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Benchmarking Naval Shipbuilding With 3D Laser Scanning, Additive Manufacturing, and Collaborative Product Lifecycle Management

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Panel 17. Reducing Life-Cycle Costs: Adopting Emerging Manufacturing Technologies

Thursday, May 5, 2016	
1:45 p.m. – 3:15 p.m.	<p>Chair: Major General L. Neil Thurgood, U.S. Army, Deputy for Acquisition and Systems Management, OASA (ALT)</p> <p>Discussant: Michael Schwind, Vice President of Federal Sector, Siemens PLM</p> <p><i>Benchmarking Naval Shipbuilding With 3D Laser Scanning, Additive Manufacturing, and Collaborative Product Lifecycle Management</i></p> <p>David Ford, Associate Professor, Texas A&M University Tom Housel, Professor, NPS Sandra Hom, Research Associate, NPS Jonathan Mun, Research Professor, NPS</p> <p><i>Materials Testing and Cost Modeling for Composite Parts Through Additive Manufacturing</i></p> <p>Eric Holm, Chief of Command Civil Engineer Inspections, Air Force Materiel Command Vhance Valencia, Assistant Professor, Air Force Institute of Technology Alfred Thal, Jr., Associate Professor, Air Force Institute of Technology Jason Freels, Assistant Professor, Air Force Institute of Technology Adedeji Badiru, Dean, Air Force Institute of Technology</p>



Benchmarking Naval Shipbuilding With 3D Laser Scanning, Additive Manufacturing, and Collaborative Product Lifecycle Management

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Abstract

Evolving threats and shrinking budgets require that the Navy adopt and implement new technologies effectively and efficiently. The current work estimates the potential cost savings of the adoption and implementation of three advanced technologies: Three Dimensional Scanning (3DLS), Product Lifecycle Management (PLM), and Additive Manufacturing (AM). A review of the capabilities and current uses of the technologies is the basis for modeling their impacts on shipbuilding operations. Knowledge Value Added models were then used to estimate returns on investment without and with the technologies. These results were used to estimate shipbuilding cost savings over the life of the current U.S. Navy shipbuilding plan. Finally, strategic real options were developed and valued to incorporate implementation flexibility into cost savings estimates. Results indicate that the U.S. Navy can save an average of over \$2.70 billion per year over 29 years if the potential improvements available through 3DLST, PLM, and AM are fully exploited, regardless of the implementation approach. If implemented fully and immediately, these three new technologies can save the U.S. Navy \$3.07 billion, or \$3.37 billion if implemented sequentially.

Introduction

The U.S. Navy estimates that it will cost \$16.7 billion per year for new-ship construction to become a 306 battle force ship over the next 30 years. It is critical that the Navy capture full benefits of new technologies such as Three Dimensional Scanning (3DLS), Product Lifecycle Management (PLM), and Additive Manufacturing (AM) to reduce costs while meeting mission needs. Research supports the adoption and use of these



commercially available technologies, yet does not address their use in naval shipbuilding. Cost savings estimates and strategies for technology adoption and use are important to capturing the full benefits of these technologies.

Our research project examines the use of 3DLS, PLM, and AM by non-shipbuilding industries as a basis for estimating potential naval shipbuilding savings. Secondary research was conducted on the three technologies used by various industries, and three models were developed on the potential cost and efficiency savings that could be derived from the use of those technologies. Recommendations are provided to Navy planners concerning the most effective and efficient strategy for exploiting these technologies.

The U.S. Navy will become a 306 battle force ship over the next 30 years, up from today's battle force of 289. A report of the Navy's 2015 shipbuilding plan covering fiscal years 2015 to 2044, submitted to Congress in July 2014, estimates that the plan will cost the Navy an average of about \$16.7 billion per year in constant FY2014 dollars to implement. The Navy plans to buy a total of 264 ships over the 2015–2044 period under the 2015 plan. According to the CBO, given the rate at which the Navy plans to retire ships from the fleet, that construction plan would not achieve a fleet equal to the inventory goal of 306 ships until 2019 under new rules for counting ships that the Navy implemented this year, or until 2022 under the old counting rules. The adoption and full utilization of three advanced technologies (3D Laser Scanning, Additive Manufacturing, and Product Lifecycle Management) can potentially generate significant cost saving in the naval shipbuilding program. Those technologies are described next as the basis for the current evaluation of potential savings.

Product Lifecycle Management

Product Lifecycle Management (PLM) is defined as an

integrated, information-driven approach comprised of people, processes/practices, and technology, to all aspects of a product's life, from its design through manufacture, deployment and maintenance—culminating in the product's removal from service and final disposal. By trading product information for wasted time, energy, and material across the entire organization and into the supply chain, PLM drives the next generation of lean thinking. (Greives, 2006)

PLM has been used by the automotive, aerospace, and other industries that build very large, very complex products and systems. It was designed to provide stakeholders with current views of every product throughout its lifecycle to facilitate decision-making and corrective actions if necessary.

PLM can be used in shipbuilding to build and maintain the next generation of ships. It spans the entire shipbuilding enterprise and lifecycle to enable shipbuilders to integrate organizational knowledge, automate processes throughout the product lifecycle and improve efficiency, accuracy and execution to reduce time to delivery. PLM can

- Provide shipbuilders and suppliers with access to relevant data.
- Achieve greater performance, lower ownership cost, offer higher fleet availability and reliability, and greater quality and compliance with the latest marine safety and regulatory requirements.
- Make ships easier to build and repair, lowering construction, service, and total ownership costs.
- Link shipbuilders with suppliers linked in the production schedule and all design aspects.



A wide range of industries using PLM are finding that 3DLS is becoming a critical tool to link the gap between physical objects in the real world and in the digital design world. The aerospace, automotive, consumer products, manufacturing, and heavy industries all have benefited from faster time to market, improved quality, and reduced warehousing costs with 3D scanning.

3D Laser Scanning

3D laser scanning technology has been used to achieve significant cost savings, optimize maintenance schedules, increase quality, improve safety and reduce rework. Commercial applications range from maritime and space applications to manufacturing and production. According to industry analysts, the industry's growth is fueled by the growing recognition that 3D aids in the design, fabrication, construction, operations and maintenance processes. Benefits of 3D laser scanning can be applied to shipbuilding.

Laser scanners use infrared laser technology to produce exceedingly detailed three-dimensional images of complex environments and geometries in only a few minutes. Millions of discrete measurements can be captured in every scan using 3D laser scanner technology. The resulting images, a cloud, are millions of 3D measurement points. A complete project may contain hundreds of millions or even billions of points, recreating the complex spatial relationships of the 3D environment.

Often used by offshore oil and gas companies to construct and repair oil rigs, 3DLS is very effective at documenting oil platforms and refineries to assist in engineering, maintenance, and planning processes. The aerospace and automotive industries have used 3DLS for retrofitting floors and measure parts for accurate fit. The DoD has tested 3DLS in several projects, as described next.

Ship Check Data Capture Projects 2005 & 2006

NSRP funded two Ship Check Data Capture projects in 2005 and 2006. Objectives of both Ship Check Data Capture projects were to

1. Develop a process that captures the as-built measurement data in digital/electronic format during a ship check
2. Process the as-built measurement data into 3D CAD models using available commercial-off-the-shelf (COTS) modeling technologies (software and hardware)
3. Provide a building block process for the anticipated development of the capabilities to generate 3D CAD models of the as-built space envelope from the geometric measurement data captured during the ship check.

Ship Check Data Capture 2005

Recognizing the potential of new technologies on the ship check process on the U.S. shipping industry, NSRP funded the Ship Check Data Capture project in 2005. Laser scanning, close-range photogrammetry, and other technologies capturing as-built ship conditions in digital format to create 3D electronic models were evaluated. The project's goals were to determine potential technology synergies producing cost-effective solutions, and prototype a ship check data capture process that could be used by the U.S. shipbuilding industry. It was also anticipated that archived digital data would provide a cost-effective solution to the lifecycle cost management of ships.



Specific benefits from the software and hardware tested include

- Creation of as-built 3D models and validation of as-built models to design models
- Reduction of costly design changes, improved design capability
- Reduced construction rework
- Accurate factory-fabricate in lieu of field-fabricate
- Reduced ship check costs: fewer days, fewer personnel
- Elimination of return visits to the ship for missed measurements
- Obtaining measurements which are difficult or unsafe for human reach (NSRP 2005).

Initial results were so encouraging from this project that a nine-month follow-on project was awarded by the NSRP in 2006.

Ship Check Data Capture Follow-On 2006 Project

The FY06 follow-on ship check project by NSRP evaluated the ship check process developed in the FY05 project further and refined the ship check process to the U.S. shipbuilding and repair industry using available (COTS) technology. In this follow-up project, the team conducted a ship check onboard a surface ship at Bender Shipbuilding & Repair Company and conducted work onboard SSGN 729 to validate the data accuracy/repeatability of the SSGN 729 ship check data collected from the FY05 project.

Performance improvement metrics were developed and tracked to compare the As-Is practice with anticipated project results. This project reported the cost/time savings metrics associated with post processing the ship check data into 3D CAD models compared to creating CAD models using the traditional ship check method with tape measures. Estimated cost savings of 37% and time savings of 39% were realized for ship check data capture/post processing with the available COTS laser scanning technology hardware and software tools results when compared to traditional ship checks using tape measures. The estimated cost savings is 7% above the project goal of 30%, and the estimated time savings is 4% above the project goal of 35%. Further cost savings can be achieved by using laser scanning technology for ship checks from cost avoidance and minimized rework.

The project conclusions were that the technology (hardware/software) was mature enough to support the ship check process. Laser scanners were found to provide a cost effective method to collect as-built data during ship checks as compared to traditional methods. 3DLS provided time and cost saving, and can be applied to the shipbuilding industry.

The ship check process developed in these projects benefits the shipbuilding industry in several ways:

- Reduces or eliminates costly “return visits” to site for measurements normally missed using traditional ship check methods.
- Provides more accurate, complete as-built data for retrofit design projects, resulting in better retrofit designs which ultimately results in cost savings and cost avoidance. With better designs, less construction rework is required (due to interference and fit-up problems and ability to factory-fabricate instead of having to field-fabricate).



3D Scanning in the Navy

NAVSEA deployed 3D laser scanning to improve the efficiency of both shipcheck and shipalt processes in 2005. Shipcheck is the front-end capture and validation of dimensional data, equipment lists, maintenance records, and performance specifications used in shipalt. Traditionally done manually by labor-intensive and costly methods, shipchecks involved using measurement methods such as tape measures, plumb bobs, and often spirit levels. Shipalt is the follow-on alterations, maintenance and modernization of a vessel.

Also in 2005, 3D laser scanning services were used for shipcheck of a three-story hangar bay on the USS *Abraham Lincoln* (CVN 72). Scanning the HVAC, piping, fuel storage tanks, and other structures allowed shipyard engineers to conduct multi-discipline “what-if” scenarios to avoid clashes in the installation of a new deck. Hundreds of hours in labor were saved with scanning versus the traditional methods. 3DIS captures data at up to 2000 points per second and has a range accuracy of 0.2 inches at 55 feet.

3DLS technology was used to assess damage to the USS *San Francisco* (SSN 711) after it collided at high speed with an undersea mountain 350 miles south of Guam. 3D laser scanning was used to evaluate the damaged areas of the submarine’s bow. In this case, scanning was invaluable for determining the ship’s centerline and collecting empirical data about torpedo tube deformation.

The Naval Undersea Warfare Center (NUWC) began using laser scanning to reverse engineer components with complex geometries in order to enable competitive bidding in 2007. In the past, the Navy did not have sufficient documentation from the original equipment manufacturer (OEM) to competitively procure replacement components which resulted in purchasing very expensive replacements from the OEM. The Navy saved \$250,000 by purchasing parts produced with laser scanning through competitive bidding. In addition, the time required to reverse engineer a typical component, including both measurement and modeling time, was reduced from 100 hours to 42 hours with a laser scanner.

3D Laser Scanning in Shipbuilding

Shipbuilding is one of the most complex and demanding of the manufacturing industries, combining aspects of both direct product manufacturing and capital project development. Moreover, shipbuilders often face huge monetary penalties amounting to hundreds of thousands of dollars per day for being off schedule. 3D laser scanning is a cost-effective, accurate, and fast method to help shipbuilders and manufacturers in designing, redesigning, modifying and salvaging ships.

However, only a handful of several progressive shipyards (i.e., Meyer Wert GmbH, Signal International, and Babcock International) use laser scanning technology because it is not currently widely adopted by the shipbuilding industry. Meyer Werft GmbH, a shipbuilder from Papenburg, Northern Germany, uses laser scanners to assist in building cruise liners, tankers and ferries. New ships are constructed from over 60 individual sections called blocks, weighing up to 800 tons each (Leica, 2015). Precise connection interfaces are critical in ship construction and block assembly; mistakes cannot be made, so consistent and accurate measurements are crucial. At every stage of new ship production, a surveying team using laser scanning technology provides services. With more ship parts being prefabricated and then attached to the ship in one piece, 3D surveys such as taking the measurements of a sun shade composed of multiple concave shapes or a 260 m-long waterslide with curves and loops, are critical.



Signal International, a shipbuilder with multiple facilities in the U.S. Gulf Coast, uses a laser scanner on as-built models to check both new production as well as to generate CAD models for refit projects. It uses the technology to assist in the creation of

- Accurate bill of materials
- General arrangements
- Pipe arrangements
- Pipe ISO's by system
- Pipe spool drawings
- Equipment details
- Structural arrangement

Additive Manufacturing

The American National Standards Institute defines additive manufacturing as the “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2013). Additive manufacturing is also commonly referred to as 3D printing. AM differs radically from the currently dominant manufacturing methodologies. Most current methods use subtractive processes (e.g., machining), but AM builds a 3D object by gradually adding successive layers of material that are laid down exactly in their final location. AM does this by fabricating objects directly from 3D computer-aided design (3D CAD) models. The 3D model is disaggregated into multiple horizontal layers, each of which is produced by the machine and added to the preceding layers. Additive manufacturing is often referred to as 3D printing.

In the automotive industry, Ford Motor Co. uses 3D printing in several areas, including the tooling used to create production parts and to build intake manifold prototypes that can be tested for up to 100,000-mile cycles. With traditional manufacturing methods, it would take four months and cost \$500,000 to build, while a 3D-printed manifold prototype costs \$3,000 to build over four days.

Additive Manufacturing in the Armed Forces

The U.S. Navy has supported research into 3D printing for more than 20 years and has approximately 70 additive manufacturing projects underway at dozens of different locations. One of the active Navy Manufacturing Technology (ManTech) Program projects active in FY14 was the “Non-Destructive Inspection for Electron-Beam Additive Manufacturing of Titanium.” In this project, the emerging AM technology of Electron Beam Direct Manufacturing (EBDM) process was evaluated for fabrication of several F-35 Joint Strike Fighter (JSF) components. EBDM is a technology that is considered vital to improving the affordability, reducing lead time and reducing industrial shortfalls inherent in traditional manufacturing technologies. In this Navy Metalworking Center (NMC) ManTech project, an integrated project team (IPT) evaluated the effectiveness of traditional and advanced non-destructive inspection (NDI) techniques, including computed tomography (CT) scanning, traditional radiography, standard hand-held ultrasonic and phased array ultrasonic inspection methods, to establish standardized NDI processes and procedures for production. According to the Office of Naval Research, studies have shown that EBDM technology has the potential to reduce per-part manufacturing costs by 35%–60% when compared to the costs to manufacture complex-shaped parts with traditional manufacturing approaches (Office of Naval Research [ONR], 2015). Product lead time might also be reduced by as much as 80%. The U.S. Army deployed its first mobile 3D printing laboratory



in Afghanistan inside a shipping container that is capable of being carried by helicopter in July 2012.

Additive Manufacturing in Naval Ship Building

The Navy Metalworking Center (NMC) is conducting the “Additive Manufacturing for Shipbuilding Applications” project to demonstrate the cost and time benefits of AM to support the construction of Navy platforms. The project is investigating how the use of AM in ship construction can save acquisition costs on several ship classes. More specifically, Ingalls Shipbuilding (Ingalls) and the Integrated Project Team (IPT) will assess and demonstrate the use of AM during ship construction activities, quantify the expected benefits, and provide a recommended path toward implementation. Ingalls has estimated a minimum acquisition cost savings of \$800,000 per year by utilizing AM for the construction of DDG, LHA and LPD. Implementation at Ingalls is planned in FY17 for DDG 121, LHA, and all future surface combatants produced there.

Summary

PLM, 3DLST, and AM are technologies that have been applied in other industries to reduce costs and increase efficiencies and have the potential to reduce naval shipbuilding costs. These technologies can save hundreds of millions of dollars in ship maintenance, suggesting that large savings in ship-building are also available.

A Simulation Model of Naval Shipbuilding Operations

Simulating shipbuilding processes requires conceptual and formal models of shipbuilding. These were combined with estimates of technology impacts and the two sets of simulations (without and with the technologies) to model shipbuilding effectiveness. The Knowledge Value Added simulation approach was then used to model the Return on Investment (ROI) of shipbuilding without and with the three technologies. The results were used to estimate shipbuilding costs and potential cost savings.

The U.S. Navy procures new ships through industry contractors. The shipbuilding processes used by those contractors are not uniform. However, the GAO report *Naval Shipbuilding: Opportunities Exist to Improve Practices Affecting Quality* (GAO, 2013) describes the generic stages of shipbuilding that were used as the basis for modeling shipbuilding in the current study. That report’s description says, in part, “There are four primary phases in shipbuilding: pre-contracting, contract award, design and planning, and construction, with each phase building upon the work completed in earlier stages.” Based on the latter part of this description, the shipbuilding process was modeled as a sequential series of phases. The GAO description continues, “Within each phase, a number of key events have an influence on the overall quality of the ship. In addition, within Navy shipbuilding, additional key activities take place following ship delivery.” A review of the report’s more specific description of the process reveals that some of the “events” identified occur relatively quickly (e.g., contract award) and are therefore true events, but that many are extended activities that require significant time and resources to accomplish (e.g., detailed engineering design, assembly and outfitting of blocks). These activities describe shipbuilding processes that can benefit from the adoption and use of the three technologies



previously described. The GAO description of shipbuilding was condensed¹ into a series of shipbuilding phases as a preliminary step in modeling naval shipbuilding:

- Concept design
- Detailed engineering design
- Pre-construction planning
- Block fabrication
- Assembly and outfitting of blocks
- Keel laying and block erection
- Pre-delivery final outfitting
- System testing and commissioning
- Sea trials
- Post-delivery final outfitting
- Post-delivery tests and trials
- Post shakedown availability

See Housel, Hom, Ford, and Mun (2016) for details. The previously listed phases are the basis of the As-Is model of naval shipbuilding.

Simulating Traditional Shipbuilding Operations

Each of the shipbuilding phases previously described is assumed to have three basic operations: initial completion, quality assurance, and rework. Each operation moves work part way through the phase. The Initial Completion activity moves work from the Initial Completion backlog and Work In Progress (WIP) to the Quality Assurance (QA) backlog and WIP. The QA operation either discovers required rework or approves and releases the work. This moves work from the QA backlog and WIP to either the Rework backlog and WIP (if rework is discovered) or to the stock of Work Completed and Released. The rework operation moves work from the Rework backlog and WIP back to the QA backlog and WIP, where it is inspected again. Figure 1 shows the arrangement of the stocks and flows of each of the shipbuilding phases. In addition to the operations processes previously described, progress through each phase depends on the sizes of the backlogs, the durations required to complete each operation, and the fraction of work that requires rework (Figure 1).

¹ Some activities were renamed and descriptions revised to reflect U.S. naval shipbuilding without losing their meaning.



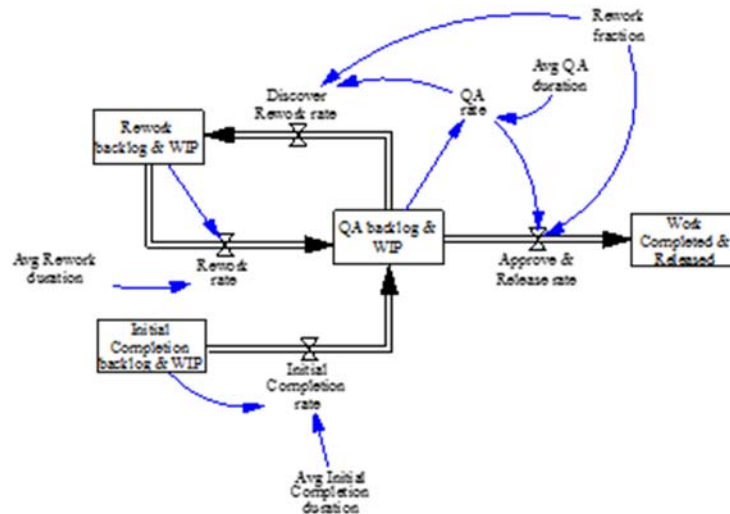


Figure 1. Simulating Shipbuilding: Drivers and Constraints on Shipbuilding Operations in a Single Phase

Each phase operation rate (initial completion, quality assurance, or rework) is driven and constrained by the amount of work waiting to be completed by that operation and the average time required to complete the operation. In the current model these operation durations include process and resource constraints and are assumed to be constant throughout the shipbuilding phase. The rate at which work within a phase is inspected (the quality assurance rate) is disaggregated into the fraction of inspections that discover required rework and the complement that are approved and released. Progress through each shipbuilding phase in the model is also depends on the completion of work in the preceding (upstream) phase and constrains progress in its downstream phase. Although some overlapping of phases is possible, for simplicity it is assumed that the phases occur sequentially.

Potential Applications of Advanced Technologies to Navy Shipbuilding

Three Dimensional Scanning (3DLS), Product Lifecycle Management (PLM) and Additive Manufacturing (AM) can impact naval shipbuilding in many ways, including

- Integrated Ship Development
- Design and construction document management
- Prototype generation
- Final parts manufacturing
- Manufacturing inspection:
- Radio Frequency Identification (RFID)
- Animated Instructions
- Construction inspection

Several of the technology applications previously listed are already in regular use in industry or fully developed for use in practice. For example, RFID is frequently used to control construction material flows (CoreRFID, 2008). Damen Industries is developing animated electronic construction instructions (Ford et al., 2012), and construction inspection by comparing laser scans of as-built conditions to design documents has been



demonstrated (Taylor, 2013). The expected application of the three advanced technologies to specific shipbuilding phases were developed (not shown for brevity).

Shipbuilding operations using the three technologies were simulated for the To-Be conditions. The potential impacts of the use of the three technologies in the shipbuilding phases were quantified in the form of fractional reductions in operation durations and rework fractions. The reduction fractions were combined with the As-Is calibration values for the parameters to generate calibration values for the To-Be simulation. These calibration values were used to simulate shipbuilding operations using the three technologies for the To-Be conditions. Simulation results for the As-Is and To-Be scenarios are shown in Table 1.

Table 1. Simulation Results: Average Completion Rates of Shipbuilding Phases for As-Is and To-Be Scenarios

No.	PHASE	AVERAGE COMPLETION RATE (work packages / day)	
		As-Is Scenario	To-Be Scenario
1	Concept design	0.593	0.8958
2	Detailed design	3.115	4.454
3	Preconstruction planning	1.407	1.741
4	Block fabrication	3.084	9.302
5	Block assembly and outfitting	2.865	11.61
6	Keel laying and block erection	3.439	13.53
7	PreDelivery outfitting	3.439	13.53
8	System testing	2.047	3.508
9	Sea trials	6.34	6.896
10	PostDelivery outfitting	3.273	13.27
11	PostDelivery tests	1.827	1.963
12	PostShakedown maintenance	1.827	1.963

Knowledge Value Added Model of Shipbuilding

The results of the simulations of shipbuilding operations were used as input to the KVA model to estimate the return on investments of the technologies. For both the As-Is and To-Be scenarios the “market” value of the hypothetical ship is assumed to be the estimated total price to the U.S. Navy of the *Arleigh Burke* (DDG51) destroyer, approximately \$1.2 billion.² This total value was allocated among the 12 shipbuilding phases based on the total learning of each phase. Other values were taken from previous KVA models of naval operations and modeler estimates. The As-Is scenario was modeled using the values previously described.

² Estimated prices of *Arleigh Burke* destroyers range were \$0.90 billion per ship (1997 dollars based on four ships) and \$0.92 billion per ship (1998–1999 dollars based on six ships) with estimates of future ships based on weight up to \$1.4 billion per ship.



The use of the three technologies was modeled in the To-Be scenario. Reductions in rework due to improved information quality and availability and the reduced operation durations due to use of richer information by field personnel that provides more specific instructions and designer intent were modeled in the operations simulation model. In addition, the technologies are expected to impact shipbuilding operations in several ways, including

- Increased design scope is required to develop the richer information for field personnel
- Reduce training time of construction personnel due to use of rich construction information
- Reduced unit labor costs as lower skill levels will be required due to providing improved construction and assembly information
- Increased use of automation

The impacts previously listed were incorporated into the KVA model. Note that the value of the ship is unchanged from the As-Is scenario, reflecting the assumption that the same ship is being created with or without the three technologies and the focus of the current work on potential cost savings. Tables 2 shows the returns on investment for the As-Is and To-Be scenarios, the changes in the returns on investment by using the three technologies, and the automation tools applied.

Table 2. Changes in Return on Investment Due to Use of Three Technologies

No.	PROCE SS / PHASE	As-is ROI	To-be ROI	Change in ROI	Automation Tools
1	Concept design	-2%	94%	96%	AM, PLM
2	Detailed design	561%	1826%	1265%	AM, PLM
3	Preconstruction planning	218%	244%	25%	PLM
4	Block fabrication	-67%	-31%	36%	3DLS, AM, PLM
5	Block assembly and outfitting	-17%	116%	133%	3DLS, AM, PLM
6	Keel laying and block erection	-63%	1%	64%	3DLS, AM, PLM
7	PreDelivery outfitting	505%	1270%	764%	3DLS, AM, PLM
8	System testing	280%	582%	301%	3DLS, PLM
9	Sea trials	1018%	961%	-57%	PLM
10	PostDelivery outfitting	476%	1243%	767%	3DLS, AM, PLM
11	PostDelivery tests	239%	282%	42%	PLM
12	PostShakedown maintenance	221%	201%	-20%	PLM
	TOTALS	135%	464%	329%	

Table 2 shows that the detailed design and outfitting phases of shipbuilding benefit most from use of the technologies, and that the sea trials and post shakedown maintenance benefit least. Of more significance to the current work, the ROI increases by 329%.



Estimating Shipbuilding Costs and Cost Savings

As used in previous research, costs for the As-Is and To-Be scenarios can be estimated using the definition of Return on Investment (ROI),

$$\text{ROI} = (\text{Benefits} - \text{Costs})/\text{Costs},$$

which can alternatively be written as

$$\text{Cost} = \text{Benefits}/(\text{ROI} + 1).$$

The previous equation was used with the benefits (\$1.2 billion) and Returns on Investment (Table 2) to estimate the costs of each scenario in millions of dollars as follows:

$$\text{Cost(As-is)} = \text{Benefits(As-is)} \div (\text{ROI(As-is)} + 1) = 1,200 \div (1.3546 + 1) = \$509.64 \text{ Million}$$

$$\text{Cost(To-be)} = \text{Benefits(To-be)} \div (\text{ROI(To-be)} + 1) = 1,200 \div (4.6409 + 1) = \$212.73 \text{ Million}$$

Therefore, estimated potential savings for the one hypothetical ship is \$296.91 million (\$509.64 million–\$212.73 million). This represents a savings of 24.74% (\$296.91 million ÷ \$1,200 million) of the total cost to the Navy. This saving fraction is conservative when compared with the results reported by industry adopters of these technologies described previously in this report (e.g., >30% cost savings for 3D LST alone and up to 80% for AM).

Estimated cost savings in U.S. naval shipbuilding are very contingent on the number and type of ships built. However, a rough estimate can be made based on the 2015 shipbuilding plan described in the first section of this report. According to that plan, the U.S. Navy will purchase 264 ships from 2015–2044 (218 combat ships and 46 combat logistics and support ships) at an average cost of \$16.7 billion per year. Based on these numbers the average ship cost will be \$1.83 billion (\$16.7 billion per year × 29 years ÷ 264 ships). Therefore, savings estimates based on a hypothetical \$1.2 billion ship above are considered conservative. Those savings are estimated to be an average of \$2.70 billion per year (\$296.91 million per ship × 264 ships ÷ 29 years).

Integrated Risk Management and Strategic Real Options Analysis

Integrated Risk Management (IRM) is an eight-step, quantitative software-based modeling approach for the objective quantification of risk (cost, schedule, technical, value), flexibility, strategy, and decision analysis. The method and toolset provide the ability to consider hundreds of thousands of alternatives with budget, schedule, value, strategic, and other program implementation uncertainties, and provide ways to help the decision-maker maximize capability and readiness at the lowest cost and highest returns (both monetized using KVA and nonmonetary strategic value). The variables simulated in the As-Is and To-Be strategies included the uncertain inputs of number of employees, actual learning time in hours, percentage automation achieved, number of times performed per ship, and the average process rates (units per day). These were simultaneously simulated for 1,000,000 trials.

Strategic Real Options

An important step in performing IRM is the application of Monte Carlo risk simulation. By applying Monte Carlo risk simulation to simultaneously change all critical inputs in a correlated manner within a model, researchers can identify, quantify, and analyze the system's risks and uncertainties. Based on the overall problem identification occurring during the initial qualitative management screening process, certain strategic options would



become apparent for each particular project. The strategic options could include, among other things, the option to wait, expand, contract, abandon, switch, stage-gate, and choose. Traditional analysis assumes a static investment decision, and assumes that strategic decisions are made initially with no recourse to choose other pathways or options in the future. Real options analysis can be used to frame strategies to mitigate risk, to value and find the optimal strategy pathway to pursue, and to generate options to enhance the value of the project while managing risks.

Figure 2 illustrates the strategic road map for implementation. Strategy A located on the top branch of the strategy tree is a sequential compound option, where the 3DLS, PLM, and AM technologies can be implemented in three phases over a period of 0–9 years, where the second phase will only be implemented if the first phase Proof of Concept (POC) proves to be successful, and the third phase can be implemented only if the second phase proves to be successful. This wait-and-see strategy creates Value of Information, where any kinks in the system's implementation will be worked out over time, focus is placed on one technology implementation in each phase, and costs are stretched out over time providing more flexibility in any budgetary constraints. Sequential compound options are often used in other applications such as

- Stage-gate implementation of high-risk project or technology development
- Prototyping prior to large scale manufacturing
- Low Rate Initial Production (LRIP)
- Technology feasibility tests
- Advanced Concept and Technology Demonstration over multiple stages
- Proof of Concept tests over various stages to determine the most valuable strategies for product rollouts in spiral development
- Government contracts with multiple stages with the option to abandon anytime
- Termination for Convenience (T-for-C) and built-in flexibility to execute different courses of action at specific stages of development
- R&D and phased options to determine most valuable strategy for system of systems technology development

Strategy B in Figure 2 illustrates an alternative course of action where all three 3DLS, PLM, and AM technologies are implemented at once. The cost will be higher (larger up front lump-sum and budgetary approval hurdles), and potential risks will be higher (problems that may arise in implementation of a new set of technologies on a larger scale). Nonetheless, the benefits that will be obtained are faster and more immediate, but these net benefits may or may not supersede the added costs and inherent risks.

Finally, Strategy C is the base case of As-Is model where legacy approaches and technologies are maintained status quo. This strategy can be valued accordingly and the difference in value between Strategies A and C and between Strategies B and C can be readily computed. See Mun (2015) for modeling details.



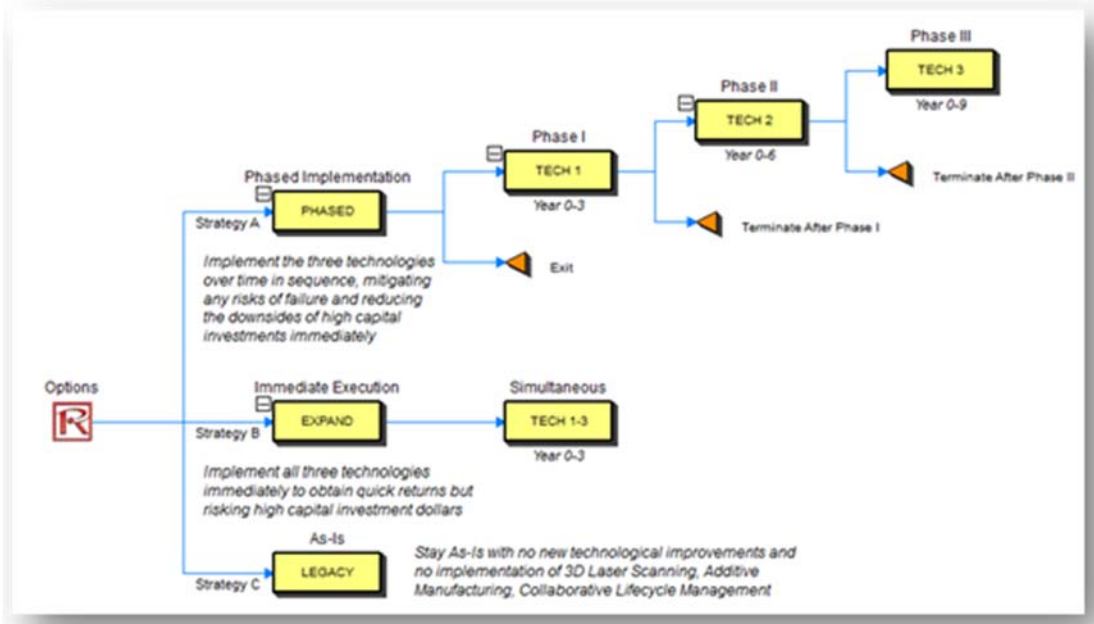


Figure 2. Strategic Real Options

As summarized in Figure 3, the following are some takeaways of the analysis results:

- The As-Is cost is \$509.64 million and the To-Be cost after implementing 3DLS, PLM, and AM is \$212.73 million, providing the U.S. Navy a cost savings of \$296.91 million.
- The \$296.91 million when multiplied by 264 ships and allocated over 29 years yields an annual savings of \$2.70 billion a year for the U.S. Navy.
- When added flexibility is analyzed, this strategic value increases to \$3.07 billion when all three technologies are implemented immediately or \$3.37 billion when implemented over multiple stages where risks and uncertainties can be hedged

As-Is Cost	\$	509,642,661
To-Be Cost	\$	212,733,874
To-Be Cost Savings	\$	296,908,787
To-Be Immediate Strategic Value	\$	337,632,796
To-Be Sequential Strategic Value	\$	370,736,221
Number of Ships		264
Number of Years		29
To-Be Sequential (Strategy A) Strategic Value	\$	3,374,978,008
To-Be Immediate (Strategy B) Strategic Value	\$	3,073,622,690
To-Be Strategy (Base Case) Strategic Value	\$	2,702,893,785

Figure 3. Summary of Strategic Values



Conclusions

Summary of the Study

We reviewed industry applications and tangible benefits resulting from PLM, 3DLS and AM to understand the potential ramifications from these technologies. We then assessed the impacts of using these technologies for naval shipbuilding. A simulation model of shipbuilding operations at the phase level was built and used to forecast the impacts of the technologies on shipbuilding processes. This required both conceptual and formal models of shipbuilding. These were combined with descriptions and estimates of technology impacts on shipbuilding operations and generated two sets of simulations (without and with technology use). The output of the operations simulation model was used to build a Knowledge Value Added model of naval shipbuilding. The KVA model was used to estimate the Return on Investment (ROI) of shipbuilding without and with the three technologies. The outputs of the KVA model were used to estimate shipbuilding costs with and without the technologies. Finally, those costs were used to estimate potential savings over the 29-year naval shipbuilding planning horizon. The uncertain inputs in the model were then subjected to a rigorous Monte Carlo risk simulation and stochastic analysis of millions of simulation trials and these three technologies were divided into various implementation paths. The Analysis of Alternatives using strategic real options were applied and the optimal implementation strategies were recommended.

Results of the Study

The research indicates that Three Dimensional Scanning (3DLS), Product Lifecycle Management (PLM) and Additive Manufacturing (AM) can beneficially impact many phases of naval shipbuilding in multiple operations to reduce costs. Simulation results suggest that the U.S. Navy can save an average of over \$2.70 billion per year over 29 years if the potential improvements available through 3DLST, PLM, and AM are fully exploited, regardless of the implementation approach.

However, with the added implementation flexibility of whether the three technologies are to be implemented concurrently, requiring a larger budget and bearing more uncertainties, or the technologies can be introduced over time sequentially where additional value is created. Based on the analysis, 3DLST, PLM, and AM technologies are fully justified, saving the U.S. Navy a base case value of \$2.70 billion per year over 29 years. And if implemented fully and immediately, these three new technologies can save the U.S. Navy \$3.07 billion, or \$3.37 billion if implemented sequentially.

That cost savings estimate and strategic real options assessment will help decision-makers choose how much, when, and how to exploit the benefits and the minimize costs of adopting and implementing the three technologies investigated.

Future Research Opportunities

The research is limited by the relatively narrow focus and assumptions used in the modeling and assessment. For example, the focus on post-technology-adoption does not address the significant challenges and costs of technology adoption, but the same focus does not include the potentially significant benefits of the three technologies during ship operations, maintenance, and repair.

Future research can collect and apply more specific parameter values for improved model calibration. In addition, specific decision-maker flexibility and inherent implementation options can be determined and modeled in more detail to provide a better implementation framework.



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Acquisition Research Program: Creating Synergy for Informed Change

Benchmarking Naval Shipbuilding with 3D Laser Scanning, Additive Manufacturing, and Collaborative Product Lifecycle Management

Thomas Housel
David N. Ford

Sandra Hom
Johnathan Mun

The DON Shipbuilding Challenge

- **Target:** Grow from 289 to 306 battle force fleet in 30 years
- **Required shipbuilding:** 264+ ships, including replacements
- **Average shipbuilding cost:** \$16.7b / year (2014\$)
- **Shrinking budgets**
- **Evolving threats**
- **Advancing technologies**



A Technology Adoption Challenge

- Cost constrained DoD environment requires cost reduction
- Threats require US military to retain technological superiority
- Complex technology acquisition process
- **Improved shipbuilding through technology adoption and implementation has the potential to successfully addressing these needs.**



Research Context

Problem: Scale of potential savings in shipbuilding is needed for technology adoption decision-making and planning.

This research estimates the potential savings of adopting and implementing three advanced technologies for naval shipbuilding.

- Product Lifecycle Management
- 3D laser scanning
- Additive Manufacturing (3D printing)



Advanced Technology: Product Lifecycle Management (PLM)



- An integrated, information-driven approach of people, processes/practices & technology from design through manufacture, deployment & maintenance, removal, and final disposal (based on Greives, 2006)
- Electronically integrates design documents, data bases, 3D LST, etc., for participant collaboration across physical distances and time
- Common, shared sets of documents improves access, collaboration, coordination, communication
- Common platform for program change management
- **Example application industries:**
 - Consumer goods
 - High tech
 - Machinery
 - Aero & defense
 - Automotive



Advanced Technology:

3D Terrestrial Laser Scanning

- Laser scans space from highly articulated mount, often combined with 360° camera
- Software processes points into 3D image of the space. Processed into CADD format
- Currently used in automotive, offshore construction and repair, civil and transportation, building construction, fossil fuel and nuclear power plants
- **Example naval uses:**
 - Shipcheck scans ship as-built interior ship spaces for retrofit & upgrades. Est. 37% cost & 39%time savings
 - Naval Undersea Warfare Center reverse engineers complex parts for competitive bidding when OEM designs are unavailable



Potential Technology:

Additive Manufacturing (“3D Printing”)



- 3D design/image of final part.
- Geometric slicing of image into horizontal layers for manufacturing
- Incrementally add small amounts of material in very thin layers of material to build-up part
- Variety of possible materials (plastic, titanium) & methods (e.g. for material bonding)
- No dominant method, materials, suppliers
- **Example Armed Forces uses:**
 - US Army AM lab deployment to Afghanistan (2012)
 - 70 Naval research projects (up to 65% cost savings)



Research Approach

1. Collect data on use of advanced technologies.
2. Build simulation model of naval shipbuilding
3. Describe potential applications of technologies to naval shipbuilding
4. Simulate steady-state shipbuilding without and with technology adoption and use
5. Build Knowledge-Value-Added models of shipbuilding, using simulated completion rates to simulate Returns-on-Investment (ROI)
6. Use Returns-on-Investment to estimate costs and thereby cost savings of technology adoption and use



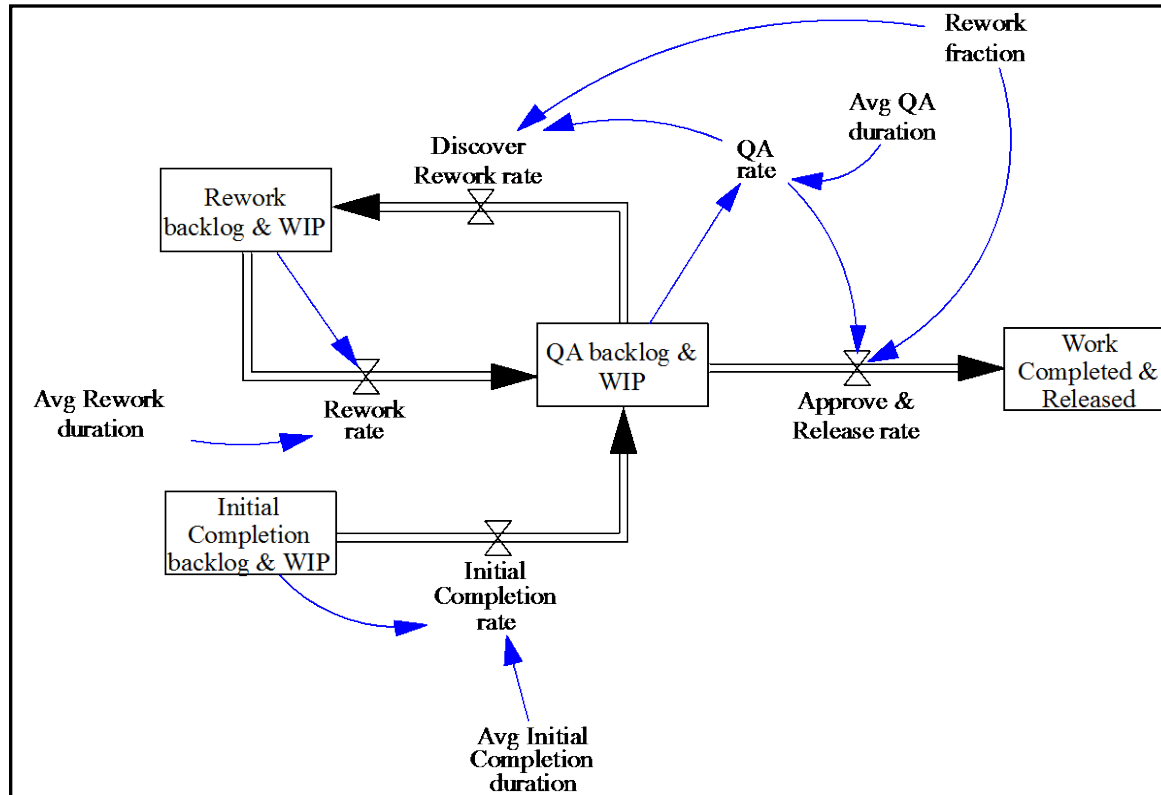
A Simulation Model of Naval Shipbuilding

Shipbuilding Phases (Based on GAO-14-122, 2013)

- Concept design
- Detailed engineering design
- Pre-construction planning
- Block fabrication
- Assembly and outfitting of blocks
- Keel laying and block erection
- Pre-delivery final outfitting
- System testing and commissioning
- Sea trials
- Post-delivery final outfitting
- Post-delivery tests and trials
- Post shakedown availability



A Simulation Model of Naval Shipbuilding Work moving through a Single Phase



Simulating Shipbuilding: Drivers and Constraints on Shipbuilding Operations in a Single Phase



Potential Applications of Advanced Technologies to Naval Shipbuilding

- Integrated Ship Development
- Design & construction document management
- Prototype generation
- Final parts manufacturing
- Manufacturing inspection
- Radio Frequency Identification (RFID)
- Animated Instructions
- Construction inspection

Examples...



Potential Applications of Advanced Technologies to Naval Shipbuilding: Examples

- **Manufacturing inspection**

- 3D images of parts are electronically compared to CADD designs to confirm compliance of manufacturing with designs or identify anomalies
- Reduces inspection times and labor costs
- Primarily uses 3D LST
- Benefits are leveraged by the application of Product Lifecycle Management

- **Animated Instructions:**

- CADD drawings used to create animated and annotated “movies” of construction or testing operations
- Viewed (e.g. on a tablet) and used in the field by the construction workforce
- Provides rich information (designer intent, access routes, potential pitfalls and solutions) – reduces required skills & labor costs & operation durations
- Reduces rework
- Primarily uses PLM with the design documents and construction plans



Potential Applications of Advanced Technologies to Naval Shipbuilding

		Advanced Technology		
		3D Laser Scanning Technology	Additive Manufacturing	Product Lifecycle Management
Shipbuilding Phase	Concept design		Prototype generation	Integrated ship development Design & construction document management
	Detailed engineering design		Prototype generation	Integrated ship development Design & construction document management
	Pre-construction planning			Integrated ship development Design & construction document management
	Block fabrication	Manufacturing inspection Construction inspection	Final parts manufacturing	Integrated ship development Design & construction document management Final parts manufacturing RFID Animated instructions Construction inspection
	Assembly & outfitting of blocks	Manufacturing inspection Construction inspection	Final parts manufacturing	Integrated ship development Design & construction document management Final parts manufacturing RFID Animated instructions Construction inspection
	Keel laying & block erection:	Manufacturing inspection Construction inspection	Final parts manufacturing	Integrated ship development Design & construction document management Final parts manufacturing RFID Animated instructions Construction inspection
	Pre-delivery final outfitting	Manufacturing inspection Construction inspection		Integrated ship development Design & construction document management RFID Animated instructions Construction inspection
	System testing & commissioning	Animated shipbuilding instructions		Integrated ship development Design & construction document management Animated instructions
	Sea trials			Integrated ship development Design & construction document management
	Post-delivery final outfitting	Manufacturing inspection Construction inspection		Integrated ship development Design & construction document management RFID Animated instructions Construction inspection
	Post-delivery tests & trials			Integrated ship development Design & construction document management Animated instructions
	Post shakedown availability			Integrated ship development Design & construction document management

Mapped technology applications to shipbuilding phases

Estimated impacts of each application on shipbuilding operations.

Simulated shipbuilding completion rates.



Naval Shipbuilding Simulation Results

		AVERAGE COMPLETION RATE (work packages / day)	
		As-Is Scenario	To-Be Scenario
Shipbuilding Phase	Concept design	0.593	0.8958
	Detailed design	3.115	4.454
	Preconstruction planning	1.407	1.741
	Block fabrication	3.084	9.302
	Block assembly and outfitting	2.865	11.61
	Keel laying and block erection	3.439	13.53
	PreDelivery outfitting	3.439	13.53
	System testing	2.047	3.508
	Sea trials	6.34	6.896
	PostDelivery outfitting	3.273	13.27
	PostDelivery tests	1.827	1.963
	PostShakedown maintenance	1.827	1.963

Used simulation output as input to Knowledge Value Added (KVA) models (As-Is and To-Be).

KVA models used to estimate returns on investment for shipbuilding without & with technologies.

Average Completion Rates of Shipbuilding Phases for As-Is and To-Be Scenarios



Knowledge Value Added Models of Shipbuilding

Returns on Knowledge (ROK) and Returns on Investment (ROI)

AS IS			
		ROK	ROI
Shipbuilding Phase	Concept design	98%	-2%
	Detailed design	661%	561%
	Preconstruction planning	318%	218%
	Block fabrication	33%	-67%
	Block assembly and outfitting	83%	-17%
	Keel laying and block erection	37%	-63%
	PreDelivery outfitting	605%	505%
	System testing	380%	280%
	Sea trials	1118%	1018%
	PostDelivery outfitting	576%	476%
	PostDelivery tests	339%	239%
	PostShakedown maintenance	321%	221%
	TOTALS	235%	135%

KVA Model Results for As-Is Scenario

TO BE				
		ROK	ROI	Automation Tools
Shipbuilding Phase	Concept design	194%	94%	AM, PLM
	Detailed design	1926%	1826%	AM, PLM
	Preconstruction planning	344%	244%	PLM
	Block fabrication	69%	-31%	3DLS, AM, PLM
	Block assembly and outfitting	216%	116%	3DLS, AM, PLM
	Keel laying and block erection	101%	1%	3DLS, AM, PLM
	PreDelivery outfitting	1370%	1270%	3DLS, AM, PLM
	System testing	682%	582%	3DLS, PLM
	Sea trials	1061%	961%	PLM
	PostDelivery outfitting	1343%	1243%	3DLS, AM, PLM
	PostDelivery tests	382%	282%	PLM
	PostShakedown maintenance	301%	201%	PLM
	TOTALS	564%	464%	

KVA Model Results for To-be Scenario



Impacts of Technologies on Shipbuilding Returns on Investment (ROI)

		As-is ROI	To-be ROI	Change in ROI	Automation Tools
Shipbuilding Phase	Concept design	-2%	94%	96%	AM, PLM
	Detailed design	561%	1826%	1265%	AM, PLM
	Preconstruction planning	218%	244%	25%	PLM
	Block fabrication	-67%	-31%	36%	3DLS, AM, PLM
	Block assembly and outfitting	-17%	116%	133%	3DLS, AM, PLM
	Keel laying and block erection	-63%	1%	64%	3DLS, AM, PLM
	PreDelivery outfitting	505%	1270%	764%	3DLS, AM, PLM
	System testing	280%	582%	301%	3DLS, PLM
	Sea trials	1018%	961%	-57%	PLM
	PostDelivery outfitting	476%	1243%	767%	3DLS, AM, PLM
	PostDelivery tests	239%	282%	42%	PLM
	PostShakedown maintenance	221%	201%	-20%	PLM
	TOTALS	135%	464%	329%	

Changes in Return on Investment due to Use of Three Technologies



Estimating Shipbuilding Costs and Cost Savings

$$\mathbf{ROI = (Benefits - Costs) / Costs}$$

$$\mathit{Cost (As-is)} = \mathit{Benefits (As-is)} \div (\mathit{ROI (As-is)} + 1)$$

$$\mathit{Cost (As-is)} = 1,200 \div (1.3546 + 1)$$

$$\mathit{Cost (As-is)} = \mathbf{\$509.64 \text{ Million}}$$

$$\mathit{Cost (To-be)} = \mathit{Benefits (To-be)} \div (\mathit{ROI (To-be)} + 1)$$

$$\mathit{Cost (To-be)} = 1,200 \div (4.6409 + 1)$$

$$\mathit{Cost (To-be)} = \mathbf{\$212.73 \text{ Million}}$$

Estimated Savings:

$$\mathbf{\$509.64m - \$212.73m = \$296.91m \text{ saved per ship}}$$

$$\mathbf{\$296.91m / \$1,200m = 24.74\% \text{ savings to DON}}$$

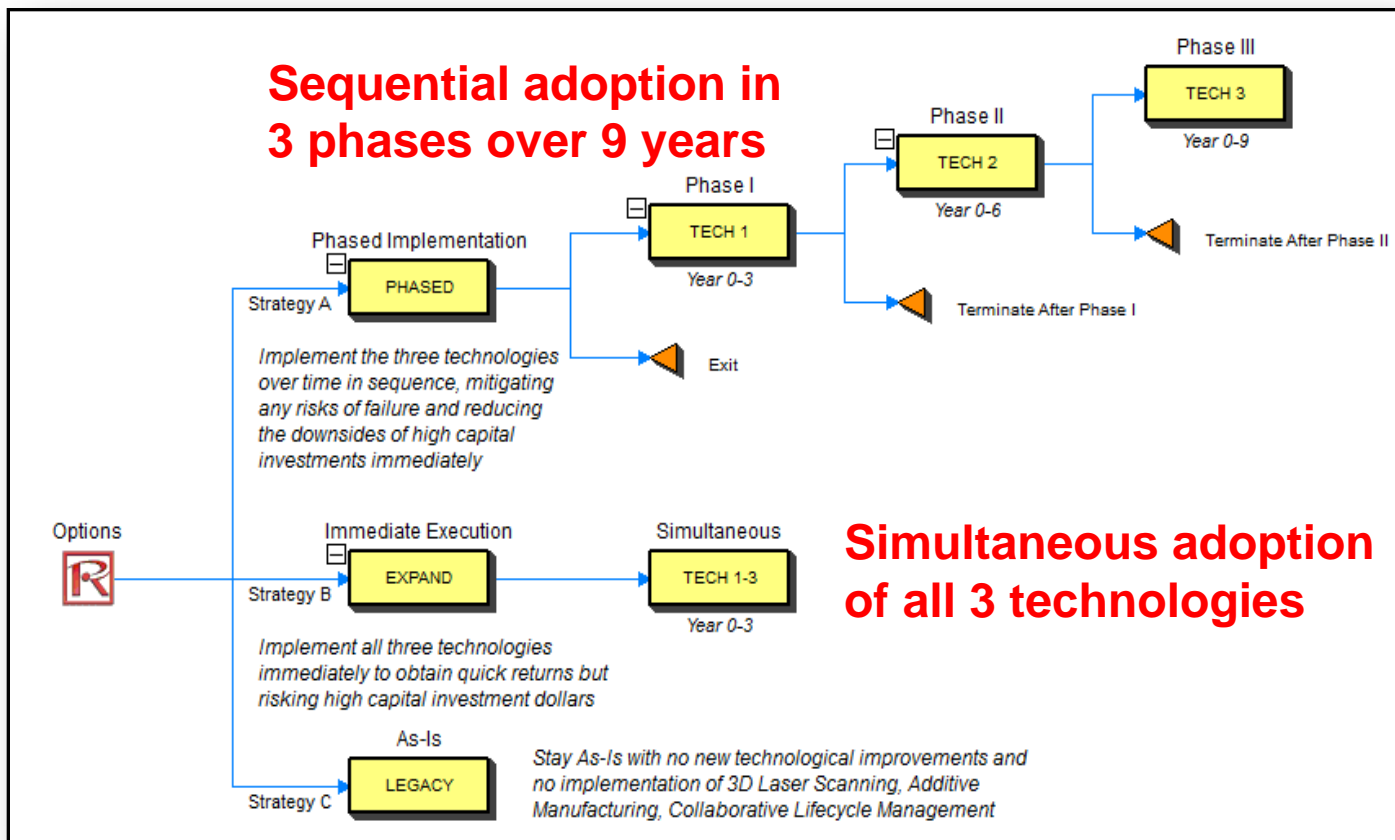


Estimating Shipbuilding Costs and Cost Savings

- Savings estimate is conservative compared to results of industry adopters (e.g. >30% cost savings for 3D LST alone and up to 80% for AM)
- **Estimated Annual Potential Savings:**
 $\$296.9\text{m}/\text{ship} \times 264 \text{ Ships} \div 29 \text{ Years} = \$2.70\text{b}/\text{yr}$



Integrated Risk Management and Strategic Real Options Analysis



Simultaneous adoption of all 3 technologies

No technology adoption (As-Is)

Strategic Real Options



Integrated Risk Management and Strategic Real Options Analysis

From KVA results

As-Is Cost	\$	509,642,661
To-Be Cost	\$	212,733,874
To-Be Cost Savings	\$	296,908,787
To-Be Immediate Strategic Value	\$	337,632,796
To-Be Sequential Strategic Value	\$	370,736,221
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To-Be Immediate (Strategy B) Strategic Value	\$	3,073,622,690
To-Be Strategy (Base Case) Strategic Value	\$	2,702,893,785

Option Values
 (value of flexibility)
\$672m/yr
\$371m/yr
\$0 (As-Is)

Summary of Strategic Values



Conclusions

- US Navy can save an average of over \$2.70b/year over 29 years with full adoption and implementation of 3DLST, PLM, and AM, ***regardless of the implementation approach***
- **Strategy 1: Sequential Adoption and Implementation**
 - Increases savings by \$672m/yr to \$3.38b/year
 - Adds flexibility to abandon
 - Requires larger budget
 - Can absorb more uncertainties
- **Strategy 2: Simultaneous Adoption and Implementation**
 - Increases savings by \$371m/yr to \$3.07b/year
 - Accelerates capture of benefits



Implications

- Savings assessment will help decision-makers choose how much, when, and how to exploit the benefits and minimize costs of advanced technology adoption and implementation for shipbuilding.
- **Future research:**
 - Collect and apply more specific parameter values for improved model calibration
 - Specific decision-maker flexibility and inherent implementation options can be determined and modeled in more detail to provide specific implementation recommendations.



Questions Comments Discussion

