122A(V); one receiver for fleet broadcast.					
- AN/WSC-3(V)15; two transceivers for digital exchange system.	2	0.04	0.057	0.074	0.11
38(V)2; one transceiver.	1	1.009	1.262	1.514	1.26
Infrared transmit and receive:					
- AN/SAT-2A; one IR transmitter.					
Landline terminations, transmit and/or receive:					
- Single channel Disable Communications (DC) secure Teletypewriter (TTY).					
- Telephone.					
Special communications channel:					
- ON-143(V)6/USQ: Officer in Tactical Command Information Exchange Subsystem(OTCIXS).					
- ON-143(V)6/USQ: Tactical Data Information Exchange System (TADIXS).					
- TADIXS-B/CTT-H3.					
- AN/SYQ-7A(V): Naval Modular Automated Communication System/Common User Digital Exchange System (NAVMACS/CUDIXS).					
- AN/UYQ-62(V)2, Command and Control Processor (C2P).	7	0.04	0.056	0.072	0.39
Underwater Communications:					
- AN/WQC-2A sonar communications set.					
- AN/WQC-6 sonar communications set.	2	4.133	5.166	6.199	10.33

Figure 11. Cost Information on Communications and Radar Systems

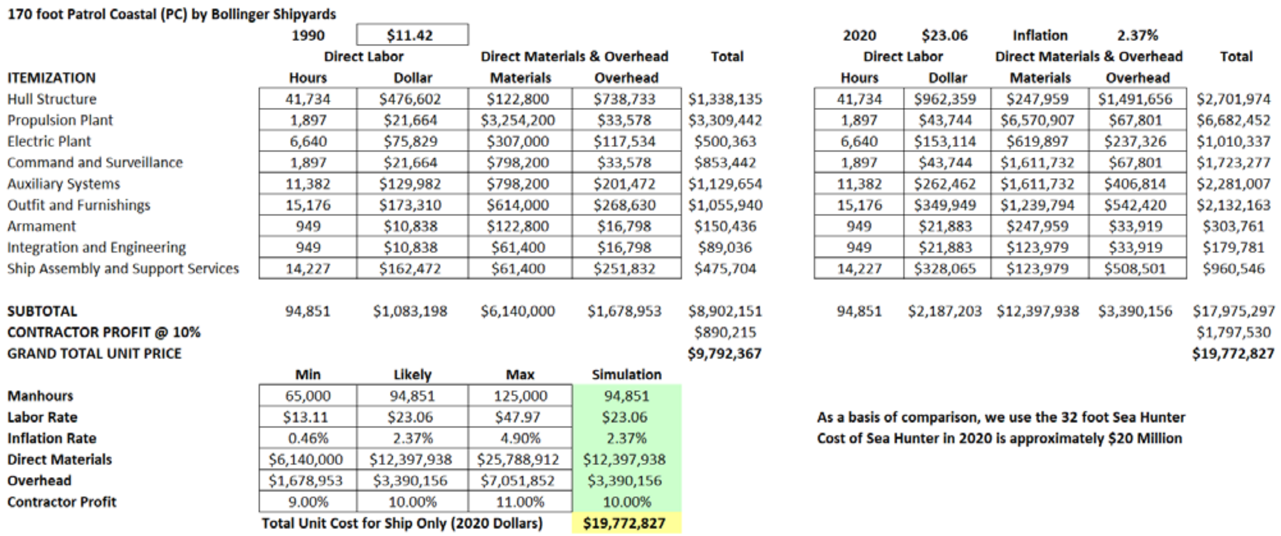


132-foot Sea Hunter @ $20 Million development cost (does not include main payload and other weapons and control systems) with daily operating costs between $15,000-$20,000

New development @ $20 Million development cost (does not include main payload and other weapons and control systems)

Cost for overhaul and recommission estimated @ $433 Million. Costs for updating operational capability (communications, computers, fire-control, hotel services requiring substantial work). The cost of manning, sustaining, schooling, training etc. have not been included. These ship building funds would not be available to be programmed into acquisition of new ships.

Figure 12. Strategic Options and Analysis of Alternatives



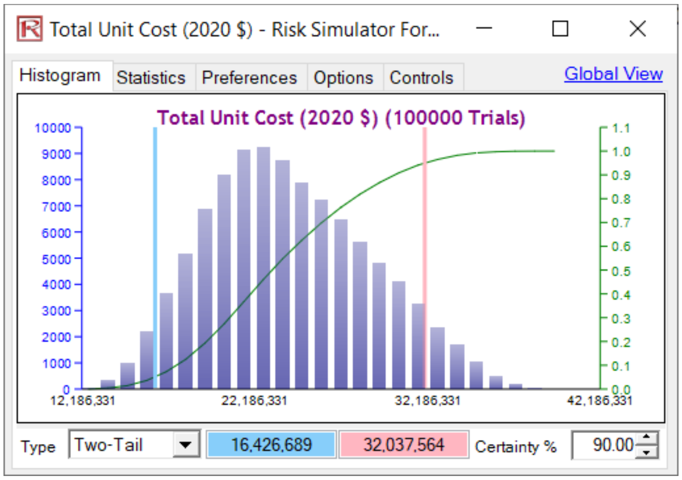
170 foot Patrol Coastal (PC) by Bollinger Shipyards

	1990	$11.42				2020	$23.06	Inflation	2.37%	
	Direct Labor		Direct Materials & Overhead		Total	Direct Labor		Direct Materials & Overhead		Total
ITEMIZATION	Hours	Dollar	Materials	Overhead		Hours	Dollar	Materials	Overhead	
Hull Structure	41,734	$476,602	$122,800	$738,733	$1,338,135	41,734	$962,359	$247,959	$1,491,656	$2,701,974
Propulsion Plant	1,897	$21,664	$3,254,200	$33,578	$3,309,442	1,897	$43,744	$6,570,907	$67,801	$6,682,452
Electric Plant	6,640	$75,829	$307,000	$117,534	$500,363	6,640	$153,114	$619,897	$237,326	$1,010,337
Command and Surveillance	1,897	$21,664	$798,200	$33,578	$853,442	1,897	$43,744	$1,611,732	$67,801	$1,723,277
Auxiliary Systems	11,382	$129,982	$798,200	$201,472	$1,129,654	11,382	$262,462	$1,611,732	$406,814	$2,281,007
Outfit and Furnishings	15,176	$173,310	$614,000	$268,630	$1,055,940	15,176	$349,949	$1,239,794	$542,420	$2,132,163
Armament	949	$10,838	$122,800	$16,798	$150,436	949	$21,883	$247,959	$33,919	$303,761
Integration and Engineering	949	$10,838	$61,400	$16,798	$89,036	949	$21,883	$123,979	$33,919	$179,781
Ship Assembly and Support Services	14,227	$162,472	$61,400	$251,832	$475,704	14,227	$328,065	$123,979	$508,501	$960,546
SUBTOTAL	94,851	$1,083,198	$6,140,000	$1,678,953	$8,902,151	94,851	$2,187,203	$12,397,938	$3,390,156	$17,975,297
CONTRACTOR PROFIT @ 10%					$890,215					$1,797,530
GRAND TOTAL UNIT PRICE					**$9,792,367**					**$19,772,827**

	Min	Likely	Max	Simulation
Manhours	65,000	94,851	125,000	94,851
Labor Rate	$13.11	$23.06	$47.97	$23.06
Inflation Rate	0.46%	2.37%	4.90%	2.37%
Direct Materials	$6,140,000	$12,397,938	$25,788,912	$12,397,938
Overhead	$1,678,953	$3,390,156	$7,051,852	$3,390,156
Contractor Profit	9.00%	10.00%	11.00%	10.00%
	Total Unit Cost for Ship Only (2020 Dollars)			**$19,772,827**

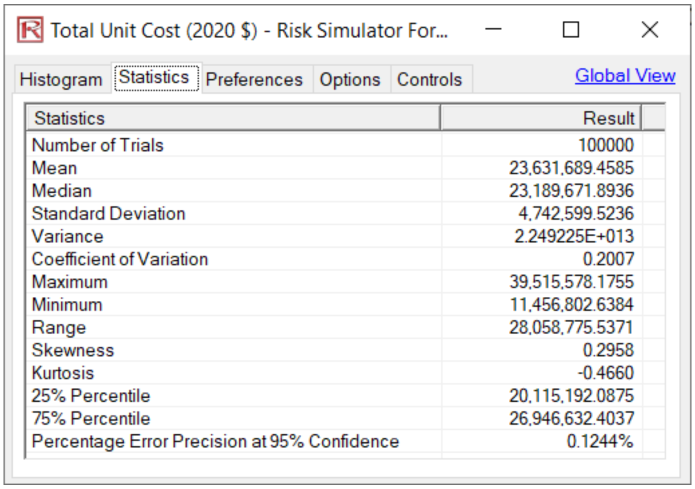
As a basis of comparison, we use the 32 foot Sea Hunter
Cost of Sea Hunter in 2020 is approximately $20 Million

Figure 13. Patrol Coastal Cost Analysis



Type Two-Tail 16,426,689 32,037,564 Certainty % 90.00

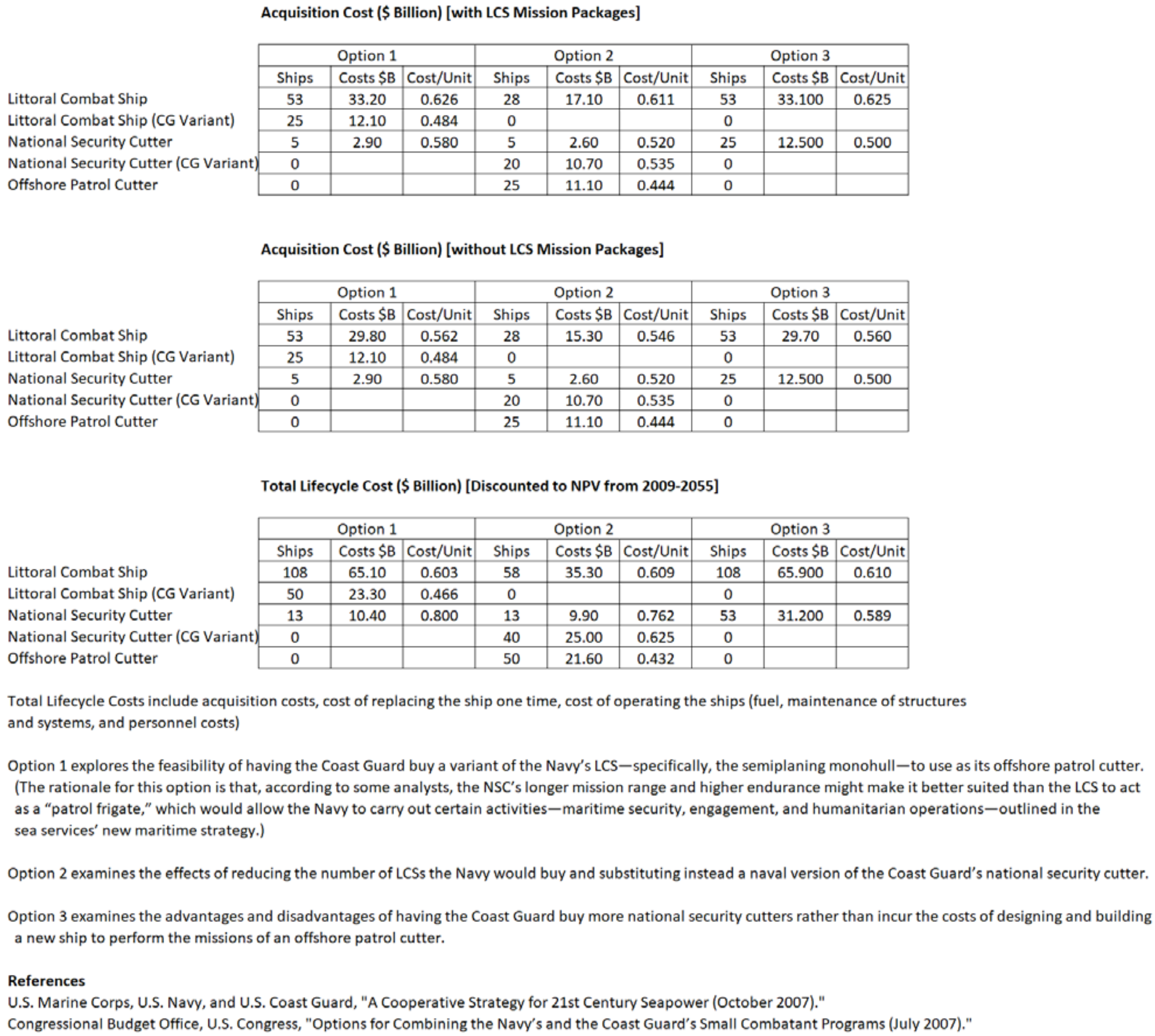
Figure 14. 90% Confidence Interval Cost



Statistics	Result
Number of Trials	100000
Mean	23,631,689.4585
Median	23,189,671.8936
Standard Deviation	4,742,599.5236
Variance	2.249225E+013
Coefficient of Variation	0.2007
Maximum	39,515,578.1755
Minimum	11,456,802.6384
Range	28,058,775.5371
Skewness	0.2958
Kurtosis	-0.4660
25% Percentile	20,115,192.0875
75% Percentile	26,946,632.4037
Percentage Error Precision at 95% Confidence	0.1244%

Figure 15. Expected Value at $23 Million

Figure 16 illustrates another example using Congressional Budget Office (2007) data on the littoral combat ship (LCS) and national security cutters (NSC), as well as the Coast Guard (CG) variant. The total life-cycle costs include acquisition costs, cost of replacing the ship one time, cost of operating the ships (e.g., fuel, maintenance of structures and systems, and personnel costs). Option 1 explores the feasibility of having the Coast Guard buy a variant of the Navy's LCS—specifically, the semiplaning monohull—to use as its offshore patrol cutter. The rationale for this option is that, according to some analysts, the NSC's longer mission range and higher endurance might make it better suited than the LCS to act as a "patrol frigate," which would allow the Navy to carry out certain activities—maritime security, engagement, and humanitarian operations—outlined in the sea services' new maritime strategy. Option 2 examines the effects of reducing the number of LCSs the Navy would buy and substituting instead a naval version of the Coast Guard's NSC. Option 3 examines the advantages and disadvantages of having the Coast Guard buy more NSCs rather than incur the costs of designing and building a new ship to perform the missions of an offshore patrol cutter.



Acquisition Cost ($ Billion) [with LCS Mission Packages]

	Option 1			Option 2			Option 3		
	Ships	Costs $B	Cost/Unit	Ships	Costs $B	Cost/Unit	Ships	Costs $B	Cost/Unit
Littoral Combat Ship	53	33.20	0.626	28	17.10	0.611	53	33.100	0.625
Littoral Combat Ship (CG Variant)	25	12.10	0.484	0			0		
National Security Cutter	5	2.90	0.580	5	2.60	0.520	25	12.500	0.500
National Security Cutter (CG Variant)	0			20	10.70	0.535	0		
Offshore Patrol Cutter	0			25	11.10	0.444	0		

Acquisition Cost ($ Billion) [without LCS Mission Packages]

	Option 1			Option 2			Option 3		
	Ships	Costs $B	Cost/Unit	Ships	Costs $B	Cost/Unit	Ships	Costs $B	Cost/Unit
Littoral Combat Ship	53	29.80	0.562	28	15.30	0.546	53	29.70	0.560
Littoral Combat Ship (CG Variant)	25	12.10	0.484	0			0		
National Security Cutter	5	2.90	0.580	5	2.60	0.520	25	12.500	0.500
National Security Cutter (CG Variant)	0			20	10.70	0.535	0		
Offshore Patrol Cutter	0			25	11.10	0.444	0		

Total Lifecycle Cost ($ Billion) [Discounted to NPV from 2009-2055]

	Option 1			Option 2			Option 3		
	Ships	Costs $B	Cost/Unit	Ships	Costs $B	Cost/Unit	Ships	Costs $B	Cost/Unit
Littoral Combat Ship	108	65.10	0.603	58	35.30	0.609	108	65.900	0.610
Littoral Combat Ship (CG Variant)	50	23.30	0.466	0			0		
National Security Cutter	13	10.40	0.800	13	9.90	0.762	53	31.200	0.589
National Security Cutter (CG Variant)	0			40	25.00	0.625	0		
Offshore Patrol Cutter	0			50	21.60	0.432	0		

Total Lifecycle Costs include acquisition costs, cost of replacing the ship one time, cost of operating the ships (fuel, maintenance of structures and systems, and personnel costs)

Option 1 explores the feasibility of having the Coast Guard buy a variant of the Navy's LCS—specifically, the semiplaning monohull—to use as its offshore patrol cutter. (The rationale for this option is that, according to some analysts, the NSC's longer mission range and higher endurance might make it better suited than the LCS to act as a "patrol frigate," which would allow the Navy to carry out certain activities—maritime security, engagement, and humanitarian operations—outlined in the sea services' new maritime strategy.)

Option 2 examines the effects of reducing the number of LCSs the Navy would buy and substituting instead a naval version of the Coast Guard's national security cutter.

Option 3 examines the advantages and disadvantages of having the Coast Guard buy more national security cutters rather than incur the costs of designing and building a new ship to perform the missions of an offshore patrol cutter.

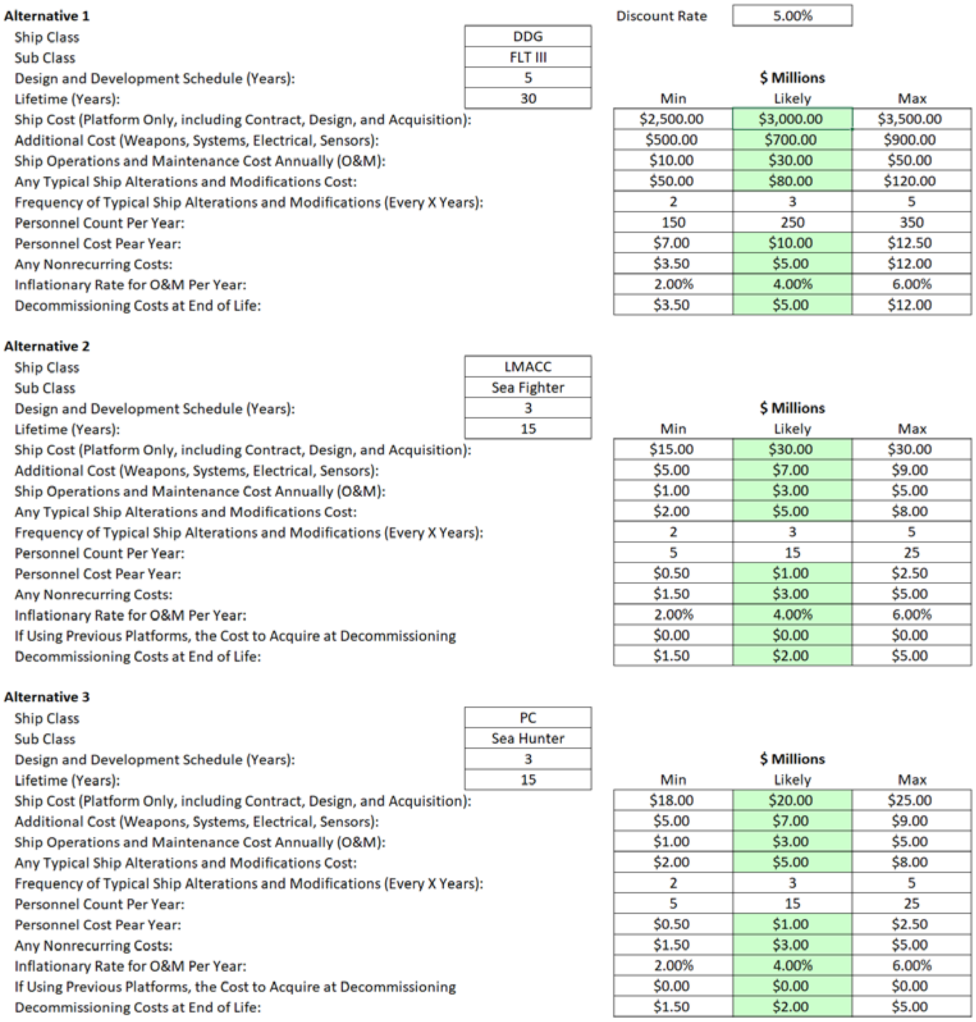
References

U.S. Marine Corps, U.S. Navy, and U.S. Coast Guard, "A Cooperative Strategy for 21st Century Seapower (October 2007)."

Congressional Budget Office, U.S. Congress, "Options for Combining the Navy's and the Coast Guard's Small Combatant Programs (July 2007)."

Figure 16. Modeling Using Congressional Budget Office Data

Using the same approach, we can estimate using notional values to determine the costs of the three alternatives as proposed (see Figure 17) using a life cycle of 30 years, with a single replacement in Year 15 (see Figure 18). Figures 19 and 20 show the confidence intervals of the costs and simulated values. Sea Fighter has a life-cycle cost of $181.9 million versus $4.76 billion for the DDG 51 FLT III. Figure 21 shows the overlay cost charts of the two alternatives.

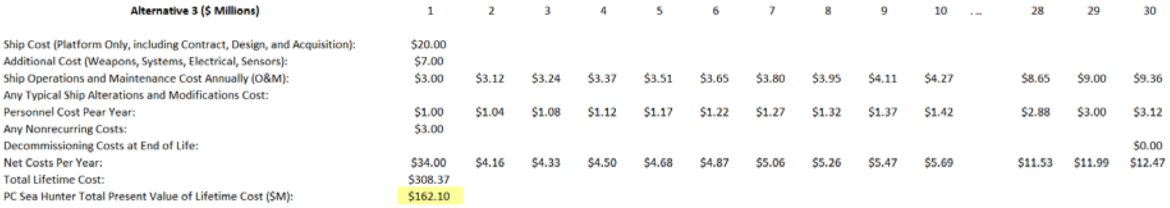


Alternative 1		Discount Rate	5.00%	
Ship Class	DDG			
Sub Class	FLT III			
Design and Development Schedule (Years):	5		$ Millions	
Lifetime (Years):	30	Min	Likely	Max
Ship Cost (Platform Only, including Contract, Design, and Acquisition):		$2,500.00	$3,000.00	$3,500.00
Additional Cost (Weapons, Systems, Electrical, Sensors):		$500.00	$700.00	$900.00
Ship Operations and Maintenance Cost Annually (O&M):		$10.00	$30.00	$50.00
Any Typical Ship Alterations and Modifications Cost:		$50.00	$80.00	$120.00
Frequency of Typical Ship Alterations and Modifications (Every X Years):		2	3	5
Personnel Count Per Year:		150	250	350
Personnel Cost Pear Year:		$7.00	$10.00	$12.50
Any Nonrecurring Costs:		$3.50	$5.00	$12.00
Inflationary Rate for O&M Per Year:		2.00%	4.00%	6.00%
Decommissioning Costs at End of Life:		$3.50	$5.00	$12.00

Alternative 2				
Ship Class	LMACC			
Sub Class	Sea Fighter			
Design and Development Schedule (Years):	3		$ Millions	
Lifetime (Years):	15	Min	Likely	Max
Ship Cost (Platform Only, including Contract, Design, and Acquisition):		$15.00	$30.00	$30.00
Additional Cost (Weapons, Systems, Electrical, Sensors):		$5.00	$7.00	$9.00
Ship Operations and Maintenance Cost Annually (O&M):		$1.00	$3.00	$5.00
Any Typical Ship Alterations and Modifications Cost:		$2.00	$5.00	$8.00
Frequency of Typical Ship Alterations and Modifications (Every X Years):		2	3	5
Personnel Count Per Year:		5	15	25
Personnel Cost Pear Year:		$0.50	$1.00	$2.50
Any Nonrecurring Costs:		$1.50	$3.00	$5.00
Inflationary Rate for O&M Per Year:		2.00%	4.00%	6.00%
If Using Previous Platforms, the Cost to Acquire at Decommissioning		$0.00	$0.00	$0.00
Decommissioning Costs at End of Life:		$1.50	$2.00	$5.00

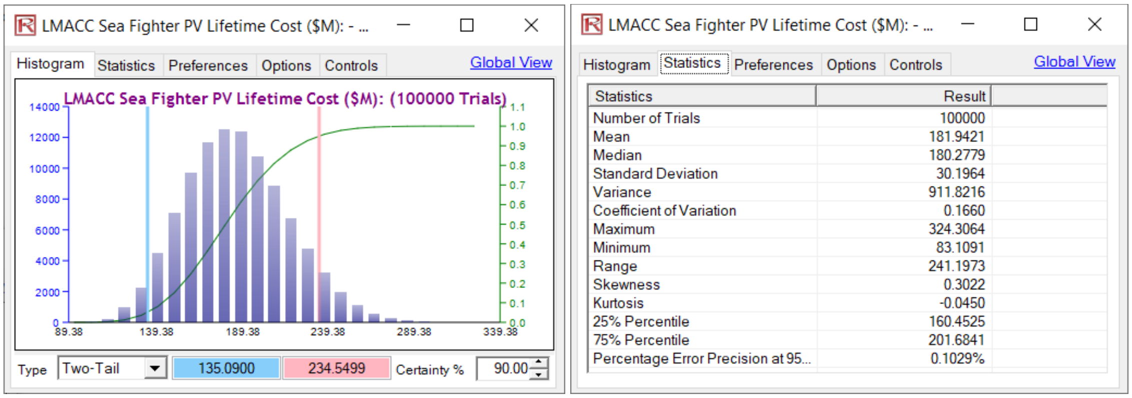
Alternative 3				
Ship Class	PC			
Sub Class	Sea Hunter			
Design and Development Schedule (Years):	3		$ Millions	
Lifetime (Years):	15	Min	Likely	Max
Ship Cost (Platform Only, including Contract, Design, and Acquisition):		$18.00	$20.00	$25.00
Additional Cost (Weapons, Systems, Electrical, Sensors):		$5.00	$7.00	$9.00
Ship Operations and Maintenance Cost Annually (O&M):		$1.00	$3.00	$5.00
Any Typical Ship Alterations and Modifications Cost:		$2.00	$5.00	$8.00
Frequency of Typical Ship Alterations and Modifications (Every X Years):		2	3	5
Personnel Count Per Year:		5	15	25
Personnel Cost Pear Year:		$0.50	$1.00	$2.50
Any Nonrecurring Costs:		$1.50	$3.00	$5.00
Inflationary Rate for O&M Per Year:		2.00%	4.00%	6.00%
If Using Previous Platforms, the Cost to Acquire at Decommissioning		$0.00	$0.00	$0.00
Decommissioning Costs at End of Life:		$1.50	$2.00	$5.00

Figure 17. Analysis of Alternatives for Ship Costs



Alternative 3 ($ Millions)	1	2	3	4	5	6	7	8	9	10	...	28	29	30
Ship Cost (Platform Only, including Contract, Design, and Acquisition):	$20.00													
Additional Cost (Weapons, Systems, Electrical, Sensors):	$7.00													
Ship Operations and Maintenance Cost Annually (O&M):	$3.00	$3.12	$3.24	$3.37	$3.51	$3.65	$3.80	$3.95	$4.11	$4.27		$8.65	$9.00	$9.36
Any Typical Ship Alterations and Modifications Cost:														
Personnel Cost Pear Year:	$1.00	$1.04	$1.08	$1.12	$1.17	$1.22	$1.27	$1.32	$1.37	$1.42		$2.88	$3.00	$3.12
Any Nonrecurring Costs:	$3.00													
Decommissioning Costs at End of Life:														$0.00
Net Costs Per Year:	$34.00	$4.16	$4.33	$4.50	$4.68	$4.87	$5.06	$5.26	$5.47	$5.69		$11.53	$11.99	$12.47
Total Lifetime Cost:	$308.37													
PC Sea Hunter Total Present Value of Lifetime Cost ($M):	$162.10													

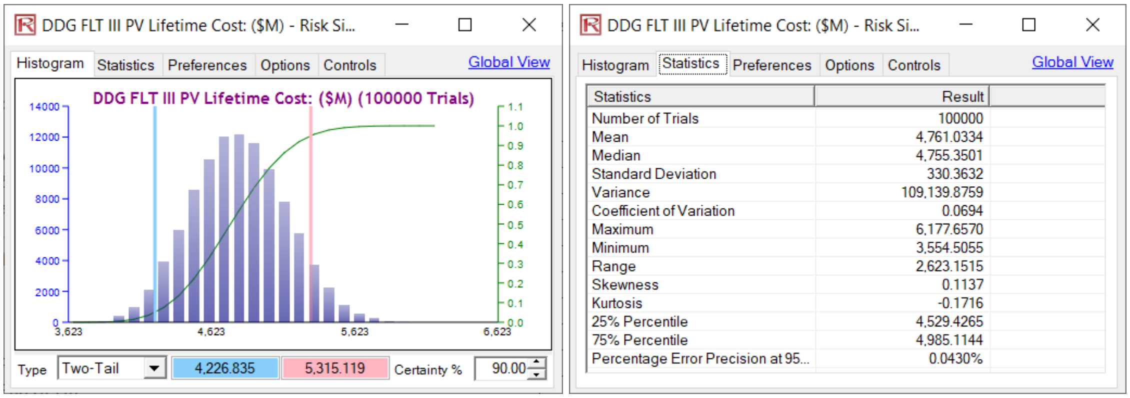
Figure 18. Life-Cycle Cost Modeling and Simulation



Type: Two-Tail | 135.0900 | 234.5499 | Certainty %: 90.00

Statistics	Result
Number of Trials	100000
Mean	181.9421
Median	180.2779
Standard Deviation	30.1964
Variance	911.8216
Coefficient of Variation	0.1660
Maximum	324.3064
Minimum	83.1091
Range	241.1973
Skewness	0.3022
Kurtosis	-0.0450
25% Percentile	160.4525
75% Percentile	201.6841
Percentage Error Precision at 95...	0.1029%

Figure 19. Simulated Sea Fighter Life-Cycle Cost



Type: Two-Tail | 4,226.835 | 5,315.119 | Certainty %: 90.00

Statistics	Result
Number of Trials	100000
Mean	4,761.0334
Median	4,755.3501
Standard Deviation	330.3632
Variance	109,139.8759
Coefficient of Variation	0.0694
Maximum	6,177.6570
Minimum	3,554.5055
Range	2,623.1515
Skewness	0.1137
Kurtosis	-0.1716
25% Percentile	4,529.4265
75% Percentile	4,985.1144
Percentage Error Precision at 95...	0.0430%

Figure 20. DDG 51 FLT III Life-Cycle Cost

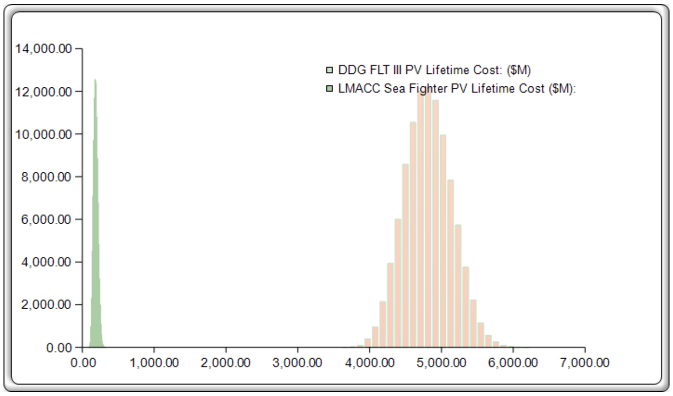


Figure 21. Analysis of Alternatives of Costs

Conclusions

The current research is still progressing, but preliminary results show a promising trajectory with the cost savings on Sea Hunter. This current study is based on publicly available information and data. In addition, when necessary, rough order magnitude notional values were used and assumed. In addition, a standard hull configuration is assumed instead of specific design specifications with more detailed cost data and precise modeling.

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