NPS-AM-13-128

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Reducing Costs and Increasing Productivity in Ship Maintenance Using Product Lifecycle Management, 3D Laser Scanning, and 3D Printing

6 March 2014

LT Cameron J. Mackley, USN

Thesis Advisors: Dr. Thomas Housel, Professor
Dr. Glenn Cook, Associate Professor

Graduate School of Operational & Information Sciences

Naval Postgraduate School

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

Abstract

The Department of Defense (DoD) spends an enormous amount of money on maintenance. For fiscal year 2011, the DoD spent almost $80 billion. Of this amount, the Navy spent almost $5.5 billion on ship depot maintenance. Going forward, the amount of money available for all DoD activities is expected to be reduced because of budgetary pressures. Unlike the budget, the need for deployed units and the maintenance to keep them operating is increasing. Given this challenge, the Navy needs to find ways to reduce costs while retaining readiness. Reducing maintenance costs is a promising way to help achieve this goal.

The purpose of this thesis is to use knowledge value added (KVA) methodology to identify additional cost savings that can be achieved in the ship maintenance process by implementing information technologies. Specifically, the technologies considered in this study are 3D printing, product lifecycle management, and 3D laser scanning. Using the current process as a baseline, KVA is applied to two notional scenarios, one using 3D printing only and one using all three technologies to reengineer the current process. The KVA methodology establishes evidence indicating that costs would be decreased by nearly $120 million a year and shipyard productivity would increase.

Keywords: Knowledge value added, KVA, ship maintenance and modernization, SHIPMAIN, return on investment, ROI, return on knowledge, ROK, information technology, IT, 3D laser scanners, 3DLS, Navy shipyards, PLM, Product Lifecycle Management, 3D printing, 3DP

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgments

I would like to thank Dr. Housel for shepherding me through the entire thesis process, including idea generation, proposal, development, and completion. It would have been impossible for me to even get this thesis started, let alone completed, without his guidance. I would also like to thank Professor Glenn Cook for all the advice and assistance he has provided me. His efforts were invaluable in helping me produce a much higher quality thesis.

This thesis would also not have been possible without the efforts of previous NPS students. In particular, the completion of this research owes a very large debt to LT Christine Komoroski and LT Nate Seaman. Their theses provided both the foundation for this research and also the basis for much of the data.

Additionally, I would like to thank the Acquisition Research Program, especially RADM James Greene, USN (Ret.) and Ms. Karey Shaffer for providing resources and assistance to ensure the success of this thesis.

Finally, I would like to thank my fiancée, Koah, for her support and encouragement. Having her support made the whole thesis process much easier.

THIS PAGE INTENTIONALLY LEFT BLANK

About the Authors

LT Cameron Mackley is an Information Professional Officer. He was commissioned through the United States Naval Academy, where he received a Bachelor of Science in Information Technology. After graduating from the Naval Postgraduate School, he will report to Naval Satellite Operations Center Point Mugu.

THIS PAGE INTENTIONALLY LEFT BLANK

NPS-AM-13-128

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Reducing Costs and Increasing Productivity in Ship Maintenance Using Product Lifecycle Management, 3D Laser Scanning, and 3D Printing

6 March 2014

LT Cameron J. Mackley, USN

Thesis Advisors: Dr. Thomas Housel, Professor
Dr. Glenn Cook, Associate Professor

Graduate School of Operational & Information Sciences

Naval Postgraduate School

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

List of Figures

THIS PAGE INTENTIONALLY LEFT BLANK

List of Tables

THIS PAGE INTENTIONALLY LEFT BLANK

List of Acronyms and Abbreviations

3DLS	3D laser scanning
ABOM	Alteration bill of material
AIT	Alteration installation team
ALT	Actual learning time
CAD	Computer-aided design
CNC	Computer numerical control
CNO	Chief of Naval Operations
CRIC	CNO's Rapid Innovation Cell
DA	Depot-level activity
DoD	Department of Defense
DP	Decision point
FDM	Fused deposition modeling
FRC	Fleet Readiness Center
FY	Fiscal year
GFE	Government furnished equipment
GS	General schedule
IAF	Industrial activity furnished
ICD	Installation control drawing
ICMP	Individual Class Maintenance Plan
IRM	Integrated risk management
KVA	Knowledge value added
LLTM	Long lead time material
LAR	Liaison action request
LOA	Letter of authorization
LENS	Laser engineered net shaping
MFOM	Maintenance figure of merit
MP	Modernization Plan
MT	Maintenance Team

NDE	Navy data environment
OEM	Original equipment manufacturer
OJT	On-the-job training
PLM	Product lifecycle management
POA&M	Plan of action and milestones
RARE	Rapid manufacturing and repair
REF	Rapid equipping force
RLT	Relative learning time
RO	Real options
ROI	Return on investment
ROK	Return on knowledge
SC	Ship change
SD	System dynamics
SFI	Strike force interoperability
SHIPMAIN	Ship maintenance
SID	Ship installation drawing
SME	Subject matter expert
SPM	Ship program manager
SSCEPM	Surface ships and carriers entitled process for modernization
SSR	Ship selected records
STL	Standard Tessellation language
TLT	Total learning time
WG	Wage grade

I. INTRODUCTION

A. BACKGROUND

This thesis adds to research conducted by Lieutenant Christine Komoroski and Lieutenant Nate Seaman utilizing the knowledge value added (KVA) methodology to evaluate the effects of incorporating new technologies, specifically three-dimensional (3D) laser scanning (3DLS) and product lifecycle management (PLM), into the ship maintenance process at public sector shipyards. LT Komoroski's (2005) research indicated that implementing 3DLS and PLM into the maintenance planning processes could shorten the duration of Navy ship availabilities while reducing the annual operating cost of the four public sector planning yards by more than $30 million. LT Seaman's (2007) research indicated that implementing 3DLS and PLM into the opposite end of the maintenance process, implementation and installation, could reduce operating costs at the public sector shipyards by nearly $78 million annually.

This research pool is critical because the Department of Defense (DoD) spends an enormous amount of money on maintenance. According to *The Department of Defense Maintenance Fact Book* (Office of the Assistant Secretary of Defense for Logistics and Materiel Readiness, 2012), DoD maintenance accounted for 12% of the total DoD resource allocation of $689.1 billion, or about $79.5 billion, in fiscal year (FY) 2011. Of this amount, the Navy spent $5.4 billion on ship depot maintenance (Department of the Navy, 2011). This money was spent on eight intermediate maintenance facilities, four Navy shipyards, and 275 ships (Office of the Assistance Secretary of Defense for Logistics and Material Readiness, 2012). Given the challenging defense environment, the Navy needs to find ways to reduce these costs while retaining the same level of effectiveness and readiness.

B. RESEARCH PROBLEM

The problem is that the cost of maintenance in the U.S. Navy has been continuously escalating. The Navy is unsure why costs continue to rise or how to halt this unsustainable trend. The Navy also lacks an effective decision support tool to help analyze various possibilities for reducing costs.

C. RESEARCH PURPOSE

The purpose of this research is to help the Navy reduce costs for ship maintenance. This research provides a decision support tool for analyzing whether PLM, 3DLS, and 3D printing can help the Navy reduce the costs and increase the productivity of U.S. shipyards.

D. RESEARCH QUESTIONS

With this research, I attempt to answer the following questions:

1. What impact will 3D printing have on maintenance costs and shipyard productivity?
2. What impact will using PLM, 3DLS, and 3D printing in conjunction have on maintenance costs and shipyard productivity?

E. METHODOLOGY

This thesis models Phases IV and V of the current ship maintenance (SHIPMAIN) process and predicts outcomes from a reengineered process model that incorporates 3D printing, PLM, and 3DLS. In this thesis, I directly map a previous model (Seaman, 2007) of these phases and apply the quantitative results of the KVA methodology to similar processes. All major inputs, processes, and respective outputs are identified by a comprehensive review of current SHIPMAIN directives. The subprocess analysis includes estimates for the time each process is executed. I use market comparable values to help estimate cost figures and add value to the methodology.

F. SCOPE

The intended scope of this thesis is to analyze the SHIPMAIN process and predict the KVA return on knowledge (ROK) and potential return on investment (ROI) that PLM, 3DLS, and 3D printing technologies could produce if they were implemented. Ideally, this research would provide a comprehensive analysis of the entire SHIPMAIN process from Phase I through all decision points and acquisition milestones to the final steps of Phase V. Because of time and resource constraints, however, I constrain the quantitative scope of this research to Phases IV and V of the SHIPMAIN process. Readers of this research should keep in mind that the technologies evaluated in this research are likely to provide additional benefits (e.g., more accurate cost estimation, higher quality, less rework, etc.) across all phases of SHIPMAIN.

G. ORGANIZATION OF THESIS

Chapter I provides the background of this research and an overview of the problem, purpose, methodology, and scope of the research. Chapter II contains a literature review of the relevant research and technologies. This chapter provides an overview of SHIPMAIN, PLM, 3DLS, 3D printing, 3D computer-aided design, KVA, and the previous research in this area. Chapter III includes a discussion of the methodology and assumptions involved with building the “as-is,” “to-be,” and “radical to-be” models. Chapter IV details the analysis of the current “as-is” scenario and the future “to-be” scenarios that include PLM, 3DLS, and 3D printing. The final chapter, Chapter V, contains conclusions derived from the analysis and recommendations for the Navy.

THIS PAGE INTENTIONALLY LEFT BLANK

II. LITERATURE REVIEW

A. SHIPMAIN

In 2002, the SHIPMAIN process was implemented in order to improve ship maintenance for the Navy. The Navy defined SHIPMAIN as a Navy-wide initiative to create a surface ship maintenance program that will support the vision of “Sea Power 21” and its “Culture of Readiness” (Haney, 2003, p. 2). The SHIPMAIN process is displayed in Figure 1.

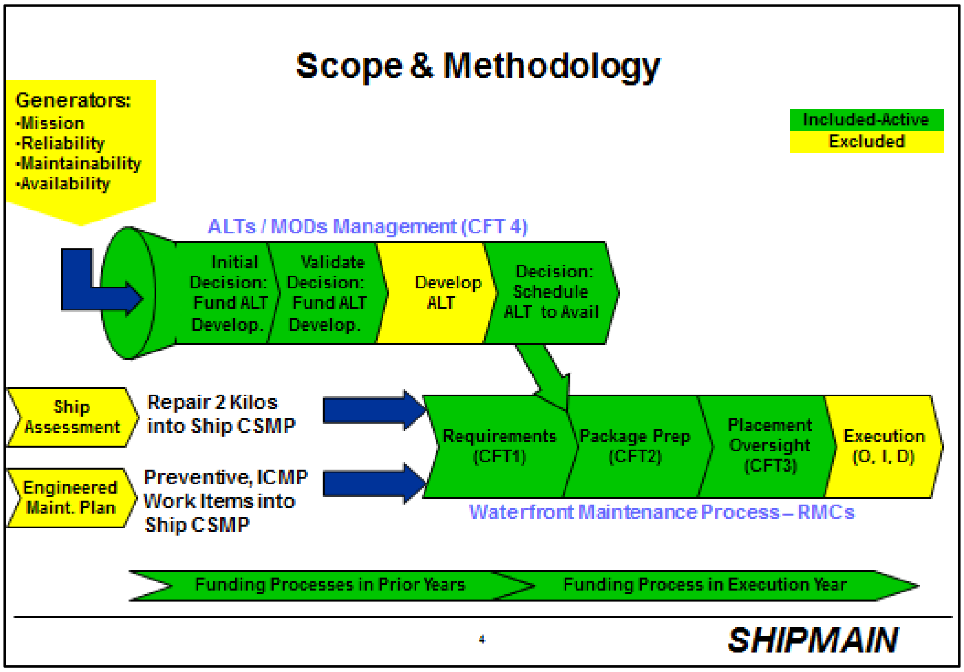

Figure 1. SHIPMAIN Process
(“SHIPMAIN Overview,” 2006)

SHIPMAIN implementation had four objectives (“SHIPMAIN Overview,” 2006):

- Implement a common planning process for surface ship maintenance.
- Increase the efficiency of ship maintenance and deliver cost savings without compromising the effectiveness of the process.
- Implement a standard management process with objective performance measurements.
- Institutionalize the process and implement continuous improvement procedures.

As part of accomplishing these objectives, SHIPMAIN made numerous enhancements to the maintenance and modernization processes. For the maintenance process, SHIPMAIN ensured that a single, universal process for maintenance was applied for all ships and that each ship had an individual maintenance team (MT) responsible for maintenance planning. SHIPMAIN also created the maintenance figure of merit (MFOM) metric to help with work prioritization, validated the *Individual Class Maintenance Plan* (ICMP) to ensure the correct items were available for MT planning, and implemented process metric collection and analysis to perform continuous improvement procedures. Finally, SHIPMAIN enhanced maintenance finance procedures by implementing annual ship business plans and reforming contracting procedures (“SHIPMAIN Overview,”2006).

For the modernization process, SHIPMAIN’s primary enhancement was to reduce the number of alteration types from 40 down to only two: program or fleet alterations. This enhancement significantly simplified and streamlined the process. In addition, SHIPMAIN created a single process for implementing alterations. This included a single database for ship changes and a gated approval process of senior Navy leaders. To track the new alteration process, SHIPMAIN introduced metric collection and analysis for modernization as well (“SHIPMAIN Overview,” 2006). The modernization plan is shown in Figure 2.

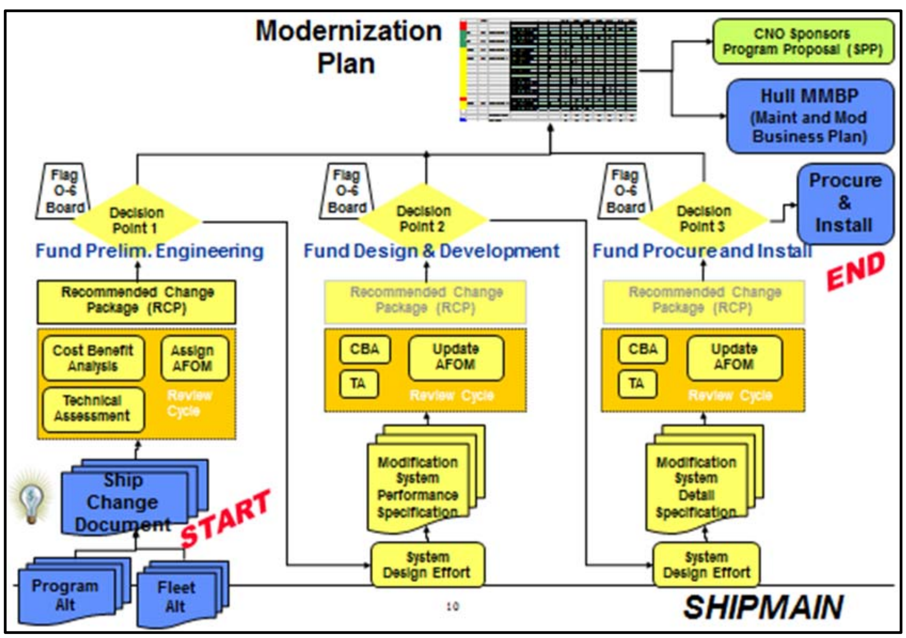

Figure 2. Modernization Plan
(“SHIPMAIN Overview,” 2006)

1. SHIPMAIN Phases

There are five phases to the SHIPMAIN process. Following are the phases in the order in which they are conducted:

I. Conceptual
II. Preliminary Design
III. Detailed Design
IV. Implementation
V. Installation

At the completion of these five phases, the targeted ship will have a new alteration or modification designed and installed. In addition, feedback on the installation will be returned to the SHIPMAIN planners (Seaman, 2007).

a. Phase I—Conceptual Phase

The purpose of the conceptual phase is to identify a change requirement, propose a resolution, and gain approval to develop the resolution into an engineered ship change (SC; Seaman, 2007). Products developed during this phase include

- requirement and proposed conceptual solution,
- proposed fielding plan,
- estimates for Phase II and III design development, and
- “best guessd estimates for Phase IV and V implementation and execution.

The flow chart for the conceptual phase is shown in Figure 3.

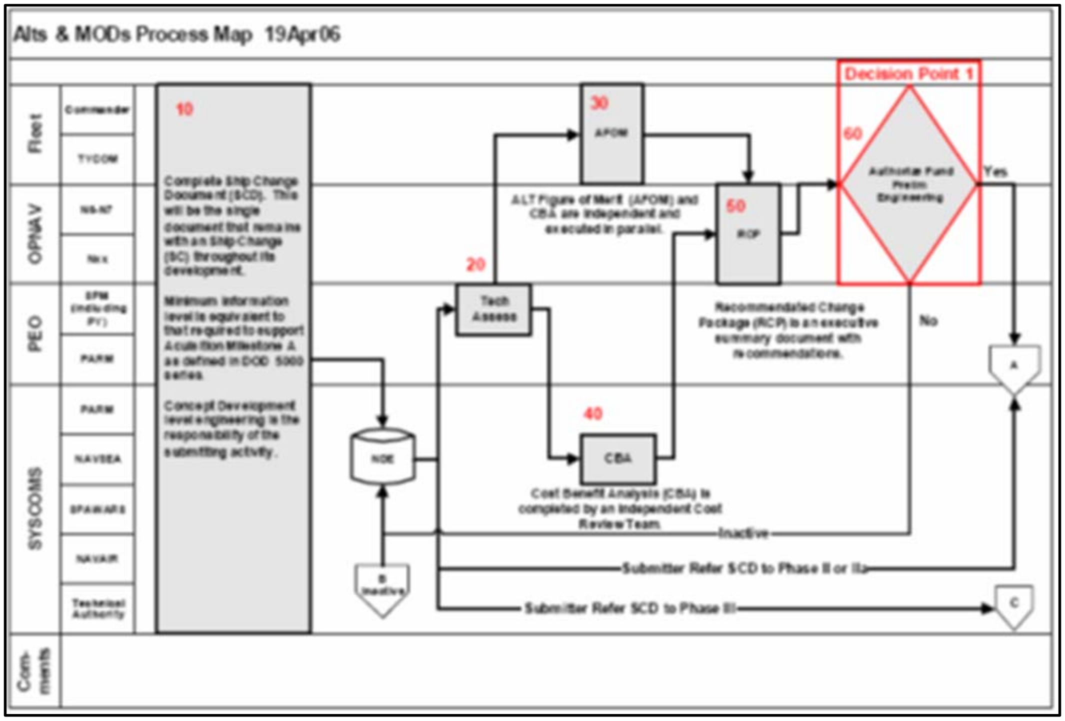

Figure 3. Phase I Diagram
(Seaman, 2007, p. 73)
Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

b. Phase II—Preliminary Design Phase

The purpose of the preliminary design phase is to conduct preliminary design development of the SC and gain approval to proceed to Phase III. This process can include technology selection, establishment of design parameters, and prototype development (Seaman, 2007). Products developed during this phase can include

- design parameters;
- updated fielding plan;
- refined estimates for Phases III, IV, and V;
- initiation of installation control drawings (ICDs) and performance specifications;
- identification of interfaces and distributive system impacts;
- design budget execution plans; and
- prototype design. (Seaman, 2007, p. 74)

The flow chart for the preliminary design phase is shown in Figure 4.

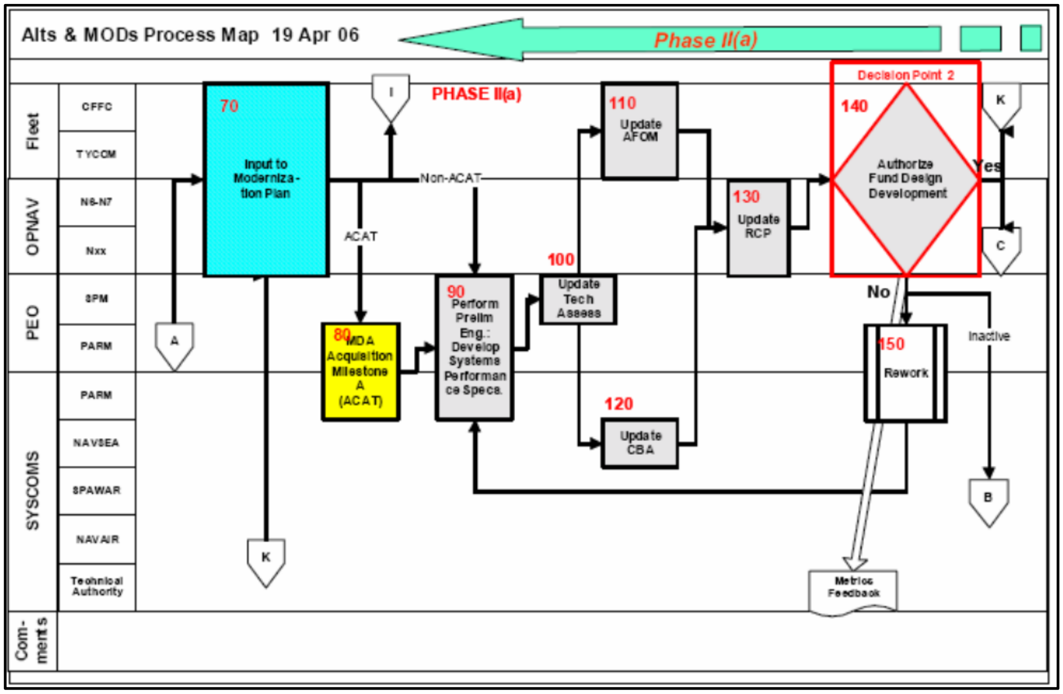

Figure 4. Phase II Diagram

(Seaman, 2007, p. 74)

Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

c. Phase IIa

Phase IIa is a combination of the Phases II and III development and review processes that ends at Decision Point (DP) 3 (Approval of Funding for Implementation). This phase is utilized when a proposed SC design is mature to the point that DP 2 (Authorize/Fund Design Development) is not required. The approving process may determine that an SC is eligible for Phase IIa during DP 1 (Authorize/Fund Problem Engineering) approval (Seaman, 2007).

If the scope of the SC is an internal equipment modification, all of the following criteria must be met:[1]

- The SC can be accomplished without changing an interface external to the equipment or system.
- The change is made within the equipment or system.
- The change does not negatively impact strike force interoperability (SFI).

[1] The requirements listed in this section come from *Joint Forces Maintenance Manual* (*JFMM*) ACN02-04, as cited in Seaman (2007).

- The change does not impact shipboard distributive systems, ship selected records (SSRs) or interfacing equipment or systems, compartmental arrangement records, or damage control records. (as cited in Seaman, 2007, p. 75)

If the scope of the SC is a ship modification, all of the following requirements must be met:

- The change does not negatively impact SFI.
- The change does not impact ship stability records (weight & moment).
- The change does not impact or alter the 3-dimensional footprint of the equipment being replaced.
- The change does not impact shipboard distributive systems, SSRs or interfacing equipment or systems, compartmental arrangement records, or damage control records.
- The change does not impact manning levels. (as cited in Seaman, 2007, p. 75)

Installation may not begin until authorized in Phase IV (Seaman, 2007).

d. Phase III—Detailed Design Phase

The purpose of the detailed design phase is to complete detailed design development of the SC. After approval during DP 3, SCs are added to either the *Authorized* or *Planned but Not Authorized* section of the ship program manager (SPM) letter of authorization (LOA). Installation of an SC may not proceed until it has been added to the Authorized Section of the LOA in accordance with identified milestones (Seaman, 2007). Products developed during this phase can include

- technical data package (must include the level of detail equivalent to preliminary class-level ship installation drawing [SID] or preliminary ICD);
- installation control drawings;
- performance specifications;
- quantification of interfaces and distributive system impacts (i.e., parametric data);
- refined estimates for Phases IV and V;
- refined fielding plan;

- list of required certifications and plan of action and milestones (POA&M) for completion; and
- alteration bill of material (ABOM) including long lead time material (LLTM), government furnished equipment (GFE), and logistically significant material.

The flow chart for the detailed design phase is shown in Figure 5.

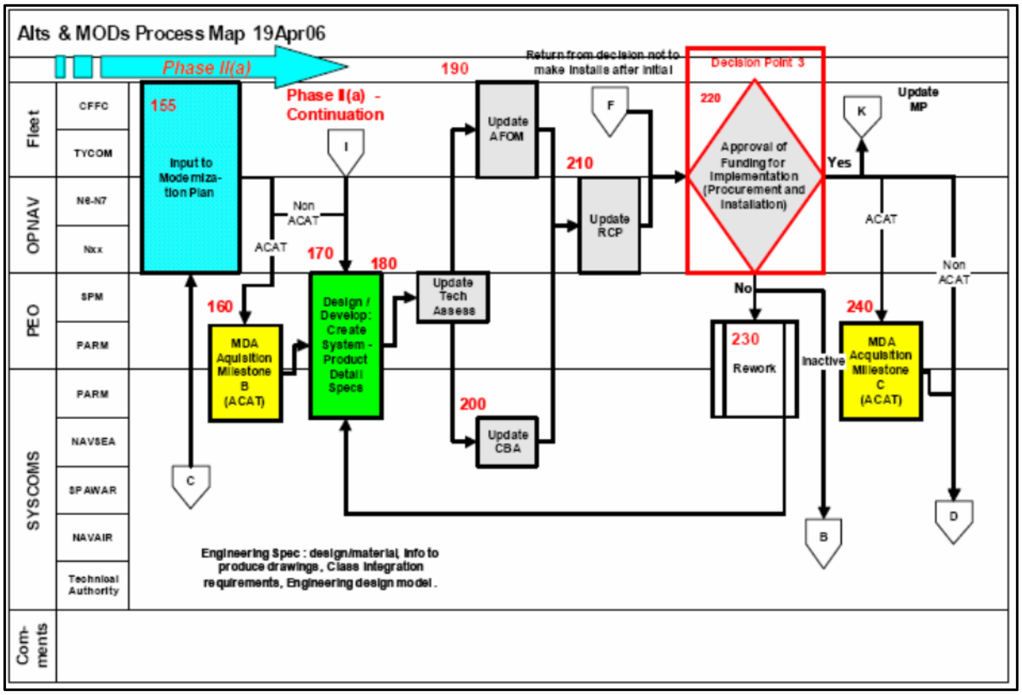

Figure 5. Phase III Diagram
(Seaman, 2007, p. 76)
Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

e. Phase IV—Implementation Phase

The purpose of the implementation phase is to complete site-specific installation planning for the SC. During this phase, the primary focus is moved from overall SC applicability to installation design for a specific location. This phase includes finalized design (including ship check/site survey, drawings, technical installation instructions, etc.), procurement initiation, pre-installation certification and testing, installation readiness assessments, and risk assessments (Seaman, 2007). Products developed during Phase IV can include

- SIDs,
- integrated logistics support (ILS) certification,

- GFE and industrial activity furnished (IAF) material procurement,
- pre-installation certifications,
- pre-installation testing,
- risk assessments,
- installation documents, and
- alteration installation team (AIT) POA&M (Seaman, 2007, p. 77).

Funding for Phase IV is budgeted as part of the modernization plan (MP) after Phase IIa or III approval. The flow chart for the implementation phase is shown in Figure 6.

After DP 3, there are two reasons for a Ship Change Department (SCD) to be revised:

1. There is a capability difference between the planned procurement and the actual procurement. This capability difference includes the changes provided by the manufacturer inherent in the design for a multi-year procurement requirement.
2. The actual costs of the SCD are projected to increase by an amount greater than +/- 10% of the estimated costs.

If either of these two events occurs, a revised SCD must be submitted to DP 3 (Seaman, 2007).

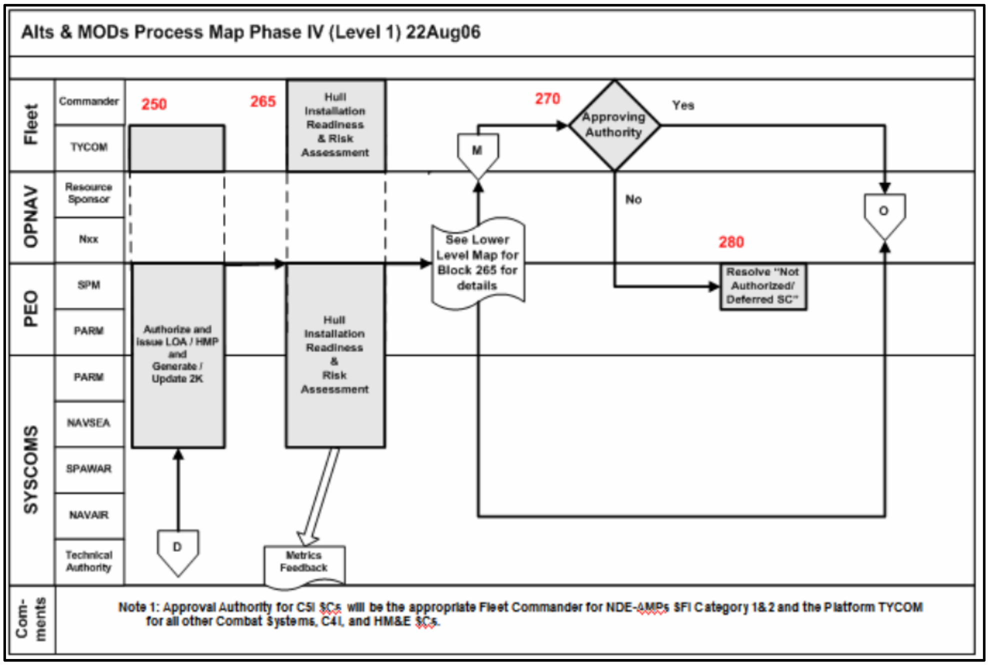

Figure 6. Phase IV Diagram

(Seaman, 2007, p. 78)

Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

f. Phase V—Installation Phase

The purpose of the installation phase is to install the SC and provide feedback for future installation decisions. Feedback from each individual installation is provided to update and refine technical information records and installation cost estimates. Once all of the planned installations have been completed, this phase and the SC are closed out by providing feedback data reflecting final installation and closeout (Seaman, 2007). Products developed/services performed during Phase V can include

- return cost reports;
- liaison action requests (LARs);
- post-installation certification and testing;
- ILS product delivery; and
- alteration completion reports. (Seaman, 2007, p. 78)

The flow chart for the installation phase is shown in Figure 7.

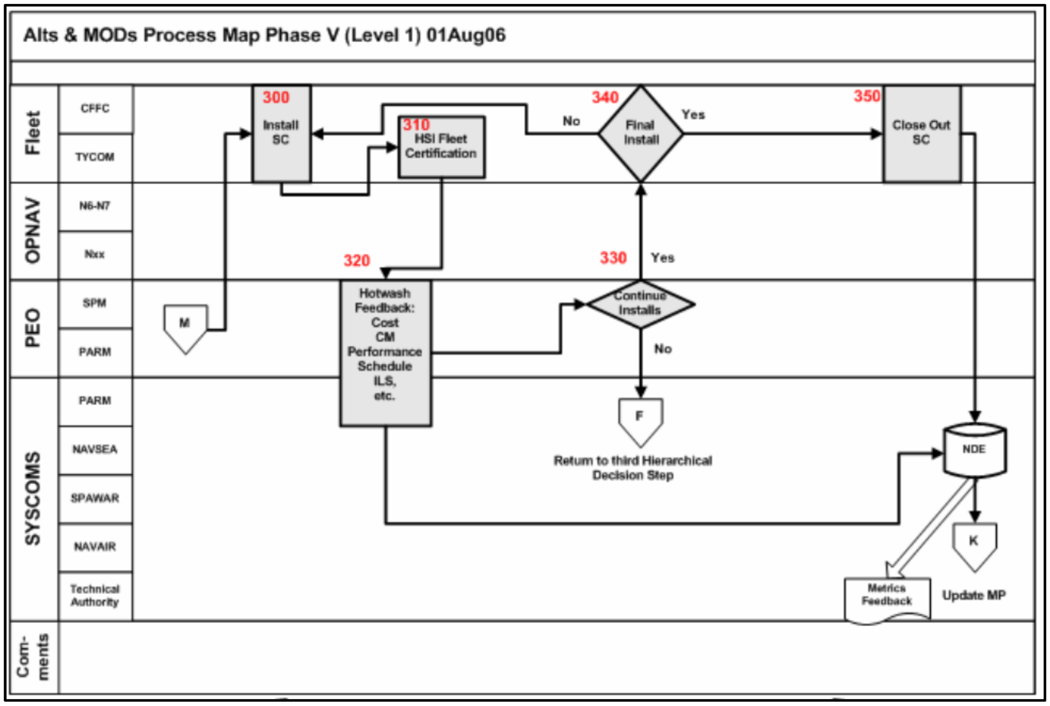

Figure 7. Phase V Diagram
(Seaman, 2007, p. 79)
Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

B. PRODUCT LIFECYCLE MANAGEMENT

The consulting firm CIMdata (2013) defines *product lifecycle management* (PLM) as the following:

- a strategic business approach that applies a consistent set of business solutions that support the collaborative creation, management, dissemination, and use of product definition information
- supporting the extended enterprise (customers, design and supply partners, etc.)
- spanning from concept to end of life of a product or plant
- integrating people, processes, business systems, and information. (p. 1)

PLM involves creating information about a product, managing the information, and disseminating the needed information to all stakeholders throughout the product's life cycle. There are three core tenets for any PLM implementation:

- universal, secure, managed access and use of product definition information

- maintaining the integrity of that product definition and related information throughout the life of the product or plant
- managing and maintaining business processes used to create, manage, disseminate, share, and use the information. (CIMdata, 2013, p. 1)

PLM has been used in numerous industries, including automobile manufacturing, cell phone production, electronic component production, utility distribution network management, and civil engineering projects (CIMdata, 2013). According to research conducted by the consulting firm Tech Clarity, PLM offers manufacturers the ability to increase revenue, decrease product cost, and reduce product development costs. The firm's research showed that a successful PLM initiative improves business performance by enhancing data management, streamlining business processes, enabling better collaboration, and enabling better product development and engineering decision-making (Brown, 2012). Examples of successful PLM initiative benefits are shown in Figure 8.

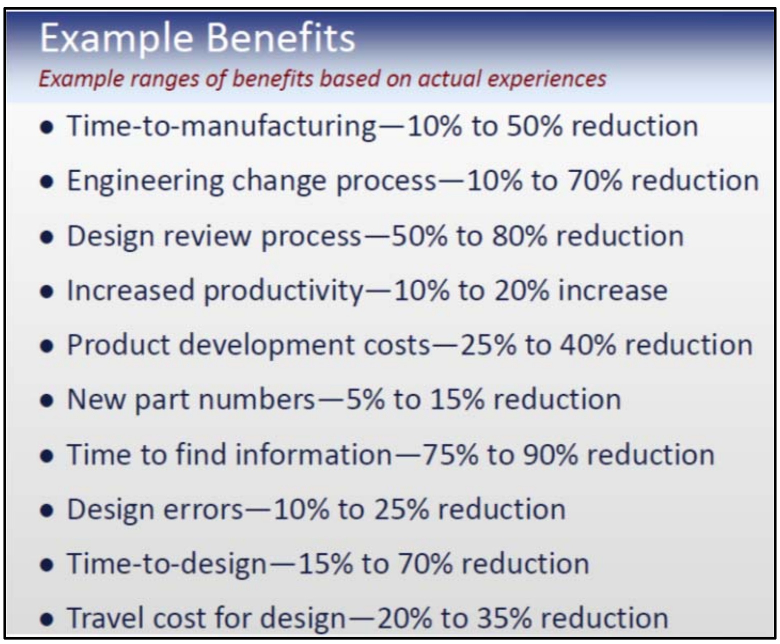

Figure 8. PLM Benefits
(CIMdata, 2011)

PLM is forecasted to grow at an 11% annual rate for the next several years as an increasing number of firms seek to capture the benefits, as shown in Figure 9.

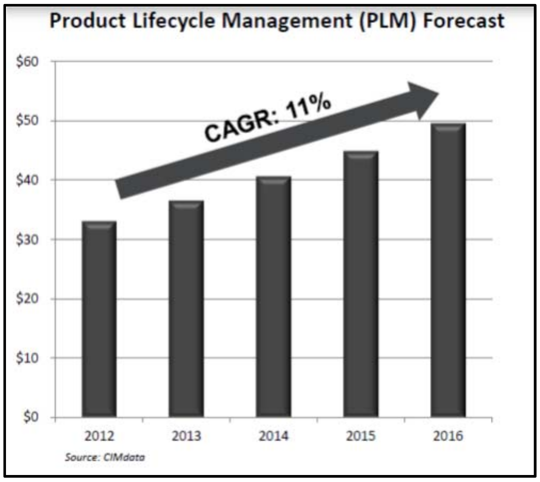

Figure 9. PLM Growth Forecast
(3D Systems, 2013)

C. 3D LASER SCANNING

According to the Spar Point Group (2013), *3D laser scanning (3DLS)* is defined as the process of graphically capturing as-built physical elements of an object, facility, or area and applying surveyed information to each visible point. 3DLS can be conducted via airborne methods (airborne laser scanning) or ground-based methods (terrestrial laser scanning). Airborne laser scanning is impractical for the purposes of this research; therefore, all further mentions of 3DLS refer to terrestrial laser scanning. 3DLS can be divided into two categories: static and dynamic scanning. Static scanning involves scanning from a fixed position, while dynamic scanning involves scanning from a moving platform (Quintero et al., 2008). For the purposes of this research, all further mentions of 3DLS refer to static scanning. 3DLS has numerous applications, including 3D modeling, surveying and mapping, reverse engineering, quality control, autonomous vehicle navigation, collision avoidance, object and target recognition, forensics, historic preservation/archaeology, disaster reconnaissance, space exploration (docking of space craft and assessing damage to the exterior of space shuttle), and forest management (General Services Administration, 2009). An example of the output of 3DLS is shown in Figure 10.

Figure 10. 3D Model of Industrial Piping
(Quintero et al., 2008)

1. 3DLS Process

The process for conducting 3DLS is shown in Figure 11.

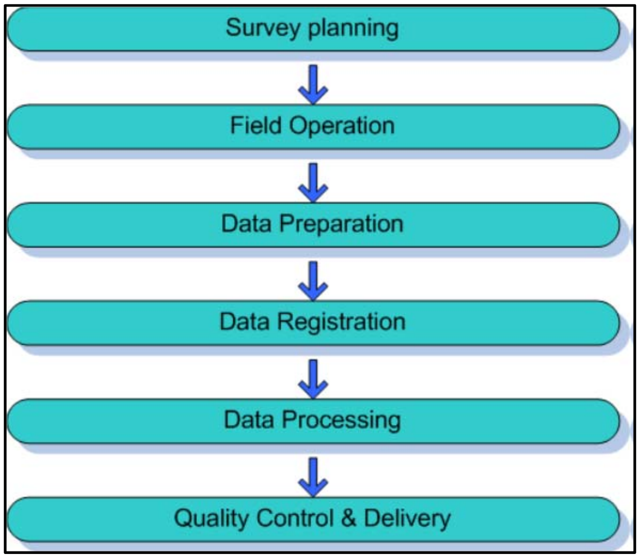

Figure 11. 3DLS Process
(Quintero et al., 2008)

After planning the scan and setting the scanner up properly, the scan can be conducted. Running the scan generates a large collection of data points referred to as a point cloud. After the scan is complete, data preparation can then proceed. The point cloud is cleared of all erroneous scans, which are caused by factors such as human error and environmental interference, and the remaining scans are prioritized by the "best views." When the data are prepared, the point cloud can then be registered. If multiple scans are required to scan an item, registration aligns the separate scans to produce one coherent data set for the scanned object. Once registration is complete, the point cloud can then be processed. Point cloud processing turns the raw data into a final product, such as a two-dimensional (2D) CAD drawing or 3D model. For 3D models, the 3D object can be detected automatically from a point cloud if the shape is known beforehand (Quintero et al., 2008). For example, a scan of a petrochemical plant can be easily converted into a 3D model, assuming that all pipes have a circular cross-section and the connecting pieces also have a specific shape (shown in Figure 12).

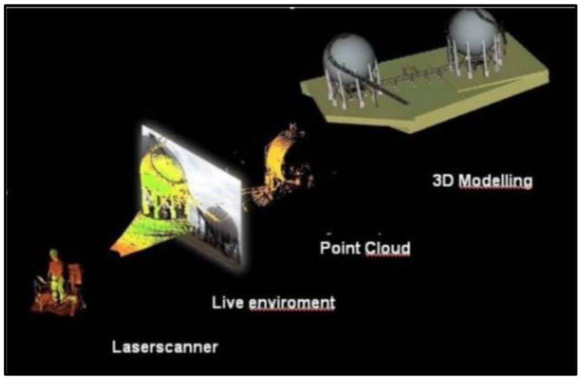

Figure 12. Steps From Scan to 3D model
(Quintero et al., 2008)

2. Benefits of 3DLS

Implementing 3DLS in an industrial process can produce numerous benefits, including increased data accuracy and reduced survey time (Quintero et al., 2008). A summary of some of the benefits is displayed in Table 1.

Table 1. 3DLS Benefits
(Quintero et al., 2008)

Topics	Benefits
Costs	One measurement campaign only
	Reduced reworks
	Reduced field fitting
	Improved reviews
	Information sharing
Project planning	Fast data acquisition
	Improved design
	Shorter downtime
Quality	Less rework
	Accurate shop fabrication of more parts
	Improved routings (clash detections)
Safety	Measurements from a distance
	Shorter exposure to hazards

D. 3D PRINTING

1. Additive Manufacturing

Additive manufacturing is defined by the American Society for Testing and Materials as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to the subtractive manufacturing process of creating an object by controlled removal of material from an input (Wohlers Associates, 2010b). Although the terms are commonly used interchangeably, 3D printing is actually a subset of additive manufacturing. The ASTM defined 3D printing as any additive manufacturing system that used a printing-like process. Through common usage, however, 3D printing has become the overarching term for all additive processes and is now synonymous with additive manufacturing (Grimm, 2012).

2. 3D Printing Process, Methods, and Materials

The general process for creating 3D objects is shown in Figure 13.

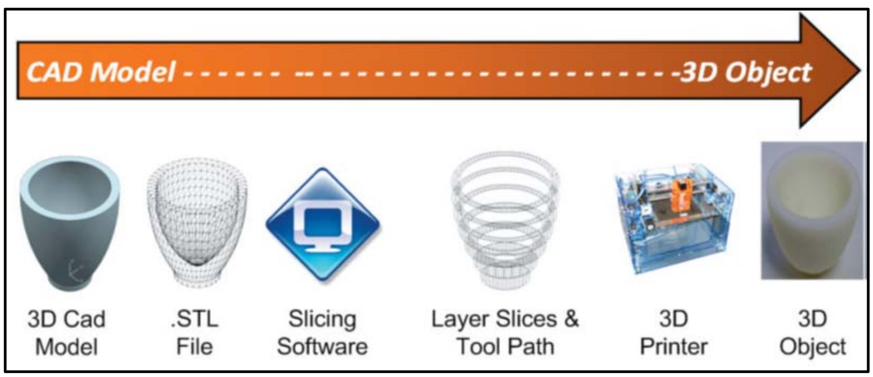

Figure 13. General 3D Printing Process
(Campbell, Williams, Ivanova, & Garrett, 2011)

There are various materials currently available to create 3D printed objects, including plastic, metal, and ceramic (Campbell et al., 2011). There are several different methods to employ additive manufacturing, and each works with different material types, as shown in Tables 2 and 3.

Table 2. AM Categories
(National Additive Manufacturing Innovation Institute, personal communication, 2013)

Additive Manufacturing Categories
As defined by ASTM F42 Committee

Category	Description
Binder Jetting	Liquid bonding agent selectively deposited to join powder
Material Jetting	Droplets of build materials selectively deposited
Powder Bed Fusion	Thermal energy selectively fuses regions of powder bed
Directed Energy Deposition	Focused thermal energy melts materials as deposited
Sheet Lamination	Sheet of material bonded together
Vat Photopolymerization	Liquid photopolymer selectively cured by light activation
Material Extrusion	Material selectively dispensed through nozzle or orifice

Note. This table is from the *MetalForming Magazine* webinar, "Additive Manufacturing for Metalformers." The webinar was retrieved from the National Additive Manufacturing Innovation Institute's website, but it is no longer available.

Table 3. AM Technologies
(National Additive Manufacturing Innovation Institute, personal communication, 2013)

Expanding Spectrum of AM Technologies

AM Process Categories		Metals	Plastics	Ceramics	Bio	Electronics	Food
Binder Jetting		X		X			X
Z-Corp				X			
ExOne		X		X			
Directed Energy Deposition							
Electron Beam Direct Manufacturing	EBDM	X					
Direct Metal Deposition	DMD	X					
Laser Engineered Net Shaping	LENS	X					
Material Extrusion							
Fused Deposition Modeling	FDM		X			X	
Fused Filament Fabrication	FFF		X	X			
Hopper Fed			X				X

AM Process Categories		Metals	Plastics	Ceramics	Bio	Electronics	Food
Powder Bed Fusion							
Direct Metal Laser Sintering	DMLS	X					
Selective Laser Sintering	SLS		X	X			
Electron Beam Melting	EBM	X					
Sheet Lamination		X	X				
Vat Photopolymerization							
Stereolithography Apparatus	SLA		X				
Direct Print							
Aerosol Jet	AJ	X	X	X		X	
Thermal Spary	TS	X				X	
Ink jet	IJ	X	X	X	X	X	X
Laser Direct Structuring	LDS	X				X	

Note. This table is from the *MetalForming Magazine* webinar, "Additive Manufacturing for Metalformers." The webinar was retrieved from the National Additive Manufacturing Innovation Institute's website, but it is no longer available.

Several companies, including 3D Systems and Stratasys, produce 3D printers for both personal and industrial use. In addition, open source models, such as RepRap, are available on the Internet (Wohlers, 2009).

3. Capability Evolution

The 3D printing industry, originally known as the rapid prototyping industry, began in 1986 when Charles Hull patented the stereolithography process and founded 3D Systems. 3D Systems began selling the first rapid prototyping device, SLA-1, in 1988. Several other firms began offering rapid prototyping methods and devices in the early 1990s. One of those companies, Stratasys, developed the Fused Deposition Modeling (FDM) process in 1991. Up to this point, the 3D printing processes only produced plastic objects. In 1993, however, "rapid tooling" became a process/goal, and the firm DTM released a product that delivered sintered metal tooling inserts. Also in 1993, the Society of Manufacturing Engineers created the Rapid Prototyping Association to represent and promote the industry. In 1996, the firm Z Corporation began selling its 3D printing products, which were based on a license from the Massachusetts Institute of Technology. Z Corporation's product was drastically cheaper and faster than previous offerings and created a new segment inside the rapid prototyping industry: 3D printers (Grimm, 2004).

The late 1990s and early 2000s saw the 3D printing industry begin to evolve and diversify. The firm Aeromet developed laser additive manufacturing in 1997. In 2000, Objet Geometries released the first 3D ink jet printer, and Z Corporation made the first multicolor 3D printer commercially available. Solidimension began the era of home 3D printing by releasing the first desktop 3D printer in 2001. In 2004, 3D Systems took a step forward in both metal printing and direct part production by producing 3D printed jewelry (Hessman, 2013). In 2005, the open source initiative RepRap was founded by Dr. Adrian Bowyer at the University of Bath to build a 3D printer that could print most of its own components. The first selective metal sintering device, which enabled 3D printing of metals and ceramics by fusing the materials together, became available, and Objet created a device capable of 3D printing a single object with several different materials in 2006 (Daly, 2013).

During this time frame, 3D printing expanded into the medical field. In 1999, the first lab-grown organ was implanted in a human using a 3D printed scaffolding. The technology making this advance possible was created at Wake Forest University and paved the way for future organ engineering and 3D printed medicine. Scientists then went on to print a miniature functioning kidney in 2002, a fully 3D printed prosthetic leg in 2008, a blood vessel in 2010, and a customized lower jaw prosthetic in 2012 (Daly, 2013).

In the early 2010s, 3D printing technologies became mature enough to finally start seeing complex direct part production. In 2010, the firm Metaltec Innovations used 3D printing to produce custom pulls, knobs, and knockers for doors; metal sculptures for homes and businesses; and custom decorative tile (Wohlers Associates, 2010a). In 2011, engineers at the University of Southampton designed and printed the world's first 3D printed unmanned aircraft. The group Kor Ecologic also created Urbee, the world's first 3D printed car. In addition, the firm i.materialise began offering 3D printing in gold and silver in 2011. In 2013, 3D Systems released a desktop home printer for under $1,000, opening the door to mass 3D printing beyond the open source 3D printing movement (Daly, 2013).

4. Rapid Prototyping

One of the current major uses of 3D printing is rapid prototyping. *Rapid prototyping* is defined as technology driven by computer-aided design (CAD) data to produce physical models and parts through an additive process. Rapid prototyping can also refer to subtractive and formative methods of quickly creating prototypes. The subtractive method involves the controlled removal of material to create a prototype, and the formative method involves the creation of a prototype via forming or molding. My research is solely concerned with the additive process (see Figure 14; Grimm, 2004).

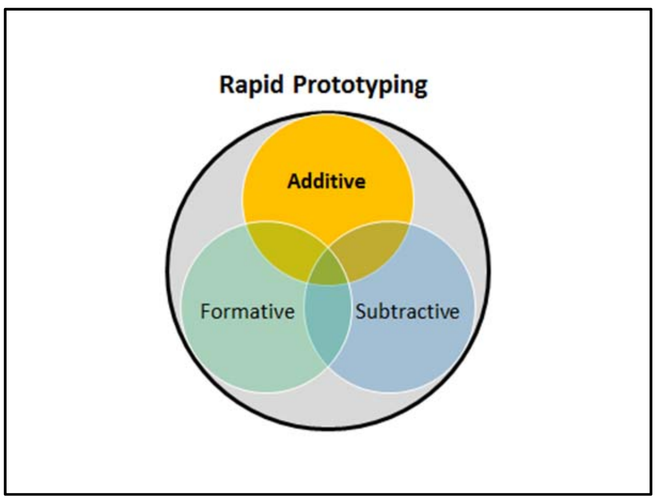

Figure 14. Rapid Prototyping Methods
(Based on Grimm, 2004)

Companies employ rapid prototyping for several reasons, including

- increased effective communication;
- decreased development time;
- decreased costly mistakes;

- minimized sustaining engineering changes; and
- extended product lifetime because of the addition of necessary features and the elimination of redundant features early in the design (eFunda, 2013, p. 1).

The rapid prototyping process consists of five steps. These steps are all highly automated with the exception of cleaning and finishing. The process is shown in Table 4, along with the typical time frame for each step (Grimm, 2004).

Table 4. Rapid Prototyping Process
(Based on Grimm, 2004)

Rapid Prototyping Process		
Step #	Step	Time
1	Generate STL file	1-10 minutes
2	File verification and repair	5-30 minutes
3	Build file creation	15-60 minutes
4	Part Construction	30 mins – 48+ hrs
5	Part finishing and cleaning	4 hours

With a 3D printer, designers can quickly build and rebuild prototype models in a fraction of the time and cost of legacy prototyping operations (Stratasys, 2012). Examples of the time savings in different industries can be seen in Figure 15.

Time saved prototyping with in-house 3D printing vs. other methods

Industry	Old Method	Time savings
Industrial design	Clay models	96%
Education	Outsourced machining	87%
Aerospace	2D laser cutting	75%
Automotive	Aluminum tooling	67%
Aerospace	Injection molding and CNC tooling	43%

Each example is based on a real customer experience.[4]

Figure 15. 3D Printed Rapid Prototyping Benefits
(Stratasys, 2012)

5. Direct Part Manufacturing

In addition to producing prototypes, many companies are now using 3D printing to produce finished products. For example, NASA and Aerojet Rocketdyne collaborated to produce a 3D printed rocket engine injector. An injector manufactured with traditional processes would take more than a year to make, but with 3D printing, it was produced in less than four months with a 70% reduction in cost (Steitz, Martin, & Dick, 2013). According to Wohlers Associates,

> The additive-manufacturing industry has tremendous untapped potential, especially when considering the opportunity in custom and short-run production. Producing parts for end-use products is more challenging than models and prototypes, so this application will take time to develop. It is expected to drive revenues from AM products and services to impressive levels in the future. (2010b, p. 1)

Direct part production currently accounts for 28% of all additive manufacturing activity (DiChristopher, 2013). The expected growth of direct part production is displayed in Figure 16.

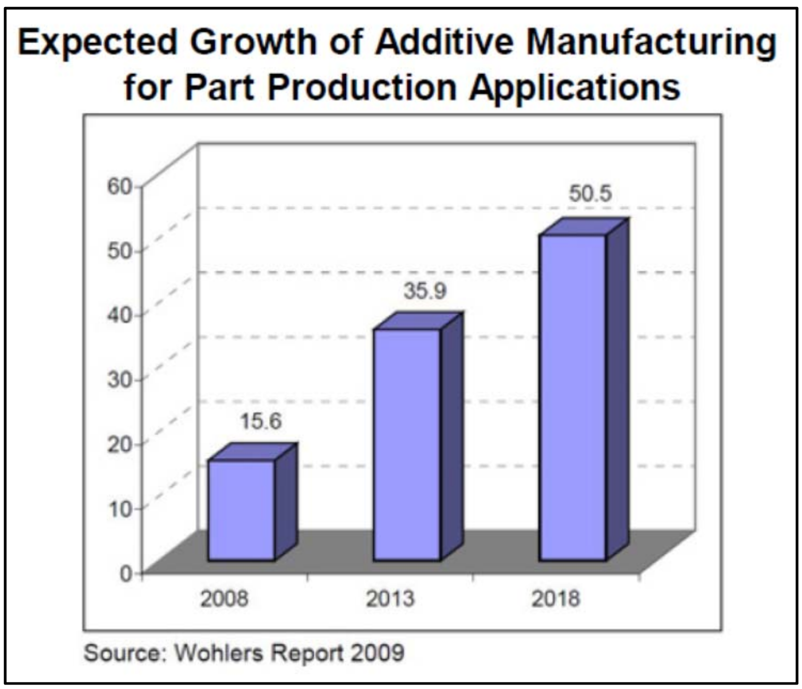

Figure 16. Expected Growth of AM for Part Production
(Wohlers Associates, 2009)

6. 3D Printing Advantages

3D printing has a variety of advantages over traditional manufacturing methods like injection molding, casting, and machining. First, 3D printed objects can be more complex. Designers can place material only where it is needed, including in intricate internal patterns that traditional manufacturing simply cannot replicate. Second, 3D printing digitizes both design and manufacturing. Digitizing the design means the final object is more likely to reflect the designer's wish than traditional methods would. Digitizing the manufacturing means that less operator expertise and involvement is necessary to produce items. Third, 3D printing reduces the cost of added part complexity to zero. Since the only tool required to produce 3D printed objects is the printer, and the only requirement the printer has is the digital 3D drawing, the process of printing does not change, regardless of any changes to the design. The design, therefore, can be as simple or as complex as necessary with no added cost to retool the process. Fourth, 3D design work can be done globally. The digital 3D drawing can be created anywhere and sent to a 3D printer with the proper capacity at any location desired. Lastly, 3D printing reduces waste. Since 3D printing uses only the material necessary to create each layer, a large portion of the material costs to produce an item are saved when compared to traditional manufacturing (Campbell et al., 2011).

As a result of the observed and potential benefits, 3D printing has been rapidly growing. According to Wohlers Associates (3D Systems, 2013), 3D printing is predicted to grow 17% per year to annual sales of $7 billion (see Figure 17).

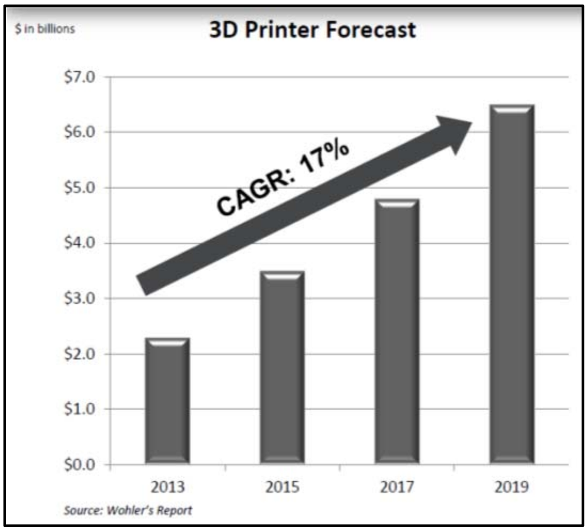

Figure 17. 3D Printer Forecast
(3D Systems, 2013)

3D printing is already a part of the automotive, aerospace, health, and defense manufacturing sectors, and usage is predicted only to increase in the future (Campbell et al., 2011).

7. 3D Printer Usage in the Department of Defense

The following paragraphs describe several 3D printing initiatives currently being conducted within the DoD.

a. Army Expeditionary Lab

The Army's Rapid Equipping Force (REF) designed self-contained spaces, referred to as Expeditionary Labs, with 3D printers and other computer-directed manufacturing devices. The labs were designed to allow soldiers and engineers to collaborate and rapidly remedy problems in the battlespace. The first two labs were deployed to Afghanistan in 2012. One example of the labs' impact involved reengineering a mine resistant ambush protected (MRAP) vehicle part. Soldiers noticed that a valve frequently broke and brought the issue to an Expeditionary Lab. The lab tested various forms of valve cover and shipped the data for the improved design to the United States. The new parts were manufactured and shipped back to Afghanistan. According to REF Director Peter Newell, it was a "30-day discussion rather than a multi-year process" (Chayka, 2013, p. 2).

b. Edgewood Chemical and Biological Center

The Edgewood Chemical and Biological Center, which is part of the Army's Research, Development, and Engineering Command, has been using 3D printing to create prototypes for testing since the 1990s. Using rapid prototyping, Edgewood has developed night-vision battery storage and unmanned vehicle tools (Chayka, 2013).

c. Chief of Naval Operations' Rapid Innovation Cell

The Chief of Naval Operations' (CNO's) Rapid Innovation Cell (CRIC) is conducting an initial trial of a 3D printer at the Navy Warfare Development Command. In 2014, a trial printer installation is anticipated on a carrier, both for medical instruments and prosthetics as well as general crew usage and experimentation. Ultimately, CRIC wants to create a database of digital models ready to be 3D printed on demand for afloat units (Chayka, 2013).

d. Rapid Manufacturing and Repair Program

As shown in Figure 18, the Rapid Manufacturing and Repair (RARE) program has a long history in the DoD.

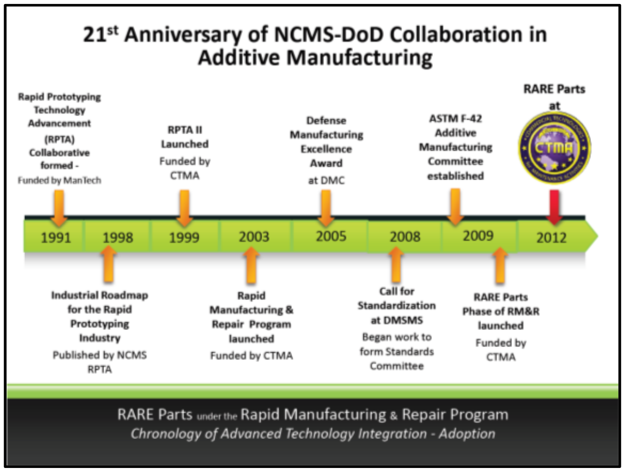

Figure 18. History of RARE
(RARE Parts Team Panel, 2012)

RARE has already integrated or is in the process of integrating the following technologies into the maintenance base:

- additive manufacturing technologies including Stratasys FDM, EOS direct metal laser sintering (DMLS), direct write, laser engineered net shaping (LENS), and the POM Prometal S15 sand printer;
- reverse engineering scanning technologies; and
- additive manufacturing part build software.

The RARE sites are utilizing 3D printing as follows:

- Fleet Readiness Center (FRC) East used FDM to create tools. The data are summarized in Figure 19.

Cost & Cycle Time Analysis

- Original Tool
  - Cost: $6,800
  - Cycle Time: 13 days
- FDM Tool
  - Cost: $3,100
  - Cycle Time: 6 days

Tool No.	Description	Material	FDM Build Cost ($) matls & run time	FDM Build Time (hrs)
1	Lay up tool – Solid	ULTEM	761	19
2	Lay up tool – Solid	PPSF	660	15
3	Lay up tool – 0.010" sparse gaps	PPSF	522	12
4	Lay up tool – 0.020" sparse gaps	PPSF	455	11

Figure 19. AM Cost and Cycle Time Analysis
(RARE Parts Team Panel, 2012)

- FRC Southwest Advanced Technology Center used 3D laser scanning and FDM to create a proof of concept project for F-18 E/F engine bay door hat stiffener layup tooling. The estimated savings could exceed $1.5 million per year.
- The Anniston Army Depot used 3D printing to add corrosion- and wear-resistant materials to specific areas of carbon steel parts and to replace balance material on components that are reassembled, rebalanced, and reused, like the external air seal edge of a gas turbine wheel.

The RARE program ultimately aims to adopt 3D printing based on demonstrated cost savings, cost avoidances, and the following improved depot efficiencies (RARE Parts Team Panel, 2012):

- flexibility;
- CAD-based solutions;
- readiness improvements;
- rapid response capability in event of supply chain deficiency/disruption;
- capability to replicate, redesign, and print obsolete but critical parts; and
- capability to create improved part designs.

e. *Walter Reed National Military Medical Center*

Walter Reed established a center for additive manufacturing in 2002. The first project conducted by the center was to create medical models of body parts, which reduced surgery times by an average of six hours. In addition to models, custom surgical guides were also printed to assist surgeons in making precise cuts and grafts. Now that 3D printing technology has advanced, Walter Reed has expanded 3D printing into custom metal implants. For example, the hospital can create a cranial implant with integrated screws and a plate for just $75 in contrast to $15,700 for a traditional implant, screws, and plate. When the cost of the printer is included, the 3D printed item's cost is roughly equivalent and fits the patient better (Scott et al., 2012).

E. COMPUTER-AIDED DESIGN

Computer-aided design (CAD), also referred to as computer-aided drafting, is the process of creating 2D or 3D graphical representations of physical objects using software programs. CAD is used to design physical products in a wide range of industries. During the design process, the software performs calculations for determining an optimum shape and size for a variety of product and industrial design applications. The industries that utilize CAD programs include aerospace and defense; automotive manufacturing; consumer product production; and oil, gas, and refining (Siemens, 2013).

In product and industrial design, CAD is primarily used to create 3D models or 2D vector-based drawings of physical components. CAD is also used throughout the engineering process for the following subprocesses:

- conceptual design and layout of products,
- strength and dynamic analysis of assemblies, and
- definition of manufacturing methods.

CAD allows engineers to interactively and automatically analyze design variants, which enables them to identify the optimal design for manufacturing while minimizing the use of physical prototypes (Siemens, 2013).

In addition to lower product development costs, increased productivity, improved product quality, and faster time-to-market, utilizing CAD software has the following benefits:

- a quicker design process because of improved visualization of the final product, sub-assemblies and constituent parts;
- reduced design errors via greater accuracy;

- easier, more robust documentation of the design, including geometries and dimensions, bills of materials, etc.; and
- easy re-use of design data and best practices (Siemens, 2013, p. 1).

1. Digital Prototyping

Some CAD products offer the ability to digitally prototype designs. A digital prototype is a digital simulation of a product that can be used to test form, fit, and function (Autodesk, 2009). As all associated industrial, mechanical, and electrical design data are integrated, the digital prototype becomes increasingly robust until a true digital representation of the entire end product emerges. The digital prototype can then be used to visualize and simulate a product to reduce the necessity of building expensive physical prototypes, as displayed in Figure 20 (Autodesk, 2009).

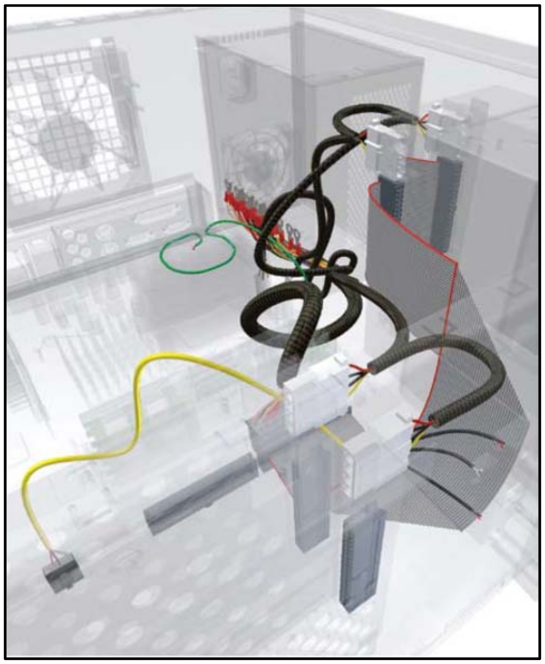

Figure 20. Digital Prototype Example
(Autodesk, 2009)

2. PLM, 3DLS, 3D CAD, and 3D Printing Relation

The relation between PLM, 3DLS, 3D CAD, and 3D printing can be modeled as shown in Figure 21.

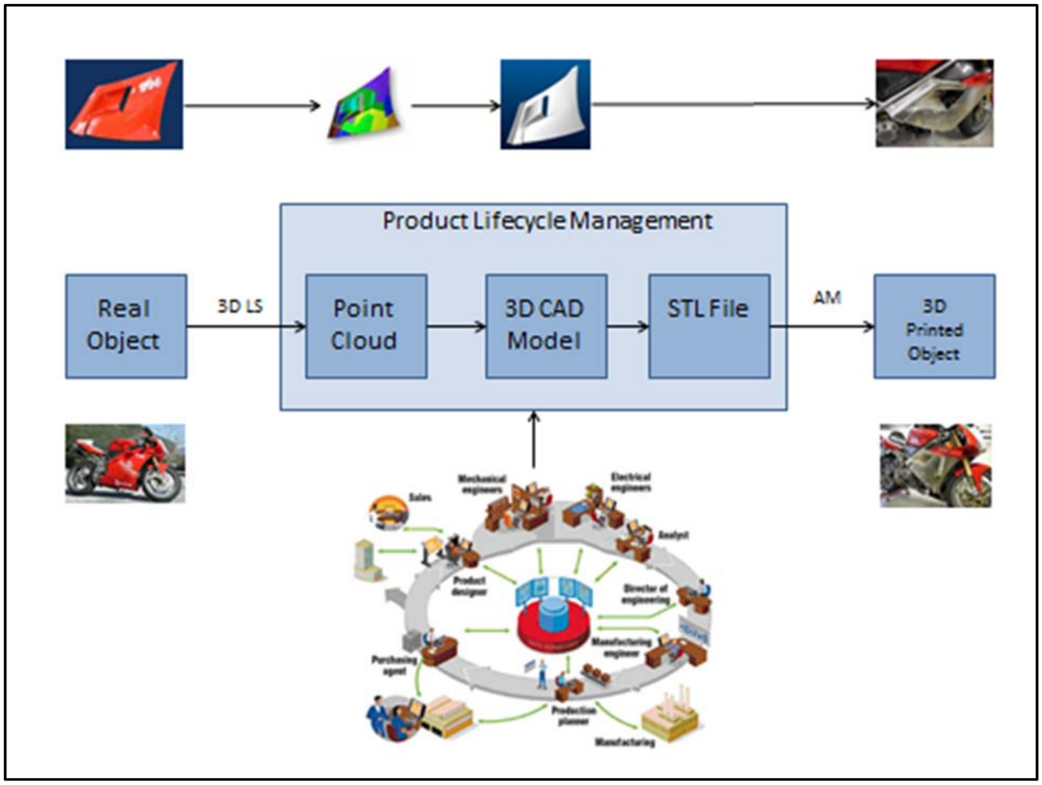

Figure 21. Technology Relation
(Based on Geomagic, 2013; Xavor, 2013)

The procedure begins with a real object. The object is then imaged using 3DLS to create a point cloud. Using CAD software, the point cloud can then be converted to a 3D model. Once the modeling is complete, the CAD file is converted into a Standard Tessellation Language (STL) file and can then be input into any 3D printer that reads the standard format. The output is a replicated real object. PLM facilitates and improves the entire process by increasing both the speed and accuracy because of collaboration, data sharing, and information management. In summary, although each of these technologies is beneficial and can deliver numerous improvements, they are far more powerful when used in conjunction with each other.

F. KNOWLEDGE VALUE ADDED METHODOLOGY

1. Measuring Performance

In the private sector, measuring the performance of an organization is relatively straightforward. Cost and revenue figures are readily available for organizations with appropriate accounting processes, so metrics such as return on investment (ROI) can be fairly simple and effective means for measuring performance. On the other hand, public sector organizations, such as the military, only have cost figures available because there is generally no revenue stream associated with the organization. This presents a problem, as there are no generally agreed upon metrics to measure how well an organization (e.g., a Navy shipyard) is performing other than how much it costs. A different method is needed to measure performance.

According to Housel and Bell (2001), all organizations use knowledge to create, build, and distribute products and/or services. These "knowledge assets" have a cost to acquire and also provide a value to the organization in the form of the output of a process or processes. If an organization can measure the cost of acquiring the knowledge to complete a process and determine the change between the input and output of that process, the value of the knowledge asset can be determined, and this knowledge metric can serve as a substitute for traditional performance metrics. In order to properly track and manage the impact of knowledge assets on value production, knowledge metrics must be based on quantifiable data that can be captured in a common unit of measurement (Housel & Bell, 2001). The knowledge value added (KVA) methodology provides this common unit of measurement.

2. KVA

The essence of KVA is that knowledge utilized in core processes is translated into numerical form (Housel & Bell, 2001). When done properly, KVA will measure the knowledge contained in processes, employees, and information technology systems and quantify the measurement in a return on knowledge (ROK) ratio. The ROK, which serves as a common unit of measurement for all processes, identifies how much value is added by the knowledge asset to the process. In addition, ROI can be determined if similar costs and benefits from the private sector, referred to as market comparable values, are available (Komoroski, 2005).

3. KVA Theory

KVA theory is based on the idea that all organizations collect input from various sources and transform those inputs to outputs. The value added during that transition is proportionate to the amount of transformation necessary to change the inputs to the desired output. The value added emerges from the organization's knowledge assets. A common unit of measurement, ROK, is derived by estimating this value using the knowledge inherent in organizational assets to describe process outputs. By this method, knowledge can be translated into a numerical format. Once the knowledge contained in processes can be valued, the processes can be reengineered to maximize value. Decision-makers can see the returns each process generates and drive better organization decision-making by utilizing this information (Komoroski, 2005). The assumptions underlying KVA are shown in Figure 22.

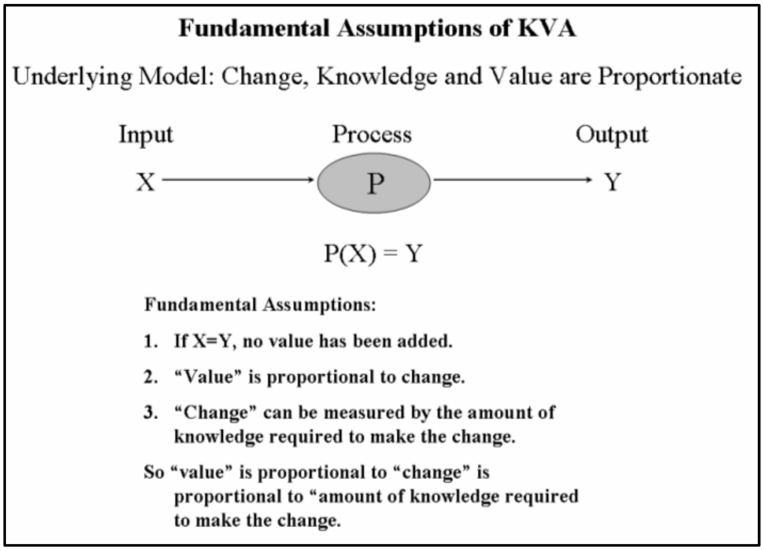

Figure 22. Fundamental Assumptions of KVA
(Housel & Bell, 2001)

By employing these assumptions, KVA can break all input down into a common unit of output, thus enabling the evaluation of all processes from a common baseline. This baseline evaluation, combined with how the data are collected, analyzed, and monetized (if desired), enables KVA to function much like accounting (Komoroski, 2005).

4. Core Process Identification

The first step to conduct a proper KVA analysis is to define the organization's core processes and the amount of change each process produces. This can be done by consulting work flow models, if they are available, or by interviewing subject matter experts (SMEs). For each of the identified processes, boundaries must be established by identifying the end output of the process, including all subprocess outputs that eventually create the end product. In addition, any contribution IT systems make to the process must be isolated (Komoroski, 2005).

5. Approaches to KVA

There are three primary approaches to apply KVA to a process, as displayed in Table 5 (Housel & Bell, 2001).

Table 5. Approaches to KVA
(Based on Housel & Bell, 2001)

Approaches to KVA		
Step	Learning Time	Process Description
1	Identify Core process and its subprocesses	
2	Establish common units to measure learning time	Describe the products in terms of the instructions required to reproduce them and select unit of process description
3	Calculate learning time to execute each subprocess	Calculate number of process instructions pertaining to each subprocess
4	Designate sampling time period long enough to capture a representative sample of the Core process' final product/service output	
5	Multiply the learning time for each subprocess by the number of times the subprocess executes during sample period	Multiply the number of process instructions used to describe each subprocess by the number of times the subprocess executes during sample period
6	Allocate revenue to subprocesses in proportion to the quantities generated by Step 5 and calculate costs for each subprocess	
7	Calculate ROK and interpret the results	

a. Learning Time Approach

For the learning time approach, an estimate of the amount of time it would take an average person to learn to execute a process satisfactorily is created to represent the amount of knowledge contained in that process. This approach relies on the assumption that learning time is proportional to the amount of knowledge learned. The estimate is referred to as actual learning time (ALT). The ALT estimate is derived by conducting SME interviews. After the interviewer has explained the KVA methodology and the ALT concept, the SME can generally be relied upon to provide a relatively accurate estimate based on formal training times, on-the-job training times, manual usage, and other training-related items. For the ALT to be accurate, knowledge must be counted only when it is in use and when it is truly necessary to execute the process (Komoroski, 2005).

Given that making ALT estimates is a subjective process, a method must be employed to ensure the reliability and confidence of the estimates. The preferred method of ensuring reliable estimates is to calculate the correlation between the ALT, ordinal ranking, and relative learning time (RLT) for each process (Housel & Bell, 2001). The ALT, ordinal ranking, and RLT are defined as follows:

- ALT: an estimate for the period of time it would take to teach an average individual to execute a given process. There is no limit to the amount of time required.
- Ordinal Rank: a measure of process complexity described as its difficulty to learn. SMEs or executives within an organization are asked to rank the processes in order from easiest to learn to the most difficult to learn.
- RLT: a measure of the time it would take to teach an average individual the core processes of an organization given only 100 hours, days, months, or other unit of time. SMEs or executives must allocate the time appropriately to each process with regard to that process's complexity. (Komoroski, 2005, p. 22)

A correlation between the three items of greater than or equal to 80% is considered sufficient to demonstrate that the estimate is reliable (Komoroski, 2005).

Once the amount of knowledge contained in a core process has been determined, the knowledge contained within the process' IT systems must be estimated. The best method for producing this estimate is identifying the percentage of the process that is automated. The percentage estimate of IT can then be used to calculate total learning time (TLT). After TLT is established, revenue can be distributed proportionally to determine the ROK (Komoroski, 2005).

b. Process Description Approach

In some circumstances, the process description approach should be conducted to gauge the reliability of learning time estimates. For this approach, SMEs must be asked to break down each core process into its various subprocess components and then to describe the instructions required to reproduce each subprocess. This captures the learning time required for each subprocess, which also indicates the knowledge contained therein. Like the learning time estimates, the knowledge being estimated for the process description must be counted only for the time it is being used and if it is necessary to execute the subprocess. Through summing the knowledge estimates for each subprocess, a useful estimate of the whole process knowledge emerges. This can then be compared to the ALT estimate to help establish credibility (Komoroski, 2005).

6. Knowledge Execution Measurement

In order to determine the ROK for a process, two values are required first. The number of times the knowledge is executed during a process serves as the process “value.” The time it takes to execute the process in a given sample period serves as the process “cost.” A flow-based estimate of the cost can then be produced by multiplying the actual time required to execute the process by the cost. The “value” figure is important, as referencing the process’ costs alone will present a different portrayal of a process’ true value (Komoroski, 2005).

7. Return on Knowledge

The ROK ratio is displayed in Equation 1:

$$ROK = \frac{Revenue\ \%\ allocated\ to\ knowledge\ required\ to\ execute\ a\ process}{Cost\ to\ execute\ process\ knowledge} \qquad (1)$$

The revenue in the numerator is allocated by comparing the knowledge used in the process in proportion to the total knowledge required to generate the organization’s total outputs. Because knowledge serves as a surrogate for the process outputs and is measured in common units, ROK can be used to compare differing processes. A higher ROK therefore indicates a process that better utilizes knowledge assets (Komoroski, 2005).

Using KVA to determine the ROK of an organization’s core processes gives decision-makers the ability to measure how efficiently a process converts existing knowledge into value. It also gives them a way to judge how investments in knowledge and learning are performing, instead of only being able to determine how much each investment costs. The ROK values allow decision-makers to determine how knowledge can be more effectively leveraged to improve performance (Komoroski, 2005).

G. KOMOROSKI’S RESEARCH

The baseline research this thesis evolved from was completed in 2005 by Christine Komoroski. Komoroski began by interviewing SMEs at the proof of concept planning shipyard, Puget Sound Planning Yard. In these interviews, she discovered seven core processes for planning shipyard availabilities (Komoroski, 2005). These processes are displayed in Figure 23.

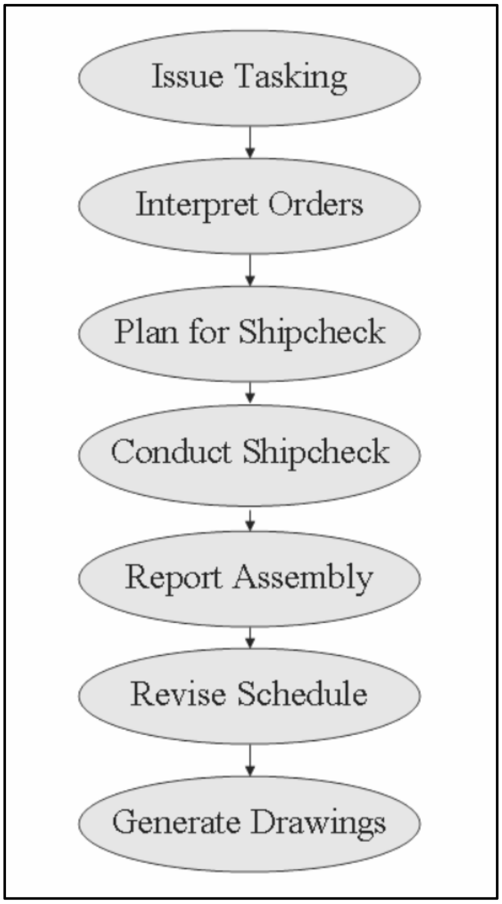

Figure 23. Core Shipyard Planning Processes
(Komoroski, 2005)

After the core processes of the proof of concept planning yard were known, Komoroski used the KVA methodology to analyze the planning yard process. The KVA analysis established an ROK for the current, or "as-is," process. Komoroski then modified the planning yard process to include 3DLS. She then conducted KVA analysis on this "to-be" scenario to determine the new notional ROK. In addition, she created a "radical to-be" scenario that included an integrated 3DLS and PLM implementation. Finally, Komoroski conducted KVA analysis on this scenario for another notional ROK. Komoroski's work showed that reengineered shipyard planning yard processes could shorten the duration of Navy ship availabilities and reduce the annual operating cost of government planning yards by more than $30 million (Komoroski, 2005).

H. EXPANSION OF KOMOROSKI'S RESEARCH

Komoroski's original research was extended to include an evaluation of PLM and 3DLS using real options (RO) analysis, which enabled risk mitigation and performance estimates. Komoroski, Housel, Hom, and Mun (2006) began by discussing the nature of portfolio management in the military and measuring value in the public sector. The authors then introduced and explained the KVA + RO methodology, which can be used to measure the value of intangible assets and the value added at the sub-corporate level. In addition, KVA + RO can provide risk mitigation and portfolio optimization.

Komoroski et al. (2006) initiated the research by interviewing SMEs at the proof of concept planning shipyard, Puget Sound Planning Yard, to gather data for a KVA audit. The authors conducted a KVA analysis on this data to establish the ROK for the "as-is" process. Once the "as-is" baseline scenario was established, the authors created a "to-be" scenario that included 3DLS and a "radical to-be" scenario that included 3DLS and PLM. The authors then conducted KVA analysis on each of the new processes for comparison to the baseline scenario. The results indicated a potential cost savings of nearly $37 million for the "to-be" scenario and potential cost savings of $40 million for the "radical to-be" scenario. After reviewing the results, the authors performed RO analysis to discover which scenario provided the highest total strategic value. The RO diagram is displayed in Figure 24.

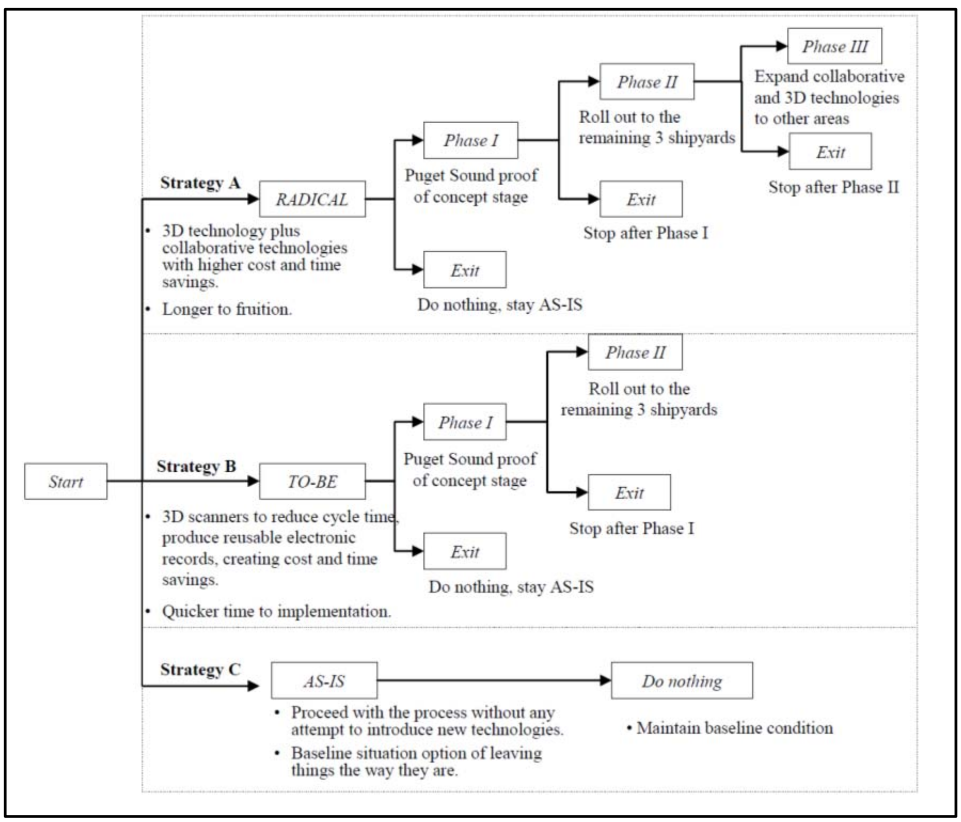

Figure 24. Real Options Analysis
(Komoroski et al., 2006)

The authors' analysis showed that 3DLS and PLM could greatly improve the productivity of Navy shipyard processes. This research also demonstrated the effectiveness of KVA + RO as a decision support tool by providing a method to compare the costs and benefits of a current situation with a hypothetical scenario that includes a proposed technology (Komoroski et al., 2006).

I. SEAMAN'S RESEARCH

Seaman (2007) expanded upon Komoroski's work by applying the KVA methodology to Phases IV and V of SHIPMAIN. He began his research by mapping the core planning process described by Komorski to the "blocks" that comprise Phases IV and V of SHIPMAIN as shown in Figure 25.

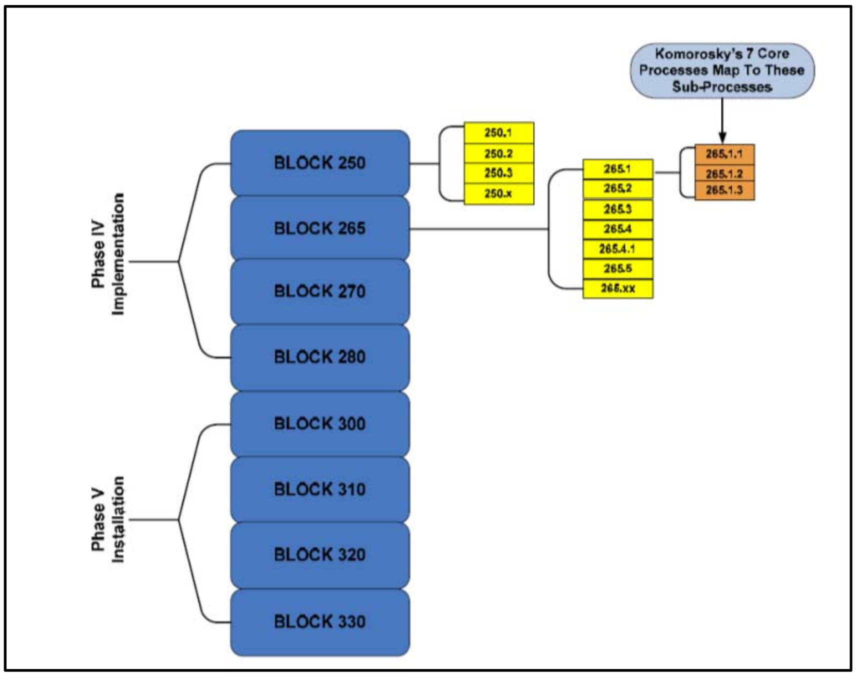

Figure 25. Komoroski's Core Processes Mapped to Phase IV and V Processes
(Seaman, 2007)

Seaman then used this knowledge to enhance his interviews with SMEs in order to collect knowledge audit data on the eight core processes of Phases IV and V, as shown in Figure 26.

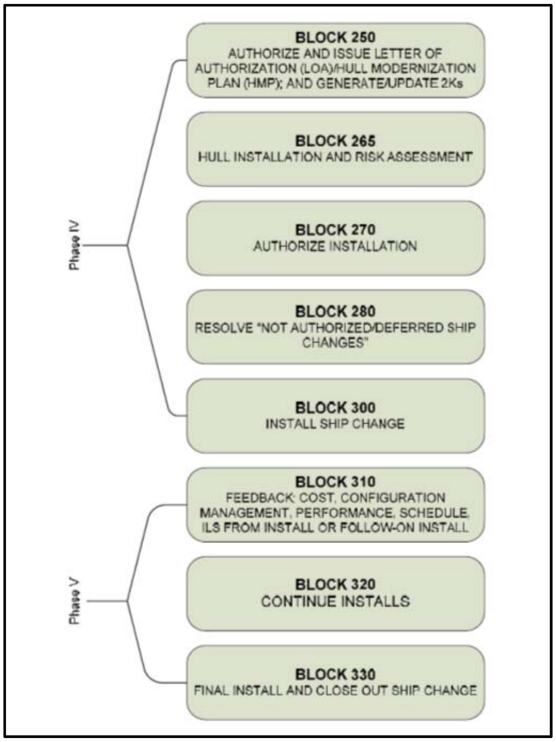

Figure 26. Phase IV and V Core Processes
(Seaman, 2007, p. 33)

Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

After he completed the knowledge audit, Seaman conducted a KVA analysis on the collected data to generate a baseline ROK for the "as-is" process. Once a baseline process and ROK were established, he modified the baseline process to utilize 3DLS and PLM technologies. KVA analysis was then conducted on the "to-be" scenario to determine the new notional ROK that would be generated by using 3DLS and PLM in the process. The results indicated that modifying the process to take advantage of the two technologies would produce an estimated savings of $78 million (Seaman, 2007).

J. FORD, HOUSEL, AND MUN'S RESEARCH

Ford, Housel, and Mun (2011) expanded upon previous research by adding system dynamics (SD) and integrated risk management (IRM) to the KVA framework for evaluating the implementation of PLM and 3DLS to SHIPMAIN Phase IV. The KVA + SD + IRM framework extends beyond the performance measure of KVA by including the measurement of cost-effectiveness, return on investment, risk quantification, strategic RO (capturing strategic flexibility), and analytical portfolio optimization. The authors began by discussing the baseline research for this analysis, the research done by Komoroski et al. (2006) and Seaman (2007). The “as-is” KVA analysis in Seaman’s research was used for the “as-is” scenario in this research and provided the inputs for the SD model (Ford et al., 2011). The authors then used the SD model to estimate the cost savings from implementing PLM and 3DLS and validated the model to ensure it produced realistic results. After validating the model, the authors used the results of the KVA + SD to conduct an IRM analysis, which provided risk analytics and portfolio optimization data. The IRM analysis indicated that either phased implementation or rapid implementation of PLM and 3DLS would deliver significant benefits to the Navy. The authors concluded that implementing PLM and 3DLS should generate approximately $550 million in cost savings over the current approach and there was no logical rationale to delay implementation (Ford et al., 2011).

K. KENNEY’S RESEARCH

Kenney (2013) began his research by conducting interviews with SMEs at Fleet Readiness Center (FRC) Southwest in San Diego, CA. During these interviews, he discovered the seven core processes of repair part manufacturing, as displayed in Figure 27.

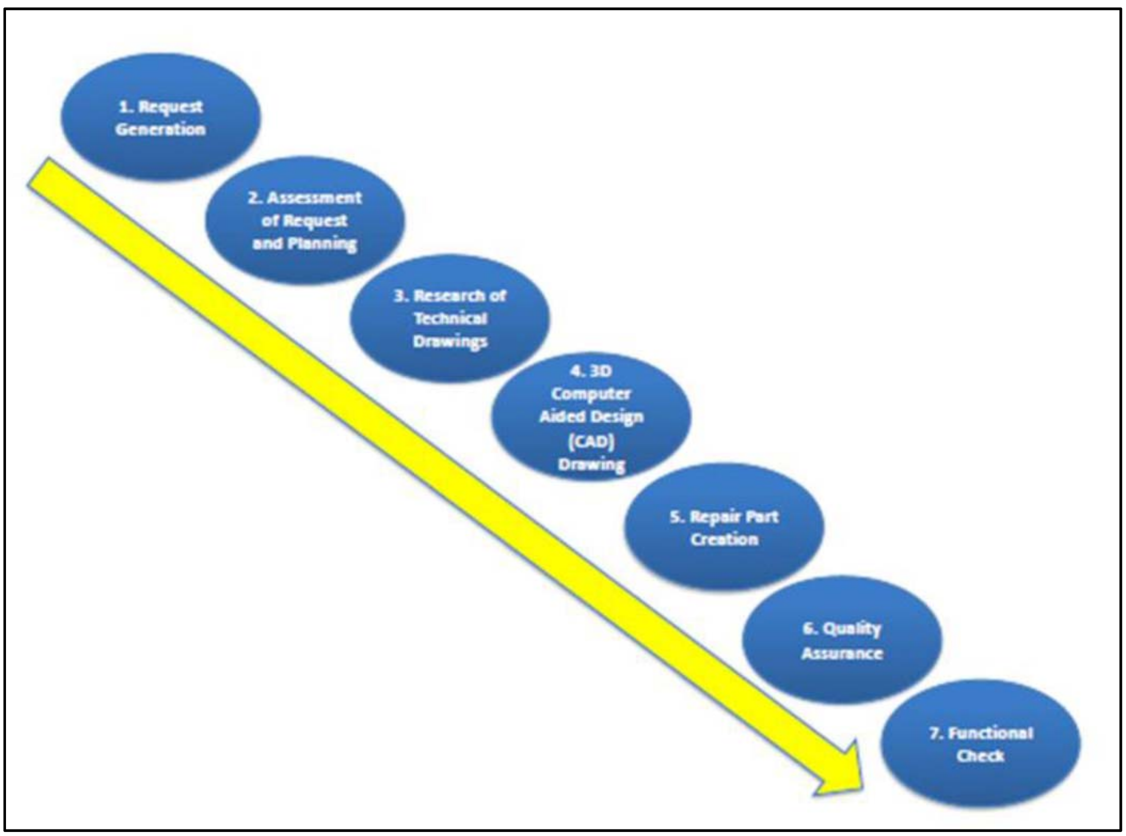

Figure 27. Repair Part Manufacturing Process
(Kenney, 2013)

After the core processes of the repair part manufacturing process were known, Kenney used the KVA methodology to analyze the manufacturing process. The KVA analysis established an ROK for the “as-is” process. Kenney then modified the manufacturing process to include additive manufacturing. KVA analysis was then conducted on this first “to-be” scenario to determine the new notional ROK. In addition, he created a second “to-be” scenario that included implementation of PLM and a third “radical to-be” scenario involving an integrated mature additive manufacturing and PLM implementation. KVA analyses for notional ROKs were conducted on these scenarios as well. Kenney’s work showed that reengineered manufacturing processes could save the Navy up to $1.47 billion per year (Kenney, 2013).

III. METHODOLOGY

A. INTRODUCTION

The model for Phases IV and V of the SHIPMAIN process was based on the research of Seaman (2007). He created his model using data gathered from subject matter expert (SME) interviews of personnel at Naval Sea Systems Command, type commands, various shipyards, Office of the Chief of Naval Operations and Space and Naval Warfare Systems Command. Seaman's model is the basis for the "as-is" model used in this research. Since the official guidance for this process has not changed since Seaman's research was conducted, the model should be accurate once the monetary values involved are updated to reflect 2013 dollars. Parts of the "to-be" models are based off of Seaman's research, as his "to-be" model includes implementation of PLM and 3DLS technology. The main portion of the "to-be" models, specifically the implementation of 3D printing technology, is based on Kenney's research (2013). He created his "to-be" process using data gathered from SME interviews and process analysis of the operations at FRC San Diego. The SME he interviewed had extensive experience in both the 3D printing industry and Navy depot-level maintenance.

The "as-is" model for this research reflects the costs (in 2013 dollars) and process executions of Phases IV and V of SHIPMAIN. The KVA methodology is then applied to analyze the effects of implementing 3D printing, PLM, and 3DLS technologies into the process. This is divided into a "to-be" model of 3D printing implementation only and a "radical to-be" model of 3D printing, PLM, and 3DLS. If the implementation of these technologies has a positive effect on the SHIPMAIN process, it will be demonstrated through increased ROK values and decreased cost estimates. If there is a negative effect, ROK values will remain stable or drop, and cost estimates will rise. These figures are shown as a comparison of the current "as-is" scenario to the "to-be" scenario using defendable future process estimates.

B. "AS-IS" DATA COLLECTION

Seaman (2007) collected the aggregate "as-is" baseline data during an initial KVA knowledge audit via a survey and group interview at the Washington Navy Yard. Three SHIPMAIN SMEs were present at the group interview, and all had expertise related to the SHIPMAIN process. Each SME had over 30 years of experience in the shipyard industry. Also included in the knowledge audit was an SME with recognized expertise in the area of cost estimation. The cost estimation process flow model developed from the business rules of the SHIPMAIN process guided the interviews and surveys.

1. KVA Learning Time Method

For his analysis of the audit data, Seaman (2007) utilized the KVA learning time method. The core processes of SHIPMAIN Phases IV and V were established via a thorough review of current SHIPMAIN business rules and discussions with SMEs. The input and output of those processes and the frequency of the core process iterations were also established. Boundaries were defined between the processes in order to effectively apply the KVA methodology and to properly evaluate the knowledge required for each. Eight core processes were identified, and detailed descriptions of each were provided by SMEs and the SHIPMAIN business rules. Each core process requires a certain level of knowledge in one or more of the following areas: administration, management, scheduling, budgeting, basic computer skills, engineering, shipboard systems, logistics, or project management.

The SMEs provided actual learning time (ALT) estimates for the amount of knowledge embedded in each core process. The established baseline level of knowledge for consideration was a GS-13 employee with one year of experience and a college degree (no field specified). Finally, the team of SMEs provided individual and uninfluenced relative learning time (RLT) and rank order estimates. A comparison of the various estimates revealed a correlation of greater than 80%, which indicated a high level of reliability for the obtained estimates. Additional discussions led to a group conclusion that SHIPMAIN process Blocks 265 (Hull Installation and Risk Assessment) and 300 (Install Ship Change) were equivalent in complexity. An adjustment of the RLT and rank order reflecting that conclusion increased the correlation to greater than 90% across the data fields (Seaman, 2007).

C. DEFINED PROCESSES

The business rules for Phases IV and V of SHIPMAIN describe eight core processes, referred to as *blocks*, which encompass the implementation and installation of an approved ship change (SC). Each block has an official title to reference the core process it accomplishes, as shown in Figure 28 (Seaman, 2007).

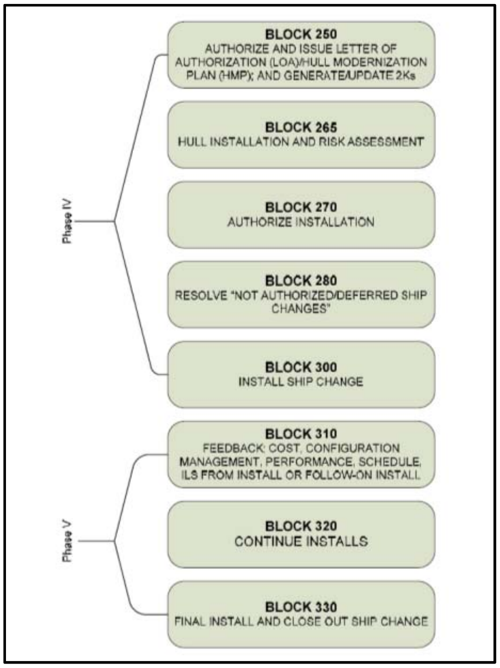

Figure 28. Phase IV and V Core Processes
(Seaman, 2007, p. 33)
Note. This figure originally appeared in the *Surface Ship and Carrier Entitled Process for Modernization Management and Operations Manual* (SL720-AA-MAN-030 ed.).

These core processes are executed for each naval vessel as it approaches, enters, and completes a shipyard availability period. The scheduled timeline and location for a shipyard availability is established by Navy leadership far in advance, but calendar dates and work assigned may be constrained by budget allowances and other prioritization factors. Availability schedules may be affected if world events trigger an unanticipated demand for operational naval assets (Seaman, 2007).

D. "AS-IS" ASSUMPTIONS

The following assumptions were made for this scenario:

1. Number of Employees

The number of employees value used for the model represents the number of employees assigned to complete the given process for each cycle or iteration. The numbers assigned were based on interviews with SMEs. Accounting for the number of personnel involved in each process provides a way to determine how often knowledge is used. In addition, it provides an approximate way to weight the cost of actual work-time in each process (Seaman, 2007).

2. Times Performed in a Year

Estimations for the number of times each process is executed per year were based on the aggregate number of occurrences for each process. The number of times performed value for Blocks 265 to 330 was based on the number of installations of maintenance or modernization items. The number of times performed value for Block 250 was based on the number of availability periods. The Navy Data Environment (NDE) database was queried using filters to gather the raw data for ship alterations for Atlantic and Pacific surface force ships from FY 2002 through FY 2007.

The data were queried in this manner to establish a five-year average of maintenance or modernization availability periods for all surface combatant ships to include aircraft carriers. The results of the query indicated an average of 1,200 availability periods occurred each year. This number was conditionally modified to take the complexity of installs during availability periods into consideration. For example, an availability period to conduct routine software upgrades would have a low complexity, while an availability period to modernize a Ticonderoga class cruiser would have a high complexity. To provide a reasonable scope, the availability periods were considered to be simple for 25% of instances, complex for 25% of instances, and moderate for 50% of instances. The 600 moderately complex installations frame the scope of this model. The number of times performed value for the remaining blocks was based on the number of installations that occurred. For each installation that occurred, a Ship Change Document (SCD) was generated and the number of SCDs provided a reliable proxy for the number of installations. SMEs provided data and analysis, which indicated that an average of 20 SCDs were initiated per week, which was extrapolated to 1,040 SCDs generated annually. After applying the same conditional modifier to account for complexity, 520 SCDs frame the scope of this model (Seaman, 2007).

3. Actual Learning Time

In order to determine the ALT from a common point of reference, the SMEs were instructed to imagine a baseline individual of a college graduate at the GS-13 civilian rank level with a year of experience in some sector of the shipyard industry. All experts understood that each process learning time estimate must adhere to the basic assumptions that knowledge is only counted if in use, and the most succinct path to achieve a unit of output must be considered. Each core process was broken down into its component subprocesses, and respective ALT values were assigned for each subprocess. The final ALT value for each core process was created by summing the subprocess ALT estimates. Finally, all ALT values were based on the following time assumptions (Seaman, 2007, p. 36):

- One year = 230 work days
- One month = 20 work days
- One week = 5 work days
- One day = 8 hours

4. Determining Value

In order to determine the ROK/ROI for a process, the value of the process must first be estimated. Each process contains a level of process automation ranging from zero to 100%. The amount of automation is a proxy for how much knowledge is embedded in the IT systems supporting the automation. It is important to estimate how much of each process is automated in order to account for the knowledge embedded in the technology resources. The total learning time (TLT) is calculated by dividing the ALT by the percentage of process automation for that process. The TLT value is then multiplied by the number of employees and the number of times the process is performed per year to establish a total knowledge factor. The total knowledge factor is then multiplied by a price per common unit, based on market comparables, to derive the “benefits” or “value” of each process. The resulting product is then used as the numerator for determining ROK and ROI (Seaman, 2007).

5. Cost Estimation

After the value of a process is estimated, the costs associated with that process must then be estimated in order to generate an ROK/ROI figure. To estimate the cost of government employees involved in the processes, Seaman (2007) utilized the 2007 civilian pay chart. For this research, the numbers are updated to reflect the 2013 civilian pay chart. Each civilian pay grade has associated “steps” to account for various unique factors of each job. All pay estimates are based on Step 6 of the associated pay grade. Since the processes take place across the globe, no locality pay differentials were taken into consideration to minimize variation. Also, because basic computing hardware and software is utilized in every scenario, IT costs were not included in the “as-is” analysis. It is assumed that each employee in this process has an email account, laptop or desktop computer with identical software, and access to a printer. Material, travel, and other miscellaneous costs were not included in this analysis to isolate the labor cost.

Establishing a market comparable for government labor was accomplished by comparing the pay of contractors who conduct the same type and scope of work as the government employees. The contracted base pay was on average 35% higher than the government employees. Only the base pay for government employees was considered to establish this rate. Benefits, locality pay differential, and other variables were not included. All government employee rates were increased by 35% to achieve the values for the market price used to establish a price per common unit of output (Seaman, 2007).

6. Key Assumptions

This analysis is based on information collected from previous research by Seaman (2007), SMEs, related research, and existing data in the NDE and current directives. For the purposes of this research, all maintenance and modernization efforts are assumed to occur as described in the current business rules listed in the Surface Ships and Carriers Entitled Process for Modernization (SSCEPM). In addition to the previously listed assumptions, the following assumptions were made:

- Of the 1,200 annual modernization and maintenance availability periods, 25 percent involve low complexity installations, 25 percent involve high complexity installations, and 50 percent involve medium complexity installations. The scope of this research is limited to only the medium complexity availabilities.
- On average, 20 SCDs are generated per week.
- The market comparable labor rate is 35 percent greater than the government labor rate.
- Price per common unit of output is $79.13. (Seaman, 2007, p. 38)

E. "TO-BE" DATA COLLECTION

Via a combination of data from the "as-is" analysis and the data from Kenney's (2013) research, this scenario represents the reengineered SHIPMAIN processes when 3D printing is applied. Kenney (2013) collected the data used for this research's "to-be" model during a KVA knowledge audit at FRC San Diego. The information used in the creation of his KVA models was generated from the SME-provided data. The SMEs possessed extensive experience working within Navy depot-level maintenance activities. Each SME had more than 15 years' experience in manufacturing technology in either military or commercial industries. After acquiring the data necessary to form an "as-is" model for part production, Kenney then used the information gathered during SME interviews to reengineer the process to include 3D printing to form his "to-be" model. The analysis he performed is generalized in this research to reflect the part production process at Navy shipyards instead of FRCs.

1. Learning Time Method

For his analysis of the audit data, Kenney (2013) utilized the learning time method. The core processes of depot-level repair part manufacturing were established via discussions with SMEs. Seven core processes were identified, and detailed descriptions of each were provided by the SMEs.

The SMEs provided ALT estimates for the amount of knowledge embedded in each core process. The established baseline level of knowledge varies for each process and is described in detail in the next section. Finally, the team of SMEs provided individual and uninfluenced RLT and rank order estimates. A comparison of the various estimates revealed a correlation of greater than 90%, which indicated a high level of reliability for the obtained ALT figures (Kenney, 2013).

F. DEFINED PROCESSES

In his interviews with SMEs, Kenney (2013) established seven core processes for part manufacturing, as described in the literature review. This notional process is performed each time a repair part is created at a manufacturing shop. The following is a description for each of the core processes.

1. Request Generation

The depot-level activity (DA) receives a request from the operational unit. This request can go to any DA decision-maker, who then takes an average of two hours (+/- five minutes) to evaluate and decide how the part is going to be acquired. If the part is within the stock system, the DA issues the part to the unit. If not, the DA issues an order to the appropriate production facility to produce the part (henceforth referred to as Widget A; Kenney, 2013).

2. Assessment of Request and Planning

Production management receives the order from the DA. After receipt of the order, a meeting with tech librarians, engineers, machinists, quality assurance (QA) inspectors, and mechanics is convened to assess the feasibility of creating the repair part. If part creation is feasible, assignments and duties are generated to create the part. This meeting can last for two hours (+/- 15 minutes; Kenney, 2013). It is assumed for the purposes of this model that meeting attendees are only talking about Widget A and not assessing any other repair parts. Following this meeting, the production management sends a response to the DA and, if the part can be created, begins the in-house production process.

3. Research of Technical Drawings

The tech librarian reviews the applicable repository for any tech drawings of Widget A. If none are found, the tech librarian contacts the original equipment manufacturer (OEM) and other DAs to find out whether the tech drawing is available. If a 3D computer numerical control (CNC) tech drawing is found, the tech librarian delivers it to the machinist for production. At this point, the assumption is that the engineer does not need to make changes or modifications to the tech drawing. If no tech drawing is found, the tech librarian confers this information to the engineer. This process takes four hours (+/- 30 minutes; Kenney, 2013).

4. 3D Computer-Aided Design Drawing Creation

The engineer, when notified that the tech drawing is not CNC ready, makes a decision on how to generate the file for the machinist. The engineers have the option of either creating the tech drawing utilizing CAD (16 hours, +/- one hour) or, if the physical part is available, performing a 3D scanning process and generating a CAD file (eight hours, +/- 15 minutes). For this physical part, it is assumed that an example of Widget A is provided by a source for the use of modeling. Upon completion of a CAD file, the engineer delivers it to the machinist. Further down the process, there are two instances that could trigger "rework" activity. The first is if Widget A fails a QA inspection, and the second is if it fails the functional check activity. If rework occurs, the process takes two hours (+/- 60 minutes), and it is assumed that the engineer is performing adjustments to the CAD based on the input that the QA inspectors or mechanics provided (Kenney, 2013).

5. Repair Part Creation

The machinist, upon receipt of the CAD file, uploads it into the respective CNC machine and begins the subtractive manufacturing process. It is assumed here that the machinist understands the CAD file and does not have questions for the engineer. This process takes 12 hours (+/- 30 minutes) and results in a finished product, which is delivered to QA for inspection (Kenney, 2013).

6. Quality Assurance

QA takes Widget A and conducts the inspection in accordance with Navy standards on a computer measuring machine. The process takes 10 hours (+/- 60 minutes), which results in either the part passing or failing (Kenney, 2013). If the part fails, it is sent back to the engineers for rework and proceeds through the process cycle again. If the part passes, it is sent to the mechanics.

7. Functional Check of Repair Part

Upon receipt of Widget A, a group of three mechanics performs a functional check by installing the repair part. The process takes 12 hours (+/- 60 minutes) and results in either passing or failing the functional check. If the functional check activity results in a failure, the repair part is sent back to the engineers with adequate descriptions for the rework process. If the part passes, the process ends with the completed part delivered to the unit (Kenney, 2013).

G. "TO-BE" ASSUMPTIONS

The following assumptions were made for this scenario:

1. Employees

The number of employees value for this reengineered model represents the number of personnel needed to manufacture one repair part. From the number of personnel utilized within the process, the total amount of knowledge available was calculated (Kenney, 2013).

2. Time Calculation to Create a Repair Part

From interviews with SMEs at a DA, it was estimated that around 27,000 repair parts are produced each year by about 400 employees (Kenney, 2013). The range of these parts extends from very simple, low-complexity parts that are generated quickly to highly complex parts that require significantly more time to produce. It is this type of complex part that was used to support the modeling within this research because of the assumption that modeling the most complex parts that can be generated supports a more conservative approach for estimation. The DA produces about 5,000 of these highly complex parts each year, approximately 19% of the total output per year. Given this estimate and using the modeling software, it takes approximately 39 man hours to complete a single repair part.

3. Actors and Actual Learning Time

The "to-be" process model involves seven actors: DA decision-makers, production management, tech librarians, engineers, machinists, QA, and mechanics. The information about the actors was provided through interviews with SMEs, and the assumptions were generated based on those interviews (Kenney, 2013). For the purposes of this research, all actors, with the exception of DA decision-makers, belong to the same organization and reside within one shop/building. The workers identified here work an eight-hour day in a shop that operates only one eight-hour shift, 230 work days a year. Assumptions about the actors' roles and hourly rates were generated from interviews with SMEs. Hourly rates were derived from U.S. government general schedule (GS) and wage grade (WG) pay scales and determined based on the average employee within that particular function. Locality and special pays are not factored in, all hourly rates are based on hourly basic rates by grade and step, and no overtime rates are included. Private-sector wage comparisons, when calculated, are measured at 50% more per hour (1.5 × calculation). The following are the assumptions for each actor, taken from Kenney (2013):

- <u>DA decision-maker</u>: determines that the repair part generation is too cost prohibitive to utilize OEM and makes the decision to utilize production resources to generate the part. This person has a minimum of a bachelor's degree and three years' experience in the position. He or she is a GS-11, Step 5, and earns an hourly rate of $27.31 per hour.

- Production management: receives the request from the DA, then confers with all members involved in the repair part generation to calculate feasibility. This person issues assignments and assigns personnel involved with the repair part generation. He or she is a GS-12, Step 5, and earns an hourly rate of $32.73.
- Tech librarian: responsible for maintaining the library of technical diagrams (tech drawings) for parts and researching in-house databases. This person possesses on-the-job training (OJT), is a GS-6, Step 5, and earns an hourly rate of $16.60.
- Engineer: responsible for the creation of tech drawings utilizing blueprints, two-dimensional (2D) CADs, or 3D CADs. This person holds a degree in engineering with five years' experience. He or she uses his or her own choice of CAD software and is highly proficient. This person is a GS-11, Step 5, and earns an hourly rate of $27.31.
- Machinist: responsible for creating the repair part utilizing available manufacturing machinery located within the shop. This person has been trained through technical schooling and holds certificates of training for the machines utilized from the manufacturer. He or she is a WG-9, Step 5, and earns an hourly rate of $25.70.
- QA inspector: responsible for inspection of created repair parts generated by the machinist against industry and government standards. He or she has an average of six years' experience, is a GS-9, Step 5, and earns an hourly rate of $22.57.
- Mechanic: responsible for the installation and testing of repair parts. This person's training was completed by a technical school and is certified to perform maintenance. He or she has an average of 10 years' experience, is a WG-8, Step 5, and earns an hourly rate of $24.25. (pp. 43–44)

ALT is the amount of time required in order for a worker to perform a particular function. For example, in the case of the QA inspector, in addition to the training required to become certified as a QA inspector, this individual has to undergo specific training on computer measuring machines in order to operate them, comprehend and interpret results, and generate reports. This training time takes 100 hours of additional training, so 100 hours are used for ALT with regard to QA inspectors. In addition, the knowledge utilized per function is counted only if it is actually used to produce a unit of output (Kenney, 2013).

4. Determining Value

Each function within the process of making a repair part involves a percentage amount of IT, ranging from 0% to 100% (Kenney, 2013). This percentage (%IT) represents the amount of knowledge embedded within that function because of the IT supporting it. Measuring the amount of embedded IT is important to account for the IT resources involved in the process and to make consistent, conservative estimates. Utilizing the %IT is required to calculate the TLT. When calculating TLT for instances of low-percentage IT enablers (< 60%), ALT is added into the multiplied output of ALT x %IT. High %IT is considered to be any function that has greater than 60% IT and utilizes ALT+(ALT/(1-%IT)) in order to calculate TLT.

5. Key Assumptions

The data gathered for this research were based on interviews with SMEs, related research, and current information about Navy maintenance activities. From this, the following assumptions were made (Kenney, 2013):

- The cost is calculated using the 13 actors involved with repair part production.
- The market-comparable labor contractor rate is 50% greater than the current government labor rate.
- The cost of the materials to produce the parts, the cost of machinery and IT assets, and infrastructure cost (e.g., electrical) are not included.
- Through the development of a prototype part, communication will improve between engineers, machinists, mechanics, and QA actors.
- Engineers are responsible for printing out the prototypes from the 3D printers.
- The conceptual output provided by 3D printers will reduce the amount of time for each following actor to complete his or her portion of the process. For example, machinists will be able to better orient the CAD model on CNC machines, reducing support structures and finishing times.
- Feedback for the design that is provided to the engineers will be beneficial to the end-result product. For example, mechanics will be

able to fit test the prototype to ensure that the part to be generated does not have to be modified after creation.

- 3D printers can only produce prototypes of repair parts; they cannot produce actual repair parts.

H. "RADICAL TO-BE" SCENARIO

This scenario reflects the reengineered SHIPMAIN process if mature 3D printing processes, PLM, and 3DLS were implemented in an integrated manner. The data in this scenario involve a combination of analysis from both Seaman's and Kenney's respective research, as well as data from research in related materials.

1. PLM and 3DLS Assumptions

The assumptions for this research's "radical to-be" model include the assumptions made in Seaman's (2007) "to-be" model. The "radical to-be" model uses the following assumptions:

- A conservative estimate of 20% greater efficiency is applied to the times fired per year for SHIPMAIN Blocks 250.1 (Create the advanced planning hull maintenance plan/execution planning hull maintenance plan [AHMP/EHMP]) and 250.3 (Initiate 2Ks into the integrated class maintenance plan [ICMP]) because of automation.
- There are 17 unique tasks involved in SHIPMAIN Block 265.1 (Installation Procurement, Design & Advance Planning).
- The 15 employees required for the ship check task of SHIPMAIN Block 265.1 do not use the entire time allotted to complete the process. The 15 ship check employees are notionally reallocated to remaining tasks of a similar pay grade.
- Two additional employees are required to accomplish the 17 tasks in SHIPMAIN Block 265 (Hull Installation and Risk Assessment).
- SHIPMAIN Block 265 cycle-time will improve by a conservative estimate of 20% with the addition of PLM and 3DLS. PLM will allow suppliers and purchasers to share requirements and plan for delivery in a real-time Integrated Data Environment. 3DLS will provide more accurate design parameters to suppliers than hand-drawn images reducing the amount of "field engineering" required.
- SHIPMAIN Block 280 (Update HMP, LOA and Fielding Plan) will become more efficient when it is accomplished with PLM tools because the personnel involved will have access to all documents and

process owners in a collaborative environment. To account for the increased efficiency, cycle-time was reduced by two days.

- The majority of management and verification tasks in SHIPMAIN Block 300 (Complete Installation and Testing) will be accomplished by 30% fewer staff because of collaboration and access to a common data environment provided by PLM.
- SHIPMAIN Block 300 cycle-time will improve by 20% because of improved coordination between suppliers and the shipyards and less rework because of installation items being built more accurately from the 3D imagery provided of the as-built configuration.
- PLM will enable a 50% reduction in staff for SHIPMAIN Block 310 (Provide Feedback Data) by having all related information available through a single interface.
- The time to complete the tasks for SHIPMAIN Block 310 will be reduced by 75% by eliminating lengthy manual data collection and aggregation.
- SHIPMAIN Block 310 will be executed 20% more often annually.
- SHIPMAIN Block 320 (Determine Impact on Future Installs From Feedback in 310) is supported by accurate and timely information available through PLM. A conservative estimate of 20% less time to complete the task was applied.
- For SHIPMAIN Block 330 (Verify all SCs Have Been Completed), the PLM product would place all verification items into a virtual environment accessible through a single interface, leading to a 20% reduction in time to complete the task (Seaman, 2007).

2. 3D Printing Assumptions

The assumptions for this research's "radical to-be" model include the assumptions made in Kenney's (2013) "radical to-be" model. The "radical to-be" model uses the following assumptions:

- The benefits from the "to-be" model remain in place.
- The following costs are not included: the cost of the materials to produce the parts, the cost of machinery and IT assets, and the infrastructure cost.

- All depot and intermediate level maintenance activities have populated the PLM repository with 3D CAD technical drawings that they have obtained through OEM resources or by in-house production.
- The 3D CAD technical drawings are valid, meaning that they are uncorrupted files that can be utilized by engineers and machinists.
- The cost of purchasing and implementing PLM software is already accounted for.
- 3D printers print out ready-to-use parts.
- Machinists will be able to directly retrieve the CAD files from PLM and will print out the parts from 3D printers rather than getting them from engineers.

Tech librarians are no longer required because the machinists will be able to retrieve the CAD files.

IV. METHODOLOGY PROOF OF CONCEPT

A. "AS-IS" ANALYSIS

A summary of the high level "as-is" KVA analysis is shown in Table 6. These estimates were compiled from Seaman's (2007) data and updated to reflect 2013 pay scales according to the methodology and assumptions in Chapter III.

Table 6. "As-Is" SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	9	$24,106,285	$5,685,864	424%	324%
Block 265	Hull Installation and Risk Assessment	44	$101,168,745	$138,454,222	73%	-27%
Block 270	Authorize Installation	4	$26,334,597	$3,294,087	799%	699%
Block 280	Resolve "Not Authorized/Deferred SC	1	$3,950,190	$663,192	596%	496%
Block 300	Install SC	46	$100,949,290	$43,481,880	232%	132%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	2	$1,975,095	$663,192	298%	198%
Block 320	Continue Installs	5	$4,937,737	$3,284,846	150%	50%
Block 330	Final Install, Closeout SC	1	$987,547	$331,596	298%	198%
			$264,409,487	**$195,858,879**	**135%**	**35%**

1. Block 250 Analysis

Table 7 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 250.

Table 7. As-Is" Analysis of Block 250

Block 250 Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
250.1	Create AHMP/EHMP	$45.45	1	40	75%	96000	$7,596,518	$1,090,683	696%	596%
250.2	Create Annual HMP/LOA	$45.45	1	40	75%	153600	$12,154,430	$2,181,365	557%	457%
250.3	Initiate 2Ks into ICMP	$38.22	3	40	0%	49920	$3,950,190	$2,384,731	166%	66%
250.x	Generate/issue QISM	$45.45	4	40	90%	5120	$405,148	$29,085	1393%	1293%
				Process Totals:			**$24,106,285**	**$5,685,864**	**424%**	**324%**

According to Seaman's (2007) SME interviews, Block 250 is primarily a low-cost management activity with few involved employees. In addition, this process contains a large percentage of automation, which enables a small number of people to execute the process many times. The high automation and low number of personnel lead to high ratios of ROK and ROI.

2. Block 265 KVA Analysis

Table 8 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 265.

Table 8. "As-Is" Analysis of Block 265

Block 265 Hull Installation and Risk Assessment										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
265.1	Installation Procurement, Design & Advance Planning	$45.87	35	160	25%	970667	$76,809,243	$133,579,889	58%	-42%
265.2	Hull Installation Readiness Review	$31.88	2	40	80%	208000	$16,459,123	$1,326,384	1241%	1141%
265.3	Evaluate Maturity Status	$53.70	1	20	0%	20800	$1,645,912	$558,503	295%	195%
265.4	Provide Risk Assessment	$53.70	1	40	0%	29120	$2,304,277	$1,117,005	206%	106%
265.4.1	Formally Propose Install for Readniess Assessment and Auth.	$53.70	1	20	0%	20800	$1,645,912	$558,503	295%	195%
265.5	Risk/Readiness Determination	$63.17	4	40	0%	29120	$2,304,277	$1,313,938	175%	75%
				Process Totals:			**$101,168,745**	**$138,454,222**	**73%**	**-27%**

According to Seaman (2007), SMEs evaluated this block as the most complex. It involves management and operational tasks that require significant knowledge assets, a large budget, and significant manpower.

3. Block 270 KVA Analysis

Table 9 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 270.

Table 9. "As-Is" Analysis of Block 270

Block 270 Authorize Installation										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
270	Installation decision	$79.18	4	20	85%	332800	**$26,334,597**	**$3,294,087**	**799%**	**699%**

According to Seaman (2007), Block 270 involves management decisions at the highest levels of the organization, typically the GS-15 or Senior Executive Service level, which involves few employees with substantial labor costs. This process has a high level of automation, which allows a small number of people to execute it often. The combination of automation and high benefits relative to cost lead to high ROK and ROI ratios.

4. Block 280 KVA Analysis

Table 10 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 280.

Table 10. "As-Is" Analysis of Block 280

Block 280 Resolve "Not Authorized/Deferred SC"										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
280	Update HMP,LOA and Fielding Plan	$31.88	1	40	75%	49920	**$3,950,190**	**$663,192**	**596%**	**496%**

According to Seaman (2007), Block 280 is primarily a managerial task. It involves a low number of employees at one of the lowest labor rates. The high level of automation, coupled with a low labor cost and high numbers of process execution, cause favorable ROK and ROI ratios.

5. Block 300 KVA Analysis

Table 11 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 300.

Table 11. "As-Is" Analysis of Block 300

Block 300 Install SC										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
300	Complete installation and testing	$45.45	46	40	25%	1275733	**$100,949,290**	**$43,481,880**	**232%**	**132%**

According to Seaman (2007), SMEs evaluated Block 300 as the second most complex process. Alterations are installed and tested during this process, which requires significant knowledge assets, a large budget, and significant manpower. This block has few management review subprocesses and is primarily focused on installation and testing. Due to the large number of times the process is performed per year, the cost is relatively low when compared to the benefits.

6. Block 310 KVA Analysis

Table 12 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 310.

Table 12. "As-Is" Analysis of Block 310

Block 310										
Feedback: Cost, CM, Performance, Schedule, ILS										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
310	Provide Feedback Data	$31.88	2	20	0%	24960	**$1,975,095**	**$663,192**	**298%**	**198%**

As shown in Table 12, there is no automation for this process. According to Seaman (2007), raw feedback data are manually entered into the required forms and databases during this process.

7. Block 320 KVA Analysis

Table 13 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 320.

Table 13. "As-Is" Analysis of Block 320

Block 320										
Continue Installs										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
320	Determine impact on future installs from Feedback in 310	$63.17	5	20	0%	62400	**$4,937,737**	**$3,284,846**	**150%**	**50%**

According to Seaman (2007), Block 320 uses the feedback provided from Block 310 to determine potential impact on follow-on installs. This management-based process is a completely manual process.

8. Block 330 KVA Analysis

Table 14 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 330.

Table 14. "As-Is" Analysis of Block 330

Block 330										
Final Install, Closeout SC										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
330	Verify all SCs have been completed	$31.88	1	20	0%	12480	**$987,547**	**$331,596**	**298%**	**198%**

According to Seaman (2007), all planned installations are reviewed to determine whether they have been completed during Block 330. This is accomplished by manually comparing planned installations against reported completions and verifying ILS completion/delivery for all installs. If all of the planned installs are complete and the ILS products are delivered, the SC can be closed out.

B. "TO-BE" ANALYSIS

This scenario represents a combination of estimated and verified data to portray the current activities contained in the SHIPMAIN process reengineered to maximize utilization of 3D printing technology. Not every subprocess will be affected in this scenario; instead, only affected processes will be used for comparison. All others may be assumed static as described in their "as-is" state.

1. Cost of Implementing 3D Printing Technology

For the purposes of this research, it is assumed that the 3D printer class required for shipyard operations is a production-level printer. The Stratasys Fortus 900mc is a production-level printer and will serve as the representative 3D printer for this research. Cost and assumptions for the Fortus 900mc are as follows:

- According to Beckhusen (2012), the current cost for the Fortus 900mc is $328,000. In order to make this a conservative estimate, that number will be raised to $400,000 to account for implementation, maintenance, and training costs.
- The use estimate is 200 days per year.
- The lifespan estimate is 10 years.
- For analysis of the "to-be" model, this cost is absorbed in Block 300 by the actual scanning process.

To properly account for the enterprise-wide cost of the Fortus 900mc, the cost was increased by a factor of four under the assumption that each shipyard received one 3D printer.

2. Reengineered Process

Very little reengineering was used for this scenario. Since 3D printers are not currently considered a mature technology, it was assumed the 3D printing portion of yearly production would be 30% of the total. The output for the year was assumed to remain the same as the "as-is" model in order to maintain a conservative outlook. Besides the block where actual production occurs (Block 300), no changes were made to the "as-is" model for this scenario.

3. Data Analysis

A summary of the high level "to-be" KVA analysis is shown in Table 15. The overall ROK and ROI of the process stayed the same, although the ROK for the part of Block 300 with 3D printing was much higher than the traditional section.

Table 15. "To-Be" SHIPMAIN Process Overview

To Be SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	9	$22,588,963	$5,685,864	397%	297%
Block 265	Hull Installation and Risk Assessment	44	$94,800,881	$138,454,222	68%	-32%
Block 270	Authorize Installation	4	$24,677,019	$3,294,087	749%	649%
Block 280	Resolve "Not Authorized/Deferred SC	1	$3,701,553	$663,192	558%	458%
Block 300N	Install SC Normal	46	$66,216,667	$30,437,316	218%	118%
300AM	Install SC AM	13	$28,374,716	$642,386	4417%	4317%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	2	$1,850,776	$663,192	279%	179%
Block 320	Continue Installs	5	$4,626,941	$3,284,846	141%	41%
Block 330	Final Install, Closeout SC	1	$925,388	$331,596	279%	179%
			$247,762,905	$183,456,701	135%	35%

a. *Block 300 "To-Be" KVA Analysis*

Table 16 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 300.

Table 16. "To-Be" Analysis of Block 300

Block 300 Install SC										
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
300N	Complete normal installation and testing (70% - 364 parts)	$45.45	46	40	25%	893013	**$66,216,667**	**$30,437,316**	**218%**	**118%**
300AM	Complete AM installation and testing (30% - 156 parts)	Various	13	22.7	Var	382668	**$28,374,716**	**$642,386**	**4417%**	**4317%**

Compared to the normal process, the personnel, time to complete, and annual personnel cost of the additive manufacturing section dropped significantly. The ROK for an SC with 3D printing is much higher than that for a normal SC.

C. “RADICAL TO-BE ANALYSIS

This scenario represents a combination of estimated and verified data to portray the current activities contained in the SHIPMAIN process reengineered to maximize utilization of 3DLS, PLM, and 3D printing technology. The cost of implementing 3D printing technology will remain the same in this scenario as it was in the “to-be” scenario.

1. Cost of Implementing 3DLS Technology

For the purposes of this research, it is assumed that the scanner required for shipyard operations would be an industrial application scanner. The Konica Minolta Range7 3D Digitizer is an industrial application scanner and will serve as the representative scanner for this research. Cost and assumptions for the Digitizer are as follows:

- The current initial cost is $80,000 for one scanner and its applicable software suite.
- The maintenance/upkeep annual cost estimate is 20%.
- The use estimate is 200 days per year.
- The lifespan estimate is 10 years.
- For analysis of the “radical to-be” model, this cost is absorbed in Block 265.1 by the actual scanning process.

To properly account for the enterprise-wide cost of the Digitizer, the cost was increased by a factor of four under the assumption that each planning yard received one scanner with the required software.

2. Cost of Implementing PLM Technology

According to Megna (2011), NAVSEA ran a pilot program that utilized PLM software referred to as Data Exchange System (DES). Due to cost figures for PLM being difficult to obtain and to maintain a conservative estimate, those same figures will be used for this research. Costs and assumptions for DES are as follows:

- Costs for DES are $49,000 per year for the core site and $5,000 per additional site.
- Each of the four shipyard sites will receive the software.
- The lifespan estimate is 15 years.
- For analysis of the “radical to-be” model, this cost is spread across all subprocesses to reflect its usage in every part of the overall SHIPMAIN process.

Total costs for DES would equal $69,000 per year over the anticipated lifespan of the software.

3. Reengineered Process

Seaman (2007) reengineered the SHIPMAIN process by adding 3DLS and PLM technology to the "as-is" scenario. Implementation of 3DLS primarily affects Block 265.1 by enabling the planning yard to scan items and output its images in a highly accurate and electronically transferable 3D format as opposed to paper drawings. Using PLM, the 3D images can be shared across the whole enterprise, which allows all stakeholders real-time access to highly accurate imagery. The production facility can then utilize the PLM software to acquire the 3D drawings necessary for 3D printing.

4. Data Analysis

A summary of the high level "radical to-be" KVA analysis is shown in Table 17. The overall ROK and ROI of the process rose significantly, including gains of over 100% in every block except Blocks 270 and 320. In particular, Block 300 showed a significant increase in ROK and ROI, which demonstrates the power of combining all three technologies.

Table 17. "Radical To-Be" SHIPMAIN Process Overview

Radical To-Be SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	4	$16,215,953	$2,230,371	727%	627%
Block 265	Hull Installation and Risk Assessment	26	$172,381,012	$67,136,526	257%	157%
Block 270	Authorize Installation	4	$26,334,464	$3,299,649	798%	698%
Block 280	Resolve "Not Authorized/Deferred SC	1	$4,937,712	$403,478	1224%	1124%
Block 300AM	Install SC	36	$121,122,075	$552,118	21938%	21838%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	1	$2,370,102	$204,520	1159%	1059%
Block 320	Continue Installs	5	$6,172,140	$2,633,439	234%	134%
Block 330	Final Install, Closeout SC	1	$1,975,085	$270,839	729%	629%
			$351,508,543	**$76,730,941**	**458%**	**358%**

a. Block 250 "Radical To-Be" KVA Analysis

Table 18 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 250.

Table 18. "Radical To-Be" Analysis of Block 250

Block 250											
Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
250.1	Create AHMP/EHMP	$42.45	0	1	$5,563	100%	28800	$2,278,944	$5,563	40970%	40870%
250.2	Create Annual HMP/LOA	$42.45	1	40	$5,563	75%	153600	$12,154,368	$2,186,928	556%	456%
250.3	Initiate 2Ks into ICMP	$35.70	1	1	$5,563	99%	19968	$1,580,068	$29,410	5373%	5273%
250.x	Generate/issue QISM	$42.45	2	8	$5,563	90%	2560	$202,573	$8,471	2391%	2291%
							Process Totals:	**$16,215,953**	**$2,230,371**	**727%**	**627%**

Automation of subprocesses caused a large change in Block 250. Block 250.1 and Block 250.3 were either mostly or entirely automated, and their required reports became auto-generated (Seaman, 2007). In addition, PLM provided some efficiency improvements to the other subprocesses. The process ROK increased to 727% from 424%.

b. Block 265 "Radical To-Be" KVA Analysis

Table 19 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 265.

Table 19. "Radical To-Be" Analysis of Block 265

Block 265											
Hull Installation and Risk Assessment											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
265.1	Installation Procurement, Design & Advance Planning	$43.10	17	128	$101,563	75%	1697280	$134,305,766	$62,387,957	215%	115%
265.2	Hull Installation Readiness Review	$29.78	2	32	$5,563	85%	277333	$21,945,387	$1,066,670	2057%	1957%
265.3	Evaluate Maturity Status	$50.16	1	20	$5,563	0%	20800	$1,645,904	$564,065	292%	192%
265.4	Provide Risk Assessment	$50.16	1	40	$5,563	0%	29120	$2,304,266	$1,122,568	205%	105%
265.4.1	Formally Propose Install for Readiness Assessment and Auth.	$50.16	1	20	$5,563	0%	124800	$9,875,424	$675,766	1461%	1361%
265.5	Risk/Readiness Determination	$59.01	4	40	$5,563	0%	29120	$2,304,266	$1,319,501	175%	75%
							Process Totals:	**$172,381,012**	**$67,136,526**	**257%**	**157%**

The main improvements from introducing 3DLS to the overall process occur in Block 265, particularly in Block 265.1. Using 3DLS in Block 265.1 would allow personnel to be reduced by at least 50% and cycle-time to improve by at least 20% (Seaman, 2007). Improvements in the rest of the block stem from the ability of users to quickly and accurately collaborate on assessments and generate reports. The process ROK increased to 257% from 73%.

c. Block 270 "Radical To-Be" KVA Analysis

Table 20 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 270.

Table 20. "Radical To-Be" Analysis of Block 270

Block 270 Authorize Installation											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
270	Installation decision	$76.00	4	20	$5,563	85%	332800	$26,334,464	$3,299,649	798%	698%

Adding technology changed very little for Block 270. Other than some small efficiencies gained through easier collaboration, the improvements to be gained from PLM appear negligible as the process is already highly automated and collaborative. The process ROK remained essentially flat at 798%, compared to the "as-is" ROK of 799%.

d. Block 280 "Radical To-Be" KVA Analysis

Table 21 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 280.

Table 21. "Radical To-Be" Analysis of Block 280

Block 280 Resolve "Not Authorized/Deferred SC"											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
280	Update HMP,LOA and Fielding Plan	$29.78	1	24	$5,563	80%	62400	$4,937,712	$403,478	1224%	1124%

The Block 280 process involves updating planning documents developed in Block 265 and authorization documents developed in Block 270 (Seaman, 2007). Improvements in this block stem from the ability of users to access required documents and collaborate with process owners in a far more efficient manner via PLM. An estimate of a two-day reduction in cycle-time was used in the scenario. The process ROK increased to 1,224% from 596%.

e. Block 300 "Radical To-Be" KVA Analysis

Table 22 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 300.

Table 22. "Radical To-Be" Analysis of Block 300

Block 300 Install SC											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
300AM	Complete installation and testing	$42.45	36	35	$165,563	35%	1530672	$121,122,075	$552,118	21938%	21838%

The change in Block 300 is the most drastic in the entire model by a significant margin. In addition to the improvements in coordination enabled by PLM and the improvements in accuracy enabled by 3DLS, the ability of the shipyard to produce full parts on site at low cost via 3D printing provides an incredible enhancement to the process. The process ROK increased to 21,938% from 232%.

f. Block 310 "Radical To-Be" KVA Analysis

Table 23 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 310.

Table 23. "Radical To-Be" Analysis of Block 310

Block 310 Feedback: Cost, CM, Performance, Schedule, ILS											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
310	Provide Feedback Data	$29.78	1	10	$5,563	50%	29952	$2,370,102	$204,520	1159%	1059%

According to Seaman (2007), the information required to complete Block 310 must be collected via manual means. Improvements in this block stem from the ability of users to access all the necessary information via a single interface and to auto-generate the appropriate reports. In addition, the life-cycle information for each platform would be completely documented, leading to a better understanding of the total cost of ownership for ships and systems. The process ROK increased to 1,159% from 298%.

g. Block 320 "Radical To-Be" KVA Analysis

Table 24 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 320.

Table 24. "Radical To-Be" Analysis of Block 320

Block 320 Continue Installs											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
320	Continue Installs	$59.01	5	16	$5,563	20%	78000	$6,172,140	$2,633,439	234%	134%

Block 320 primarily relies on humans to evaluate installation risk, which leads to a relatively low utilization of technology (Seaman, 2007). Improvements in this block stem from the ability of users to access any relevant information in a single networked interface via PLM. A conservative estimate of a 20% reduction in time required for completion is used in the scenario. The process ROK increased to 234% from 150%.

h. Block 330 "Radical To-Be" KVA Analysis

Table 25 shows key KVA estimates used to determine the total process benefits, annual cost, ROK, and ROI for Block 330.

Table 25. "Radical To-Be" Analysis of Block 330

Block 330 Final Install, Closeout SC											
	Sub process	Hourly Personnel Cost	Head count	Time to Complete (Hrs)	IT Cost	%IT	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
330	Verify all SCs have been completed	$29.78	1	16	$5,563	50%	24960	$1,975,085	$270,839	729%	629%

Block 330 also primarily relies on humans to determine whether an SCD can be closed out (Seaman, 2007). It requires more technology than Block 320, however, as indicated by the 50% technology utilization. Improvements in this block stem from the ability of users to access all the required verification items in a single networked interface via PLM. An estimate of a 20% reduction in time required for completion is used in the scenario. The process ROK increased to 729% from 298%.

V. CONCLUSIONS

A. RESEARCH LIMITATIONS

The KVA models for this research were generated primarily from SME interview data. These data were then generalized across enterprise management and shipyard activities. Although the data in this research are not as specific as objective data collected from ongoing pilot projects or operations, they can be assumed to be reliable due to the high levels of correlation across key KVA data points. Due to time constraints and the large scope of Phases IV and V of SHIPMAIN, the scope was limited to only the core processes and the first level of subprocesses. Several additional sub-layers could be modeled for higher levels of accuracy specific to a given community of interest. Finally, the data for 3D printing were generalized from a non-shipyard production process. If the Navy begins a pilot program specifically for ship part production, a more detail-specific model could be created.

B. RESEARCH QUESTIONS

The following paragraphs address each of the research questions posed in Chapter I. The model representing the current "as-is" process is shown in Table 26 for easy comparison.

Table 26. "As-Is" SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	9	$24,106,285	$5,685,864	424%	324%
Block 265	Hull Installation and Risk Assessment	44	$101,168,745	$138,454,222	73%	-27%
Block 270	Authorize Installation	4	$26,334,597	$3,294,087	799%	699%
Block 280	Resolve "Not Authorized/Deferred SC	1	$3,950,190	$663,192	596%	496%
Block 300	Install SC	46	$100,949,290	$43,481,880	232%	132%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	2	$1,975,095	$663,192	298%	198%
Block 320	Continue Installs	5	$4,937,737	$3,284,846	150%	50%
Block 330	Final Install, Closeout SC	1	$987,547	$331,596	298%	198%
			$264,409,487	**$195,858,879**	**135%**	**35%**

1. What impact will 3D printing have on maintenance costs and shipyard productivity?

The "to-be" scenario answers this question through a model representing the SHIPMAIN process reengineered to include utilization of 3D printing technology.

Using a combination of estimated and verified data to portray the current activities of the SHIPMAIN process and a series of conservative assumptions to account for the lack of direct production data, the model demonstrates the value 3D printing technology adds to the process. The overall ROK and ROI of the process stayed the same, although the ROK for the portion of Block 300 with 3D printing was much higher than the traditional section (shown in Table 27).

Table 27. "To-Be" SHIPMAIN Process Overview

To Be SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	9	$22,588,963	$5,685,864	397%	297%
Block 265	Hull Installation and Risk Assessment	44	$94,800,881	$138,454,222	68%	-32%
Block 270	Authorize Installation	4	$24,677,019	$3,294,087	749%	649%
Block 280	Resolve "Not Authorized/Deferred SC	1	$3,701,553	$663,192	558%	458%
Block 300N	Install SC Normal	46	$66,216,667	$30,437,316	218%	118%
300AM	Install SC AM	13	$28,374,716	$642,386	4417%	4317%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	2	$1,850,776	$663,192	279%	179%
Block 320	Continue Installs	5	$4,626,941	$3,284,846	141%	41%
Block 330	Final Install, Closeout SC	1	$925,388	$331,596	279%	179%
			$247,762,905	$183,456,701	135%	35%

Compared to the normal process, the personnel numbers, time to complete, and annual personnel cost of the additive manufacturing section dropped significantly, leading to a 3D printing ROK that is much higher than the ROK for the normal production process. For the overall process, however, 3D printing in its present immature form with the likely constraints enumerated in the model assumptions does not appear to significantly decrease costs or impact overall productivity.

2. What impact will using PLM, 3DLS, and 3D printing in conjunction have on maintenance costs and shipyard productivity?

The "radical to-be" scenario answers this question through a model representing the SHIPMAIN process reengineered to maximize utilization of 3DLS, PLM, and 3D printing technology. Using a combination of estimated and verified data to portray the current activities of the SHIPMAIN process and a series of conservative assumptions to account for the lack of direct production data, the model demonstrates the value that the combination of 3DLS, PLM, and 3D printing technologies adds to the process. In contrast to 3D printing alone, using PLM, 3DLS, and 3D printing in conjunction had an enormous impact in the model (shown in Table 28). The overall ROK and ROI of the process rose significantly, including gains of over 100% in every block except Blocks 270 and 320.

Table 28. "Radical To-Be" SHIPMAIN Process Overview

Radical To-Be SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	4	$16,215,953	$2,230,371	727%	627%
Block 265	Hull Installation and Risk Assessment	26	$172,381,012	$67,136,526	257%	157%
Block 270	Authorize Installation	4	$26,334,464	$3,299,649	798%	698%
Block 280	Resolve "Not Authorized/Deferred SC	1	$4,937,712	$403,478	1224%	1124%
Block 300AM	Install SC	36	$121,122,075	$552,118	21938%	21838%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	1	$2,370,102	$204,520	1159%	1059%
Block 320	Continue Installs	5	$6,172,140	$2,633,439	234%	134%
Block 330	Final Install, Closeout SC	1	$1,975,085	$270,839	729%	629%
			$351,508,543	**$76,730,941**	**458%**	**358%**

In particular, Block 300's ROK increased to 21,938%, which demonstrates the power of combining all three technologies. Costs declined by 60.8%, decreasing from $195,858,879 in the "as-is" model to $76,730,941 in the "radical to-be" model. In addition, the productivity of the shipyards increased. The reduced cost corresponded to 624 parts produced per year, compared to only 520 in the "as-is" model. This represents a 120% increase in production. Since this research focuses specifically on the effect of technology on the four public shipyards only, the models in this these imply the Navy could save millions of dollars if these technologies were implemented at all shipyards servicing Navy vessels.

C. REAL OPTIONS

Although no RO analysis was conducted for this research, the technologies presented here could be implemented in many different ways, including phased-in acquisitions and multiple up-front purchases. The following are several options scenarios:

- Do nothing and allow the "as-is" process to continue.
- Immediately acquire the 3DLS capability for the public shipyards without PLM tools. If successful, expand to all yards.
- Immediately acquire 3DLS and PLM technologies for the public shipyards. If successful, expand implementation across all yards.

- Immediately acquire the 3D printing capability for the public shipyards. If successful, expand to all yards.
- Immediately acquire the 3DLS and 3D printing capabilities for the public shipyards. If successful, expand to all yards.
- Immediately acquire 3DLS, PLM, and 3D printing technologies for the public shipyards. If successful, expand implementation across all yards.
- Immediately acquire comprehensive PLM software for all government agencies involved in Surface Fleet Modernization and Maintenance.

D. RECOMMENDATIONS TO THE NAVY

The Navy should immediately begin implementing 3DLS and PLM technology into the SHIPMAIN process. Even without 3D printing, the previous research indicates that there are large reductions in cost and large gains in productivity to be achieved with relatively low technology risk. Since it has been seven years since Seaman's thesis, the technology involved is much more mature and the gains should be even greater than his original conservative estimates.

Regarding 3D printing, the Navy should begin running pilot projects to investigate its application to ship maintenance and repair. Utilizing 3D printing to augment shipyard processes should be experimented with, as well as using 3D printing to create repair parts at intermediate and shipboard locations. Not only would having data specifically for ship maintenance parts improve any future research, but it could also help move the 3D printing technology further along the maturity curve. The possibilities for 3D printing are too enormous to ignore.

E. FOLLOW ON AND FUTURE RESEARCH OPPORTUNITIES

The greatest future research opportunity for expanding on this thesis depends on the Navy conducting pilot projects in the ship maintenance/production field involving 3D printing. The validity and accuracy of the models contained in this research could be significantly improved using actual production data.

In addition, there are research opportunities in investigating the effect of technology on SHIPMAIN in more detail. SHIPMAIN is a large program involving many personnel from several large organizations. This study took a top-level view at how 3DLS, PLM, and 3D printing could potentially affect the ROK and ROI of Phases IV and V of the SHIPMAIN process. Communities of interest could conduct additional research on specific blocks of the SHIPMAIN program down to the lowest level of decomposition, particularly in the production and installation section.

REFERENCES

Autodesk. (2009). *Digital prototyping: Questions and answers* [Brochure]. Retrieved from http://www.cadac.com/nl/brochures/Documents/autodesk-digital-prototyping-questions-answers-en.pdf

Beckhusen, R. (2012). 3D-printer company sells to gun companies, but not desktop weaponeers. Retrieved from http://www.wired.com/dangerroom/2012/10/stratasys-followup/

Brown, J. (2012). *Issue in focus: Assessing the cloud PLM opportunity*. Retrieved from http://www.autodeskplm360.com/assets/content/resources/Tech-Clarity_Issue_in_Focus_Assessing_the_Cloud_PLM_Opportunity.pdf

Campbell, T., Williams, C., Ivanova, O., & Garrett, B. (2011). *Could 3D printing change the world? Technologies, potential, and implications of additive manufacturing*. Washington, DC: The Atlantic Council of the United States. Retrieved from http://www.atlanticcouncil.org/publications/reports/could-3d-printing-change-the-world

Chayka, K. (2013, August). Why is the Pentagon dragging its feet on 3D printing? Retrieved from http://www.defenseone.com/ideas/2013/08/Why-Is-Pentagon-Dragging-Feet-3D-Printing/68936/?oref=d-interstitial-continue

CIMdata. (2011, April). *The ROI of PLM.* Retrieved from http://www.aras.com/Blogs/ACE-2011-International/CIMdata-ROI-of-PLM.pdf

CIMdata. (2013). Product lifecycle management (PLM) definition. Retrieved from http://www.cimdata.com/plm/definition.html

Daly, J. (2013, August). The history of 3D printing. *StateTech Magazine*. Retrieved from http://www.statetechmagazine.com/article/2013/08/history-3d-printing-infographic

Department of the Navy. (2011). *Fiscal year 2012 budget estimates: Operations and maintenance, Navy.* Retrieved from http://www.finance.hq.navy.mil/FMB/12pres/OMN_Vol1_book.pdf

DiChristopher, T. (2013, August 17). From teeth aligners to engine parts, 3-D printing business grows. *CNBC*. Retrieved from http://www.cnbc.com/id/100962824

eFunda. (2013). Rapid prototyping: An overview. Retrieved from http://www.efunda.com/processes/rapid_prototyping/intro.cfm

Ford, D. N., Housel, T., & Mun, J. (2011). *Ship maintenance processes with collaborative product lifecycle management and 3D terrestrial laser scanning* *tools: Reducing costs and increasing productivity*. Monterey, CA: Naval Postgraduate School, Acquisition Research Program.

General Services Administration. (2009). *GSA building information modeling guide series: 03—GSA BIM guide for 3D imaging* (Ver. 1). Retrieved from http://www.gsa.gov/graphics/pbs/GSA_BIM_Guide_Series_03.pdf

Geomagic. (2013). 3D systems creates legacy motorcycle fairing in less than three days. Retrieved from http://www.geomagic.com/en/community/case-studies/3d-systems-recreates-legacy-motorcycle-fairing-in-less-than-thre/

Grimm, T. (2004). *User's guide to rapid prototyping*. Dearborn, MI: Society of Manufacturing Engineers.

Grimm, T. (2012). 3D printing: Speaking the language. Retrieved from http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/3918/3D-Printing-Speaking-the-Language.aspx

Haney, P. (2003). *SHIPMAIN: An overview of the SHIPMAIN maintenance and alterations planning process*. Retrieved from http://www.nstcenter.biz/docs/PDFs/JINII/2003November/JINII-Meeting-2003November-Presentation-SHIPMAINModernization.pdf

Hessman, T. (2013). The history of 3D printing [Slideshow]. Retrieved from http://www.industryweek.com/emerging-technologies/history-3-d-printing-slideshow

Housel, T. J., & Bell, A. H. (2001). *Measuring and managing knowledge*. New York, NY: McGraw-Hill.

Kenney, M. (2013). *Cost reduction through the use of additive manufacturing (3D printing) and collaborative product life cycle management technologies to enhance the Navy's maintenance programs* (Master's thesis). Monterey, CA: Naval Postgraduate School.

Komoroski, C. L. (2005). *Reducing cycle time and increasing value through the application of knowledge value added methodology to the U.S. Navy shipyard planning process* (Master's thesis). Monterey, CA: Naval Postgraduate School.

Komoroski, C. L., Housel, T., Hom, S., & Mun, J. (2006). *A methodology for improving the shipyard planning process: Using KVA analysis, risk simulation and strategic real options* (NPS-GSBPP-05-000). Monterey, CA: Naval Postgraduate School.

Megna, F. F. (2011). *The use of a collaborative common parts catalog to achieve increased efficiency and cost savings in the fleet modernization plan.* (Master's thesis). Monterey, CA: Naval Postgraduate School.

Office of the Assistant Secretary of Defense for Logistics and Materiel Readiness. (2012). *Department of Defense maintenance fact book*. Retrieved from http://www.acq.osd.mil/log/mpp/factbooks/DoD_Maintenance_Fact_Book_2012.pdf

Quintero, M. S., Genechten, B. V., De Bruyne, M., Poelman, R., Hankar, M., … Taronger, J. M. B. (2008). *3D risk-mapping: Theory and practice on terrestrial laser scanning* (4th ed.). Retrieved from http://jllerma.webs.upv.es/pdfs/Leonardo_Tutorial_Final_vers5_ENGLISH.pdf

RARE Parts Team Panel. (2012). *Printing parts is possible: Turning science into sustainable substance*. Paper presented at the 13th Annual Commercial Technologies for Maintenance Activities Symposium, North Island, CA.

Scott, J., Gupta, N., Weber, C., Newsome, S., Wohlers, T., & Caffrey, T. (2012). *Additive manufacturing: Status and opportunities*. Retrieved from https://www.ida.org/stpi/occasionalpapers/papers/AM3D_33012_Final.pdf

Seaman, N. L. (2007). *The use of collaborative and three dimensional imaging technology to increase value in the SHIPMAIN environment of the fleet modernization plan* (Master's thesis). Monterey, CA: Naval Postgraduate School.

SHIPMAIN overview [Presentation slides]. (2006). Retrieved from https://www.spear.navy.mil/Docs/ShipMAIN/Tools/STANDARD%20BRIEF.ppt

Siemens. (2013). CAD/computer-aided design. Retrieved from http://www.plm.automation.siemens.com/en_us/plm/cad.shtml

Spar Point Group. (2013). Industry glossary: 3D laser scanning. Retrieved from http://www.sparpointgroup.com/Wiki.aspx?id=2147486179

Steitz, D. E., Martin, K. K., & Dick, E. (2013, July). NASA, industry test additively manufactured rocket engine injector [Press release]. Retrieved from http://www.nasa.gov/press/2013/july/nasa-industry-test-additively-manufactured-rocket-engine-injector-0/#.UfsEb5JtPPX

Stratasys. (2012). *A new mindset in product design: 3D printing can help bring better products to market faster* [White paper]. Retrieved from http://www.stratasys.com/~/media/Main/Secure/White%20Papers/Rebranded/SSYS_WP_new_mindset_in_product_design.pdf

3D Systems. (2013). *3D Systems: Creativity reimagined*. Retrieved from http://www.3dsystems.com/files/downloads/3D-Systems-Investor-Presentation-Jan-2013.pdf

Wohlers Associates. (2009). Expected growth of additive manufacturing for part production applications. Retrieved from http://wohlersassociates.com/partproduction.html

Wohlers Associates. (2010a). Industry briefing: Direct part production from AM. Retrieved from http://wohlersassociates.com/brief02-10.htm

Wohlers Associates. (2010b). Industry briefing: Revenues from additive manufacturing. Retrieved from http://wohlersassociates.com/brief07-10.htm

Wohlers, T. (2009). 3D printing goes open-source. Retrieved from http://wohlersassociates.com/NovDec09TC.htm

Xavor. (2013). PLM overview. Retrieved from http://www.xavor.com/high-tech/product-record/

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL
555 DYER ROAD, INGERSOLL HALL
MONTEREY, CA 93943

www.acquisitionresearch.net