NPS-LM-13-126

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Potential Cost Savings for Use of 3D Printing Combined With 3D Imaging and CPLM for Fleet Maintenance and Revitalization

4 December 2013

Dr. David N. Ford, Research Associate Professor

Dr. Tom Housel, Professor

Graduate School of Business & Public Policy

Naval Postgraduate School

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

Abstract

Initiatives to reduce the cost of ship maintenance have not yet realized the normal cost-reduction learning curve improvements. One explanation is the lack of some of the technologies recommended by the developers of SHIPMAIN, an initiative designed to improve ship maintenance performance within the Navy by standardizing processes in order to take advantage of learning curve cost savings and other technologies. Two such recommended technologies are collaborative product lifecycle management (CPLM) and three-dimensional laser scanning technology (3DLST). One quickly emerging new technology is additive manufacturing (AM). The research team collected data on AM use by U.S. Navy in maintenance operations and extrapolated them to build two types of computer simulation models of ship maintenance and technology adoption. The models were used to investigate the impacts of 3DLST and scaling up AM use on potential cost savings. The results were analyzed and compared with previously developed modeling results of the use of AM in U.S. Navy ship maintenance. Results support the adoption of AM in ship maintenance. 3DLST increases savings slightly over the use of AM alone or with CPLM. Cost savings when AM and other technologies are used only to make prototypes are significant but limited. In contrast, savings are significantly larger if AM use is expanded to include the manufacturing of final parts. The primary implication for acquisition practice is the importance of scaling up the use of AM and other new technologies to capture potential savings.

Keywords: Technology adoption, ship maintenance, additive manufacturing, laser scanning technology, collaborative product lifecycle management

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgments

The authors thank Michael Kenney for assistance in data collection.

THIS PAGE INTENTIONALLY LEFT BLANK

About the Authors

Dr. David N. Ford received his BS and MS from Tulane University, New Orleans, LA, and his PhD from the Massachusetts Institute of Technology, Cambridge. He is an associate professor in the Construction Engineering and Management Program, Zachry Department of Civil Engineering, Texas A&M University, College Station; and the Urban/Beavers development professor. He also serves as a research associate professor of acquisition with the Graduate School of Business and Public Policy at the U.S. Naval Postgraduate School in Monterey, CA. Prior to joining Texas A&M, he was on the faculty of the Department of Information Science, University of Bergen, Bergen, Norway, where he researched and taught in the System Dynamics Program. For over 14 years, he designed and managed the development of constructed facilities in industry and government. His current research investigates the dynamics of development supply chains, risk management with real options, and sustainability. Dr. Ford is a member of ASCE and other professional organizations.

Dr. David N. Ford
Graduate School of Business & Public Policy
Naval Postgraduate School
Monterey, CA 93943-5000
Tel: (831) 656-3759
Fax: (831) 656-3407
E-mail: DavidFord@tamu.edu

Dr. Tom Housel specializes in valuing intellectual capital, knowledge management, telecommunications, information technology, value-based business process reengineering, and knowledge value measurement in profit and non-profit organizations. He is currently a tenured full professor for the Information Sciences (Systems) Department. He has conducted over 80 knowledge value added (KVA) projects within the non-profit Department of Defense (DoD) sector for the Army, Navy, and Marines. He has also completed over 100 KVA projects in the private sector. The results of these projects provided substantial performance improvement strategies and tactics for core processes throughout the DoD organizations and the private sector companies. He has managed a $3 million+ portfolio of field studies, educational initiatives, and industry relationships. His current research focuses on the use of KVA and “Real Options” models in identifying, valuing, maintaining, and exercising options in military decision-making. Prior to joining NPS, he also was a research fellow for the Center for Telecommunications Management and associate professor at the Marshall School of Business at the University of Southern California. Dr. Housel has been the chief business process engineer for Pacific Bell, where he completed numerous reengineering projects and developed the KVA methodology that objectively measures the value added by process reengineering. His last assignment in the corporate world was as the chief of consumer market research for Telecom Italia in Venice, Italy, where he developed new methods for predicting the adoption rates for new interactive multimedia broadband applications. He is managing partner for Business Process Auditors, a firm that specializes in training Big Six consultants, large manufacturing, and service companies in the KVA methodology for objectively measuring the return generated by corporate knowledge assets/intellectual capital. He received his PhD from the University of Utah in 1980. He won the prestigious Society for Information Management award for best paper in the field in 1986. His work on measuring the value of intellectual capital has been featured in a *Fortune* cover story (October 3, 1994) and *Investor's Business Daily*, numerous books, professional periodicals, and academic journals (most recently in the *Journal of Intellectual Capital*, volume 2, 2005). His latest books include *Measuring and Managing Knowledge* and *Global Telecommunications Revolution: The Business Perspective* with McGraw-Hill (both in 2001).

Dr. Thomas Housel
Graduate School of Business & Public Policy
Naval Postgraduate School
Monterey, CA 93943-5000
Tel: (831) 656-7657
Fax: (831) 656-3407
E-mail: tjhousel@nps.edu

NPS-LM-13-126

ACQUISITION RESEARCH PROGRAM SPONSORED REPORT SERIES

Potential Cost Savings for Use of 3D Printing Combined With 3D Imaging and CPLM for Fleet Maintenance and Revitalization

4 December 2013

Dr. David N. Ford, Research Associate Professor

Dr. Tom Housel, Professor

Graduate School of Business & Public Policy

Naval Postgraduate School

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

THIS PAGE INTENTIONALLY LEFT BLANK

List of Figures

THIS PAGE INTENTIONALLY LEFT BLANK

List of Tables

THIS PAGE INTENTIONALLY LEFT BLANK

Executive Summary

Statement of Research Issue/Results

The Department of Defense (DoD) cost reduction imperatives have forced a review of the normal ship maintenance methods with a focus on reducing costs. Savings from the use of additive manufacturing (AM), collaborative product lifecycle management (CPLM), and three-dimensional laser scanning technology (3DLST) tools can potentially provide the means to capture significant potential savings.

Executive Summary

To comply with cost-cutting directives and good acquisition practice, the Navy must seek new approaches to ship maintenance to ensure that required capabilities are produced at the lowest possible cost. This requires analyses of the cost/benefits of using AM + CPLM + 3DLST tools in ship maintenance. This research compares and extends an existing knowledge value added (KVA) model of using AM in ship maintenance and existing KVA + systems dynamics (SD) models that have forecasted the potential benefits of CPLM + LST to estimate the potential cost savings from using a combination of all three technologies at different scales of use (i.e., for prototypes only or also for final parts).

The ultimate goal of the current research is to find effective ways to help the U.S. Navy reduce its ship maintenance costs without compromising its vessels' capabilities. Results indicate that large cost savings are possible if the adoption of these technologies is extended beyond testing and use for manufacturing prototypes to include the manufacturing of final parts. The results provide a defensible estimate of the returns on investments (ROI) and savings from using a combination of these three tools at different scales, thereby providing Navy decision-makers with a way to compare the relative cost/benefits of combining the three tools for purposes of increasing ship maintenance efficiency.

THIS PAGE INTENTIONALLY LEFT BLANK

Potential Cost Savings for Use of 3D Printing Combined With 3D Imaging and CPLM for Fleet Maintenance and Revitalization

Introduction

The current cost-constrained environment within the federal government and the Department of Defense (DoD) requires a defensible approach to cost reductions without compromising the capability of core defense processes and platforms. Due to this environment, defense leaders today must maintain and modernize the U.S. armed forces to retain technological superiority while simultaneously balancing defense budget cost constraints and extensive military operational commitments. At the same time, defense leaders must navigate a complex information technology (IT) acquisition process. Maintenance programs play a critical role in meeting these DoD objectives. One such core process that is central to U.S. naval operations is the ship maintenance process. This process alone accounts for billions of dollars in the U.S. Navy's annual budget. There have been a series of initiatives designed to reduce the cost of this core process, including ship maintenance.

SHIPMAIN, and its latest derivatives, was one of the initiatives designed to improve ship maintenance performance within the Navy by standardizing processes in order to take advantage of learning curve cost savings. Figure 1 provides a notional picture of this phenomenon.

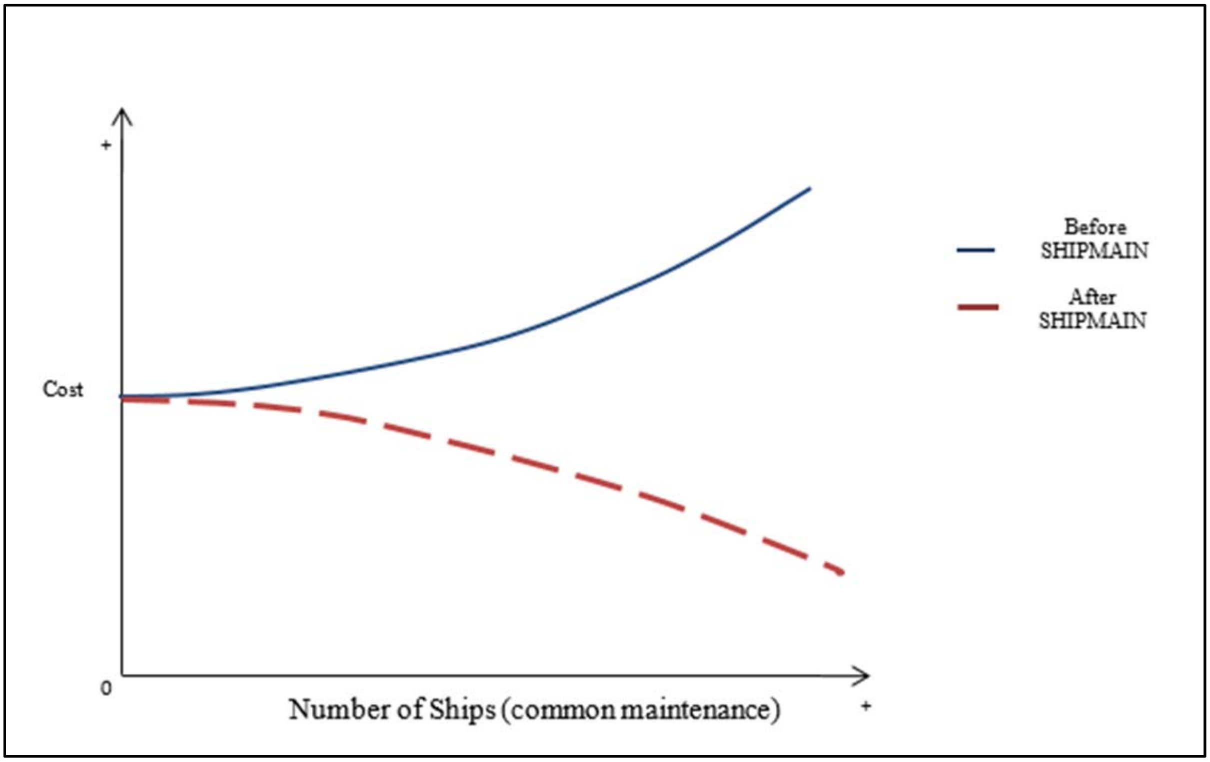


Figure 1. Ship Maintenance Learning Curve

However, these process improvement initiatives have not yet realized the normal cost-reduction learning curve improvements for common maintenance items for a series of common platform ships. One explanation is that the initial instantiation of SHIPMAIN did not include the requisite technologies. Two of these technologies, three-dimensional laser scanning technology (3DLST) and collaborative product lifecycle management (CPLM), were deemed necessary by the creator of SHIPMAIN for ensuring the success of the new standardized approach (i.e., normal learning curve cost savings). A third technology, additive manufacturing (AM), has developed quickly over recent years and shows potential to generate even greater cost savings if combined with the other two technologies.

But these technologies have not been widely implemented for ship maintenance across the Navy. Several explanations have been suggested for the Navy’s slow adoption of these technologies, including the lack of a technology adoption strategy, current military certification and acquisition processes, and contracting regulations (G. Draguecevich, personal communication, July 17, 2012; Chayka, 2013). An alternative explanation is that the combination of the three technologies, unless scaled up, will not provide adequate cost savings. The combination of these three technologies at different operational scales will significantly affect the potential returns and savings when compared to their application alone, in pairs, or at inefficient scales of operation. An improved understanding of the cost impacts of the adoption of all three technologies at different scales of adoption can facilitate Navy decision-making about the possible acquisition and use of these technologies. The current work estimates the cost reduction impacts of adopting AM, CPLM, and 3DLST for ship maintenance at different scales of operation.

Problem Description

AM + CPLM + 3DLST have demonstrated the capacity for improving military operations, such as Navy ship maintenance. The U.S. Army has successfully deployed three "expeditionary labs" to Afghanistan. These self-contained spaces use AM as well as computer numerical control (CNC) machines to quickly reequip the Army's Rapid Equipping Force (Chayka, 2013). As an example of this success, former Rapid Equipping Force (REF) director Peter Newell describes circumstances in which the valve stem on the front tires of the Mine-Resistant Ambush Protected (MRAP) vehicles were often exposed to rough terrain and failed. Using AM to design and test multiple potential solutions quickly, the interaction of war fighters with the engineers in the expeditionary lab reduced the development of a solution to a "30-day discussion rather than a multi-year process." The Army's Edgewood Chemical and Biological Center in Maryland has used AM for rapid prototyping of objects such as battery storage containers for night-vision helmets. The Navy has initiated testing of AM at the Navy Warfare Development Command and limited use at NAVAIR in San Diego and Fleet Readiness Center Southwest at Port Hueneme. Industry leaders, such as Boeing and GE, currently use AM to create final parts for machines and vehicles. Current U.S. military certification processes prevent them from using these methods for military components (Chayka, 2013). Damen, the primary naval contractor for the Dutch navy, has successfully adopted and is currently using core components of CPLM (Ford, Housel, & Mun, 2012), and two U.S. navy shipyards have begun the transition to CPLM for shipbuilding.

Previous related research has investigated the cost/benefits impacts of the U.S. Navy using 3DLST and CPLM (Komoroski, 2005), CPLM and 3DLST (Ford et al., 2012) and AM and CLPM in ship maintenance (Kenney, 2013). Ford et al. (2011) modeled the cost/benefits impacts of CPLM and 3DLST ship maintenance operations. Kenney (2013) modeled two levels of AM adoption: use only for making prototypes; and use for both prototypes and final parts, referring to these as "immature" and "mature" AM, respectively. All of these studies predicted that significant cost reductions can be captured through the use of these new technologies. These results typically focused on operating savings after adoption is complete and use conservative assumptions, such as ignoring savings from reduced inventory costs and manufacturing infrastructures. Therefore, actual steady state cost savings may be larger than forecasted. Although adoption and ramp-up costs and other issues (e.g., contracting regulations) are not included in these cost/benefits impact studies, the scale of potential savings is so large (exceeding $1 billion in some cases) that projected cost savings appear to have been adequate for adoption of the technologies.

With budgetary constraints worsening and the operational feasibility and potential enormous cost savings demonstrated, the Navy's slow adoption of at least some of these technologies for widespread use in ship maintenance is puzzling to some researchers and observers of military acquisition (Chayka, 2013; G. Draguecevich, personal communication, July 17, 2012). However, tests of the combined use of the three technologies at different levels of use for cost savings impacts may facilitate naval decision-making and progress. Therefore, the current work addresses the following questions:

- How does the use of 3DLST impact the returns on investment and cost savings that can be expected from the use of AM and CPLM alone for ship maintenance?
- What returns on investment and cost savings can be expected from the use of AM, CPLM, and 3DLST in combination for rapid prototyping in ship maintenance?
- What returns on investment and cost savings can be expected from the use of AM, CPLM, and 3DLST for rapid prototyping and final parts manufacturing in ship maintenance?

Background

The use of multiple relatively new technologies in combination may be able to dramatically improve U.S. Navy ship maintenance. These technologies include CPLM, 3DLST, and AM. These three technologies are described next as a basis for the research.

Collaborative Product Lifecycle Management

CPLM technology provides a common platform to electronically integrate other technologies, such as 3DLST images and manufacturing files for AM, to enable collaboration among all parties involved in a given project across project phases and regardless of their geographic location (e.g., on a ship at sea and at a land-based depot). Schindler (2010; see Figure 2) illustrated the potential of CPLM to facilitate integration of the development of materiel solutions.

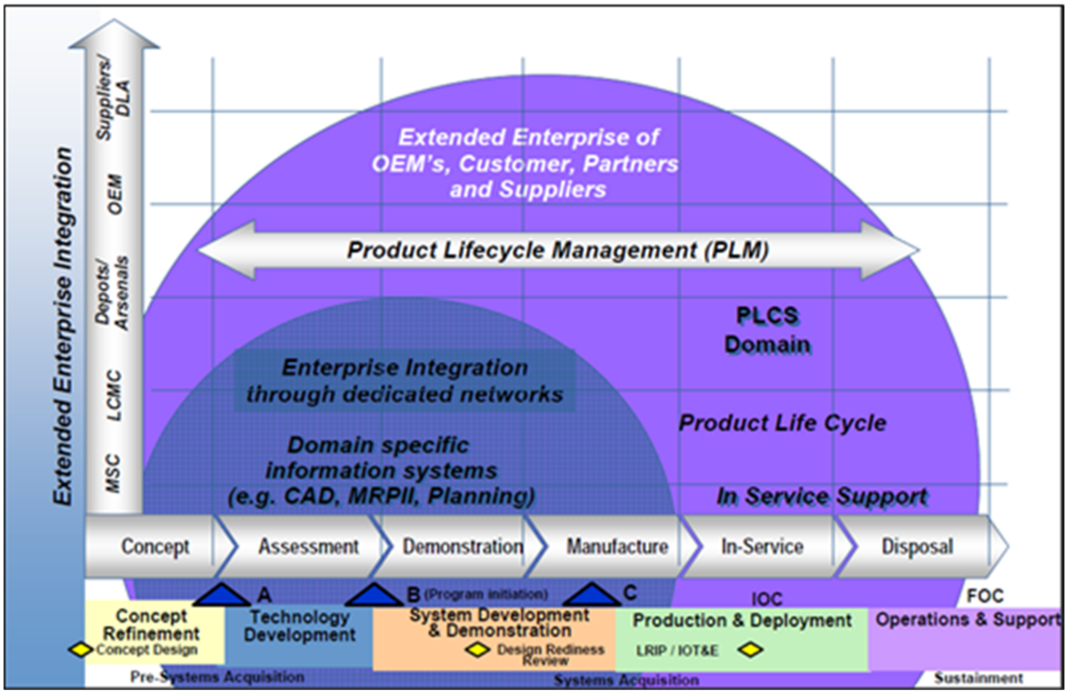


Figure 2. Collaborative Product Lifecycle Management Across the Life Cycle

(Schindler, 2010).

CPLM tools also provide a means to store the images and all related maintenance work within a common database accessible by all participants in a ship alternation or modernization project. PLM is defined by CIMdata as a strategic business approach applying a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise, from concept to end of life (CIMdata, 2007a).[1] It integrates people, processes, and information.

More specific CPLM tools include technologies that support data exchange, portfolio management, digital manufacturing, enterprise application integration, and workflow automation. A range of industries have invested in CPLM solutions, including those involved in aerospace and defense, automotive and transportation, utilities, process manufacturing, and high-tech development and manufacturing. The CPLM market is poised for further growth with vendors expanding product offerings as the industry evolves.[2] Figure 3 indicates the evolution of CPLM applications,

---

[1] CIMdata is a consulting firm with over 20 years of experience in strategic IT applications and is an acknowledged leader in the application of PLM and related technologies (CIMdata, 2007a).

[2] The two largest U.S. shipyards that construct aircraft carriers and submarines are also transitioning into collab-PLM solutions. Typically, PLM vendors do not focus efforts on the shipbuilding industry because of its size relative to other products, such as automotive or aerospace. Having a PLM tool

illustrating their stages before reaching the “plateau of productivity” in the mainstream market.

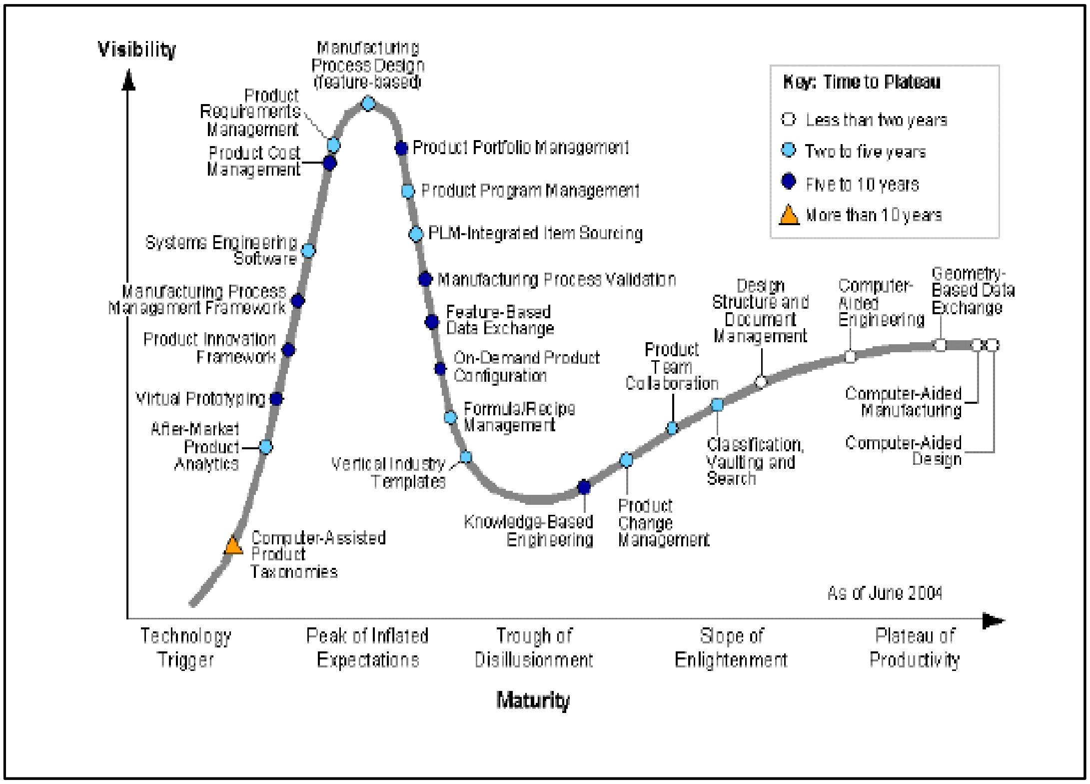


Figure 3. Evolution of PLM
(Halpern & Smith, 2004)

Three-Dimensional Laser Scanning Technology

3D scanners create a “point cloud” of the surface of an object. 3D scanners are similar to cameras in some ways. They have a cone-shaped field of view. But 3D scanners can also collect distance information about each point, allowing each point to be located in a three-dimensional space. Usually, multiple scans are required from different directions to capture adequate information to create a description of the object. Most manufacturers’ scanners work by scanning a target space with a laser light mounted on a highly articulating mount, enabling data capture in virtually any orientation with minimal operator input. Some also incorporate a digital camera that simultaneously captures a 360° field-of-view color photo image of the target. Once the capture phase is complete, the system automatically executes proprietary point-processing algorithms to process the captured image. The system can generate an accurate[3] digital 3D model of the target space, automatically fuse image texture onto

---

designed specifically for an industry has a significant impact on the tools efficiency within that industry.

[3] NSRP’s study (2006 & 2007b) requirement was within 3/16 of an inch to actual measurements.

3D model geometry, export file formats ready for commercial, high-end design, and import them into 2D/3D computer-aided design (CAD) packages.

Terrestrial laser scanning technology is well established as a useful tool in practice and is currently used in a variety of industries. According to industry analysts, laser scanner manufacturers and related software and service providers report strong activity across many markets, including shipbuilding, offshore construction and repair, onshore oil and gas, fossil and nuclear power, civil and transportation infrastructure, building, automotive and construction equipment, manufacturing, and forensics (Greaves & Jenkins, 2007). In the latest data available, sales of terrestrial 3D laser scanning hardware, software, and services reached $253 million in 2006—a growth of 43% over 2005 (Greaves & Jenkins, 2007).

Additive Manufacturing

Additive manufacturing (AM) is the youngest and most diverse technology addressed in this research. Therefore, more background is required to understand its potential role and impacts. AM has quickly moved through technology development into the mainstream, with web pages now offering services that allow the public to design and use AM to produce products of their choosing (e.g., see Kronsberg, 2013). The following descriptions, based primarily on Gibson, Rosen, and Stucker (2010) and Lipson and Kurman (2013), first describe the principles and techniques, followed by a comparison with conventional manufacturing and specific AM technologies. Finally, a brief description of current applications is provided.

Principles and Techniques

AM is defined by the American National Standards Institute (ASTM, 2013) as the “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing and freeform fabrication” (Wohlers 2010). AM is a state-of-the-art manufacturing methodology, which has radical differences with the currently dominant manufacturing methodologies. Although most current methods use subtractive processes (e.g., machining), AM builds a 3D object by gradually adding successive layers of material which are laid down exactly in the final location they should be.

The basic principle of the AM process is to fabricate an object directly from a three-dimensional computer-aided design (3D CAD) model. During the manufacturing process, the 3D model is disaggregated into multiple layers, each of which is produced by the machine and added to the preceding layers. Integration of all layers forms the final 3D object. Figure 4 illustrates how a 3D object can be considered as integration of several layers.

Figure 4. A 3D Object in Several Layers
(Gibson et al., 2010)

AM is a computer-sided design/computer-aided manufacturing CAD/CAM) process, which reduces manual manufacturing tasks as much as possible. The process generally involves a number of steps that move from a virtual 3D CAD model to a real physical 3D object, as follows:

- **CAD:** First a 3D CAD model of the target object is in software. The 3D CAD model determines only the geometry of the target object, and so its design detail is not of interest. That is why it can be replaced by an output model of a laser scanner.
- **Conversion to Stereolithography STL files:** Although the CAD model is the basis of the AM process, it cannot be used directly by AM machines. The 3D CAD model needs to be converted to STL format before it can be used as the system input. An STL file describes the external closed surfaces of the original CAD model and forms a basis for calculation of layers. Technically speaking, STL removes trivial data from the CAD file, such as construction data, modeling history, and so forth, and approximates surfaces of the model with a series of triangular facets. STL files are readable by almost all AM machines. Figure 5 illustrates a 3D CAD model along with its STL format. The maximum size of STL triangles must be in compliance with resolution of AM machine (i.e., less than the tiniest size the machine understands) to ensure that the machine is able to produce the required combinations of shapes.

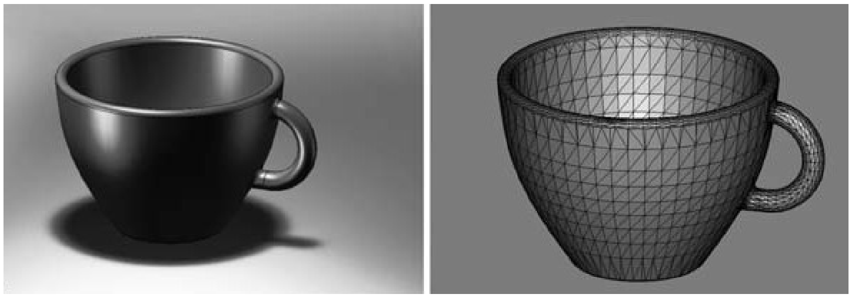


Figure 5. A 3D Object in Several Layers
(Gibson et al., 2010)

- **Revise STL File:** Before starting the manufacturing process, many AM machines allow the operator to manipulate the STL file, which is usually necessary. For example, a visualization tool (i.e., monitor) shows the location and position of the final object within the machine and allows the operator to change this if needed. In many cases, more than one object is planned to be built at a time. This can be done simply by copying the same file or adding a different object from another STL file. These replicas can also be scaled up or down in this step.
- **Machine Setup:** AM machines have setup parameters, such as material constraints, layer thicknesses, and timing, which are specific to that machine and corresponding technique. As a case in point, for those machines that have been designed to work with a variety of materials, it must be determined what materials are included in the process. In many machines, for example, a range of layer thicknesses are available. Layer thickness directly affects both the quality of the final fabricated object and the fabrication time. The thinner the layers are, the more delicate the object that will be produced, and the more time it takes to complete.
- **Build:** Target objects are automatically fabricated by a computer-controlled machine. Although all AM machines follow the layer-by-layer fabrication process, they utilize different techniques and technologies. For example, some of them use a high-power laser beam to melt a very fine metal powder in order to form a thin layer, while some others use UV light to solidify a specific kind of liquid polymer, called *photopolymer*.
- **Post-Process:** Post processing may be required after the machine concludes the fabrication process and before the object is ready for use. As an illustration, many kinds of photopolymers need a curing process after taking out of the machine to reach their anticipated

strength. Post-processing measures differ from technique to technique and from machine to machine.

Additive Manufacturing vs. Conventional Manufacturing Methods

AM is occasionally referred to as rapid prototyping. The term *rapid* implies a faster manufacturing process. This, nonetheless, does not mean that it takes a shorter time to build a part within a machine. High-speed CNC machines, for example, work much faster than AM machines. In this case, *rapid* refers to the whole process of manufacturing. AM is aimed at minimizing intermediate steps and streamlining manufacturing process. Although it is a common and inevitable practice in conventional manufacturing methods to produce different parts of a product separately and then install them, AM provides the opportunity to make a product in one part, regardless of the number of its components and complexity of their connections. In addition, Design changes are relatively easy to execture in AM. Suppose casting or injection methods are used to make a product: Any tiny change in design may lead to discarding the current mold and building a new one, which is time and resource consuming. As a result of simplifying the manufacturing process, AM can decrease the time required, as well as the amount of required resources.

One of the greatest advantages of AM is the freedom it provides for designers. This is the result of layer-by-layer fabrication. In that any geometric form is broken into very thin layers, which are produced and connected successively, there is no difference between a simple and a very complex shape in the AM process. The more complexity, the more advantage can be gained by using AM. Even CNC processes, which similarly benefit from the most advanced computing technologies, have a lot of limitations in producing complex designs because of their subtractive approach. In many instances, the CNC process needs to be broken into several steps, as different machining measures are required to complete the product. In some cases, CNC technology is ultimately unable to make all details required for the product.

Another advantage of AM is its accuracy. AM processes can operate with resolution of a few tens of microns. In other words, AM machines can produce layers as tiny as diameter of human hair. Figure 6 illustrates a micro-scale AM product. Resolution that can be achieved differs from one AM technique to another, regarding the technologies they use.

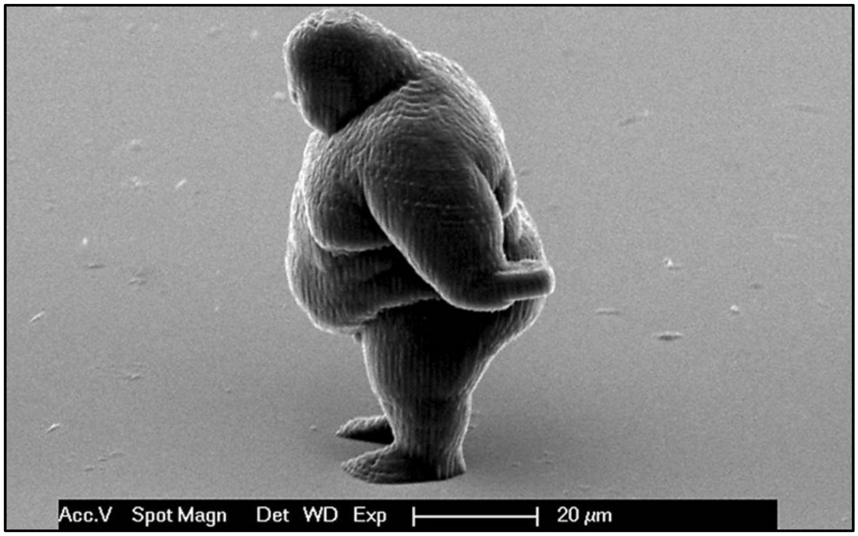


Figure 6. Fat Man, a Micro-Scale AM Product
(Reuters, 2013)

AM also has limitations. A primary limitation concerns the materials that can be used in AM. AM technologies were originally developed around polymer materials. Then some other materials, such as metals, were introduced. But the current approach remains limited to a range of materials and their physical properties (e.g., strength). Some of the AM methods (described in the next section) can only use one or a few materials.

Some AM materials require careful handling. They usually have a limited shelf life and must be kept in conditions that prevent them from unwanted chemical reactions. Exposure to moisture, excessive light, and so forth, may degrade or destroy some materials. Another problem is that, although most of the AM materials can be used several times theoretically, in practice reuse can degrade their properties over time.

Additive Manufacturing Technologies

Although all AM methods use layer-by-layer production, they differ in terms of procedures, technologies, materials, and applications.

Photopolymerization: The basic principle of photopolymerization is to solidify a special type of liquid polymer using UV light. The liquid polymer is sensitive to UV light, and under a chemical reaction turns to solid state if exposed to UV light. Because of this characteristic, the polymer is generally called photopolymer. Stereolithography (SL or SLA) is a well-known photopolymerization technique. In SL, a vat of liquid photopolymer sits in an AM machine. There is a source of UV light above the vat, which is able to emit a narrow beam of light. Accuracy of the UV beam determines the accuracy of the SL process. Once the UV beam touches the photopolymer, it hardens the liquid as big as its footprint on the surface. There is also a moving, computer-controlled table in the vat, which can move upward and downward. At the start point of the process, the table, which is actually a supporting platform for the final product, is almost at the level of liquid surface. In fact, it is lower than the liquid surface by a fraction of millimeter, allowing a very thin layer of liquid to cover it. The UV beam sweeps the liquid surface and touches target points of the lowest layer of final object in the CAD model. The moving table (with the first layer stuck on it) sinks a bit (equal to the next layer) into the liquid polymer, and so a film of photopolymer covers the first layer. This process is repeated with each sweep of the surface, creating a layer of the object until the whole object is fabricated. Photopolymerization is not limited to UV light; visible lights or other radiations can also be used in the process (based on the photopolymer properties).

Powder Bed Fusion: Powder bed fusion (PBF), also widely referred to as selective laser sintering (SLS), is similar to SL in terms of procedure. But this method uses powder materials instead of "liquid polymer" and a heating source (usually a high-power laser) instead of UV light. As the first step, a roller brushes a thin layer of powder over a platform. Then the high-power laser start sweeping the first powder layer on the platform and touches required points defined in the STL file. The laser melts the steel powder, causing the steel particles to stick together. The platform moves down a bit and the process is repeated. A pre-heating system is usually used in the process to increase the temperature of raw powder. This helps to minimize the laser power requirements, as well as prevents the product from wrapping due to heat concentration. The fabrication process is also done in an enclosed chamber filled with nitrogen gas (or in a vacuumed chamber), because the hot powder is highly vulnerable to oxidation. No temporary support is required because the unused powder acts as built-in support and prevents the product from collapsing.

There are several variants of PBF manufacturing, one of which is called indirect processing. In this method, a polymer-coated powder (say metal powder) is used instead of pure powder. The laser heat does not affect the metal powder but melts the polymer cover, which binds the metal particles. The created object in this step is then put in a furnace. The furnace heat melts the metal particles and makes them join together, while vaporizing the polymer cover. Similar process of coating main particles with a binding polymer is sometimes used to make molds. Both sand and ceramics, for example, are used to make metal-casting molds. Another variant is electron beam melting (EBM), in which electron beam is used in the process as the focused heat source.

Three-Dimensional Printing: Three dimensional printing (3D printing or 3DP) is a confusing name in that it currently refers to both the whole AM process and one of its techniques. The 3DP technique, which was developed by MIT researchers, is inherently a powder-bed approach. It shares the principle of using powder material with PBF, but it does not use a heating-based sintering system. Instead, a high-power laser beam touches a thin layer of powder material, and the print head (nozzle) squeezes adhesive to bind the powder particles together. Almost all materials that can be supplied in powder can be used in this method. 3DP is very similar to SLS systems. One of the advantages of a 3DP system is its simplicity in that it does not utilize highly complicated technologies such as lasers. In addition, it provides the possibility of printing in colors. In order to make colorful objects, the printer just needs to squeeze color droplets along with glue. Although simplicity of the system brings some advantages, it cannot make high resolution products like the laser-based systems can.

Beam Deposition: *Laser engineered net shaping (LENS)*, *laser metal deposition* or *laser-based metal deposition*, *laser freeform fabrication*, *construction laser additive direct*, *directed light fabrication*, and *directed metal deposition* are terms used to refer to the beam deposition (BD) process. Beam deposition is dominantly used for metal powders. It is similar to the SLS technique in that it uses laser as a focused heat source to melt and bind powder materials. Lasers, nevertheless, are not used to melt material that is pre-laid in a powder bed. Instead, the laser is used to melt materials as they are being deposited. The principle of this technique is that powder particles are blown into a laser beam. While depositing, some of them meet the laser beam in its focal point, and others do not. Those particles which deposit on the focal point are melted. As the laser beam is sweeping the substrate, molten material is being deposited and gradually forms a new layer. The powder material is blown through a tiny nozzle, which is attached to the laser device and is connected to a powder reservoir. Integration of the laser device and powder nozzle forms the deposition head. Other focused heat sources, such as electron beam, can be also used in this technique instead of a laser. Technically, more than one powder nozzle is used in a deposition head so that more powder can be blown and more particles are likely to be melted and deposited. This can increase the quality of deposited layer. Having more than one powder nozzle also provides the possibility of fabricating an object composed of different alloys in different parts. In fact, different nozzles can be used to blow different metal powders into the laser beam, which will be mixed while depositing and form a metal alloy. The ratio of alloy constituents can be changed at any time, so different alloys can be used while fabricating a single part. Another advantage of this technique is that the substrate can be either a flat plate on which a new part will be fabricated, or an existing part onto which additional geometry will be added.

Polyjet Printing: Polyjet printing is one the newest AM techniques. It can be considered to be a combination of LENS and SL techniques. A polyjet printing system utilizes a deposition head like LENS, using a photopolymer and UV light instead of metal powder and laser. The photopolymer liquid is sprayed through the nozzles into a narrow beam of UV light, and solidified polymer particles are deposited on the surface and form a new layer of solid material. Polyjet printing systems can fabricate high resolution objects.

Laminated Object Manufacturing (LOM): LOM or sheet lamination involves layer-by-layer lamination of very thin sheets of material. Each sheet represents one cross sectional layer in the CAD model. In LOM, each layer is cut—using laser or mechanical tools—from a larger sheet of material. The unused part of each sheet is cut into small cubes using a cross-hatch cutting operation. Several sheets (laminas) are cut and bound together to form the final object. Different methods are used to bind the laminas. One of them is gluing or adhesive bonding. Coating sheets with a thin thermoplastic cover, which acts as glue, is a common practice to bind them together. Thermal bonding is another approach to bind the layers. In this method, no coating is used, and heat brings about fusion of layers. Thermal bonding is widely used for metal sheets. Clamping is another simple and mechanical solution for metal laminated objects. Ultrasonic consolidation is also another fusion method, which binds metal sheets using powerful ultrasonic vibrations. The vibration causes the sheet to rub against the previous layer and consolidate into densely packed layers.

Extrusion-Based Systems: Extrusion, also called fused deposition modeling (FDM), is a simple form of AM. It is quite similar to putting icing on a cake. A creamy (semi-solid) substance is gradually extruded through a nozzle by applying pressure. The extruded material forms a track of the under-printing layer. In a horizontal level, integration of these tracks forms one layer of the final product. Extrusion-based systems are limited to materials with semi-solid (creamy) forms, which can be solidified after extrusion. Thermoplastic polymers are perfect materials for this approach. They are easily liquefied by heat and solidify instantly when they become cold. Thermoplastic materials exist in form of rolled filaments. In an extrusion-based AM machine, the filament is guided through the nozzle (deposition head). A built-in heating system in the deposition head melts the plastic filament so that it can easily flow through the nozzle. The extruded semi-solid plastic then becomes hard as it gets cold.

Commercial Applications

AM has a great advantage in making prototypes for concept modeling and functional testing. Prototypes can be directly fabricated from a CAD design with very high level of accuracy (necessary for complex designs). The process is also rapid, especially when several prototypes are to be built after small changes in design. Almost all AM systems can be used in prototyping because prototypes do not need to have specific mechanical properties in many applications.

Some companies have developed AM systems for the aerospace industry, which usually does not require high-volume production. These systems are capable of fabricating aircraft engine parts as well as interior parts of airplanes. Similar to the aerospace industry, AM systems are capable of producing functional parts for automobiles, especially race cars. Engines of racing autos have usually specific designs and include special parts that are not produced in mass quantities.

One of the major applications of AM is production of medical prostheses and implants. AM is very suitable for this purpose because artificial parts implanted in a human's body must be unique to the patient's body and damage, such as replacing a portion of a damaged skull. The implant geometry can be captured using advanced medical imaging procedures, such as a CT scan, and can be produced using the AM process with high accuracy and resolution. Another advantage of using AM for this kind of bone replacement is that AM makes it possible to produce porous implants so that bone cells can grow through it and fix the damage naturally over time. Production of dental crowns and partials also benefit from AM. Similar to medical implants, the required geometry can be captured using advanced imaging technologies, so that the artificial part would be produced as exactly as it is needed.

Summary

AM is a relatively new technology that directly deposits materials to make products by sequentially depositing millions of particles in thousands of layers to "build up" the final component. Three-dimensional design documents direct manufacturing hardware. By controlling the movement of the material deposition equipment and the flow of material, the process controls where particles are deposited in each layer, thereby creating surfaces, shapes, and cavities. Materials can be plastic for fast prototyping, metals, ceramics, or human tissue. 3D printing has several advantages over traditional manufacturing methods. First, a primary advantage is the ability to create almost any shaped product, with the only limitation being the need for each layer of material to have a layer below it for support, although secondary materials can be used to provide support under overhanging component parts during manufacturing. Second, the process is additive, whereas traditional methods are subtractive. This greatly reduces waste materials.

Research Methodology

The research team collected data on the use of AM by the Navy and used it and information from the literature to build two types of computer simulation models of ship maintenance: a system dynamics (SD) model of ship maintenance operations, and knowledge value added (KVA) models of return on technology investments. The models were used to simulate six scenarios that represent realistic conditions of the use of the technologies. The results were then used to estimate cost savings for each scenario if they were applied to routine ship maintenance processes more generally. This extrapolation from the actual experience with AM at the NAVAIR maintenance depot to wider use is supported by the similarity in the processes and kinds of legacy repair and replacement parts that are most prevalent in routine ship maintenance. The results from this modeling were then compared with previously developed modeling results of U.S. Navy ship maintenance and technology adoption. In this section, we review the two approaches, beginning with a general review of the KVA and SD approaches. This is followed in a description of the data collection and the models in the next section and the projected results from applying these approaches. A comparison of the results with previous results and discussion follows.

Knowledge Value Added

KVA measures the value provided by human capital and IT assets by an organization, process, or function at the subprocess level (see Figure 7). It monetizes the outputs of all assets, including intangible knowledge assets. Capturing the value embedded in an organization's core processes, employees, and IT enables the actual cost and revenue of a product or service to be calculated (see Figure 8).

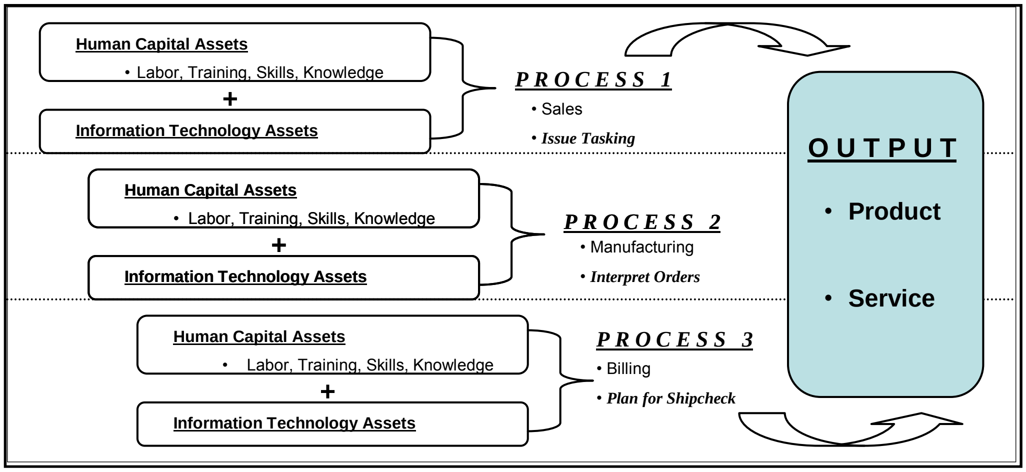
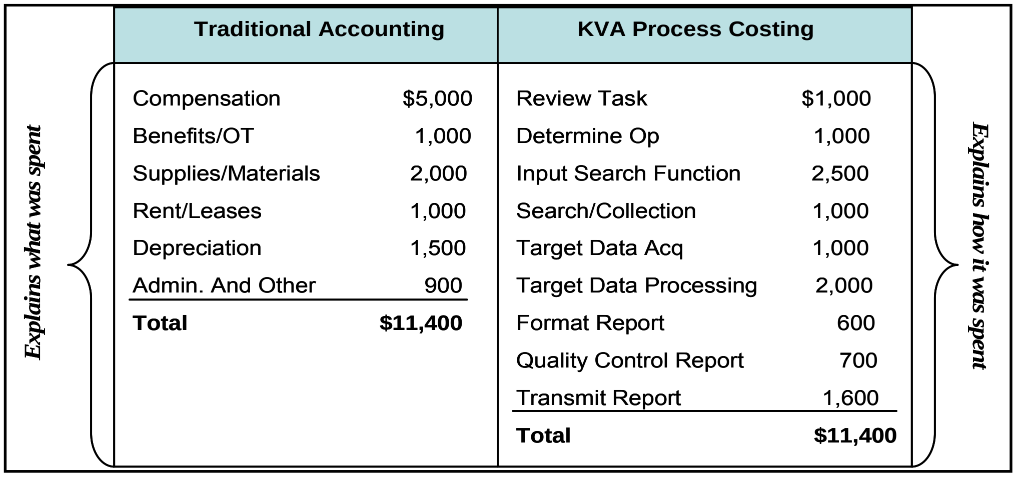


Figure 7. Measuring Output



Explains what was spent

Traditional Accounting		KVA Process Costing	
Compensation	$5,000	Review Task	$1,000
Benefits/OT	1,000	Determine Op	1,000
Supplies/Materials	2,000	Input Search Function	2,500
Rent/Leases	1,000	Search/Collection	1,000
Depreciation	1,500	Target Data Acq	1,000
Admin. And Other	900	Target Data Processing	2,000
Total	**$11,400**	Format Report	600
		Quality Control Report	700
		Transmit Report	1,600
		Total	**$11,400**

Explains how it was spent

Figure 8. Comparison of Traditional Accounting Versus Process-Based Costing

Total value is captured in two key metrics: return on investment (ROI) and return on knowledge (ROK; see Table 1). Although ROI is the traditional financial ratio, ROK identifies how a specific process converts existing knowledge into producing outputs so decision-makers can quantify costs and measure value derived from investments in human capital assets. A higher ROK signifies better utilization of knowledge assets. If IT investments do not improve the ROK value of a given process, steps must be taken to improve that process's function and performance.

Table 1. Knowledge Value Added Metrics

Metric	Description	Type	Calculation
Return on Knowledge (ROK)	Basic productivity, cash-flow ratio	Subcorporate, process-level performance ratio	(Outputs-Benefits in Common Units) Cost to Produce Output
Return on Investment (ROI)	Same as ROI at the sub-corporate, process level	Traditional investment finance ratio	(Revenue-Investment Cost) Investment cost

The goal is to determine which core processes provide the highest ROIs and ROKs, and to make suggested process improvements based on the results. In the current work, KVA is used to measure the benefits of technology adoption in ship maintenance. This analysis provides a means to check the reliability of prior studies' estimates of the potential ROI core process improvements from using CPLM, AM (3DP), and 3DLST in ship-maintenance core processes in the U.S. Navy yards.

System Dynamics

The system dynamics methodology applies a control theory perspective to the design and management of complex human systems. System dynamics combines servo-mechanism thinking with computer simulation to analyze systems. It is one of several established and successful approaches to systems analysis and design (Flood & Jackson, 1991; Jackson, 2003; Lane & Jackson, 1995). Forrester (1961) developed the methodology's philosophy, and Sterman (2000) specified the modeling process with examples and described numerous applications.

The methodology has been extensively used for this purpose, including studying development projects. The system dynamics perspective focuses on how the internal structure of a system impacts system and managerial behavior and, thereby, performance over time. The approach is unique in its integrated use of stocks and flows, causal feedback, and time delays to model and explain processes, resources, information, and management policies. Stocks represent accumulations or backlogs of work, people, information, or other portions of the system that change over time. Flows represent the movement of those commodities into, between, and out of stocks. The methodology's ability to model many diverse system components (e.g., work, people, money, value), processes (e.g., design, technology development, production, operations, quality assurance), and managerial decision-making and actions (e.g., forecasting and resource allocation) makes system dynamics useful for modeling and investigating military operations, the design of materiel, and acquisition.

When applied to acquisition programs, system dynamics has focused on how performance evolves in response to interactions among development strategy (e.g., evolutionary development versus traditional), managerial decision-making (e.g., scope developed in specific blocks), and development processes (e.g., concurrence). System dynamics is appropriate for modeling acquisition because of its ability to explicitly model critical aspects of development projects. System dynamics models of development projects are purposefully simple relative to actual practice in order to expose the relationships between causal structures and the behavior and performance that they create. Therefore, although many processes and features of system design and participants interact to determine performance, only those that describe features related to the topic of study are included. The importance of deleted features can be tested when system dynamics is used to test the ability of the model structure to explain system behavior and performance.

System dynamics has been successfully applied to a variety of development and project management issues, including rework (Cooper, 1993a, 1993b, 1993c; Ford & Sterman, 1998), the prediction and discovery of failures in project fast-track implementation (Ford & Sterman, 2003b), poor schedule performance (Abdel-Hamid, 1988), tipping point structures in projects (Taylor & Ford, 2006, 2008), contingency management (Ford, 2002), resource allocation (Joglekar & Ford, 2005; Lee, Ford, & Joglekar, 2007), and the impacts of changes (Cooper, 1980), and concealing rework requirements on project performance (Ford & Sterman, 2003a). See Lyneis and Ford (2007) for a review of the application of system dynamics to projects and project management.

System dynamics has also been applied to military systems, including planning and strategy (Bakken & Vamraak, 2003; Duczynski, 2000; McLucas et al., 2006; Melhuish et al., 2009), workforce management (Bell & Liphard, 1978), technology (Bakken, 2004), command and control (Bakken & Gilljam, 2003; Bakken, Gilljam, & Haerem, 2004), operations (Bakken, Ruud, & Johannessen, 2004; Coyle & Gardiner, 1991), logistics (Watts & Wolstenholme, 1990), acquisition (Bartolomei, 2001; Ford & Dillard, 2008, 2009a, 2009b; Homer & Somers, 1988), and large system programs (Cooper, 1994; Homer & Somers, 1988; Lyneis, Cooper, & Els, 2001). Coyle (1996) provided a survey of applications of system dynamics to military issues.

The system dynamics methodology provides several advantages in simulating complex dynamic systems such as the use of advanced technologies for naval ship maintenance. First, system dynamics models make feedback explicit. Feedback can be critical in understanding, explaining, and exploiting the structure of dynamic systems. An example of feedback in the current work is the return of prototypes to design after they fail the inspection or functional tests. Other features of system dynamics models can be used in the future to improve the understanding of the drivers of behavior and performance, including the ability to simulate related activities and costs (e.g., materials savings and manufacturing infrastructure) and the ability to simulate transitions from one steady state to another, such as from current levels of adoption to full adoption.

Data Collection and System Description

One member of the research team (Housel) and a graduate student (Kenney) visited the Naval Surface Warfare Center Port Hueneme Division (NSWC PHD) on May 10, 2013, and collected detailed information on the use of AM by that facility. They then visited the Naval Air maintenance depot in San Diego on July 17 and 18, 2013, and interviewed Gabe Draguicevich of the Fleet Readiness Center Southwest concerning the use of AM at the North Island NAVAIR maintenance depot. Based on that data and a review of the literature Kenney (2013) developed a description of the current processes based on the collected information, summarized next.[4]

The parts maintenance process includes both administrative and manufacturing-related processes. The manufacturing related processes include both information processing and processes performed on the materials that eventually become the part itself. Although the system includes a number of iterative loops (described later), the processes are generally sequential.

---

[4] See Kenney (2013) for details of the data collected.

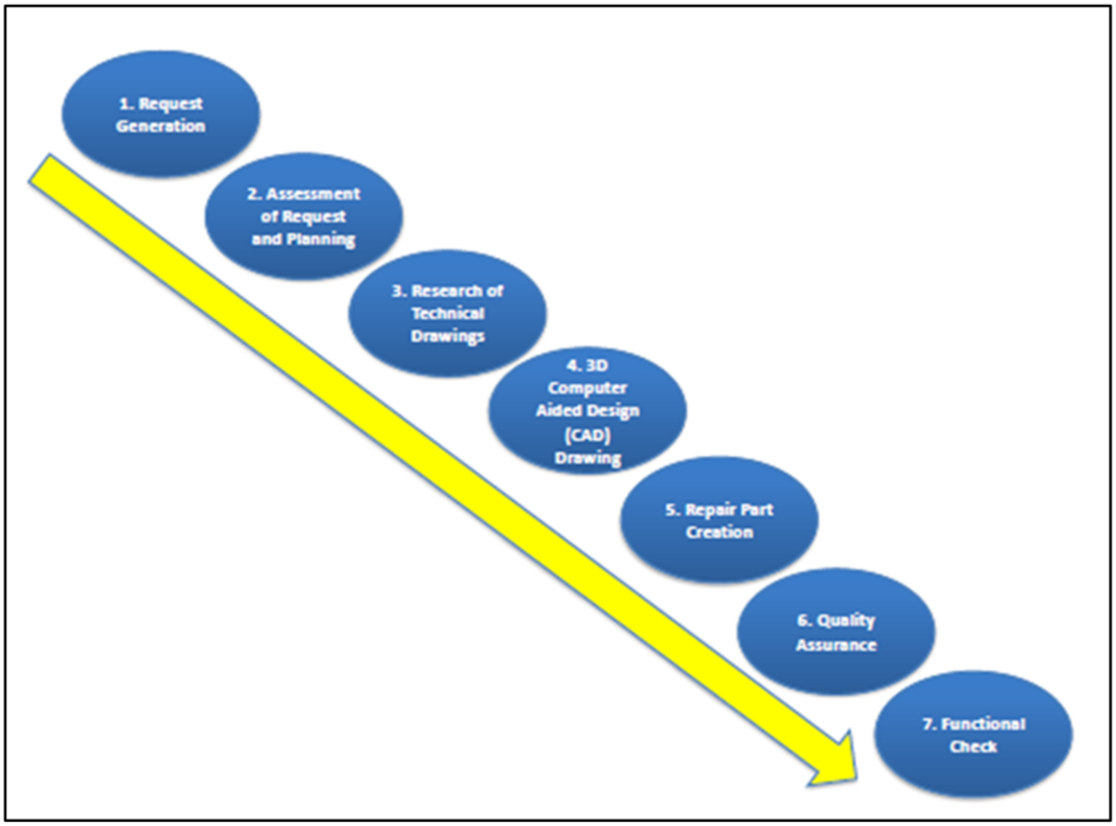


Figure 9. Repair Part Manufacturing Process
(Kenney, 2013)

The process as depicted in Figure 9 does not include feedback, which is important in modeling the processes. However, Kenney (2013) partially described this feedback with the iteration in the depot-level machining shop process (see Figure 10) based on the data gathered.

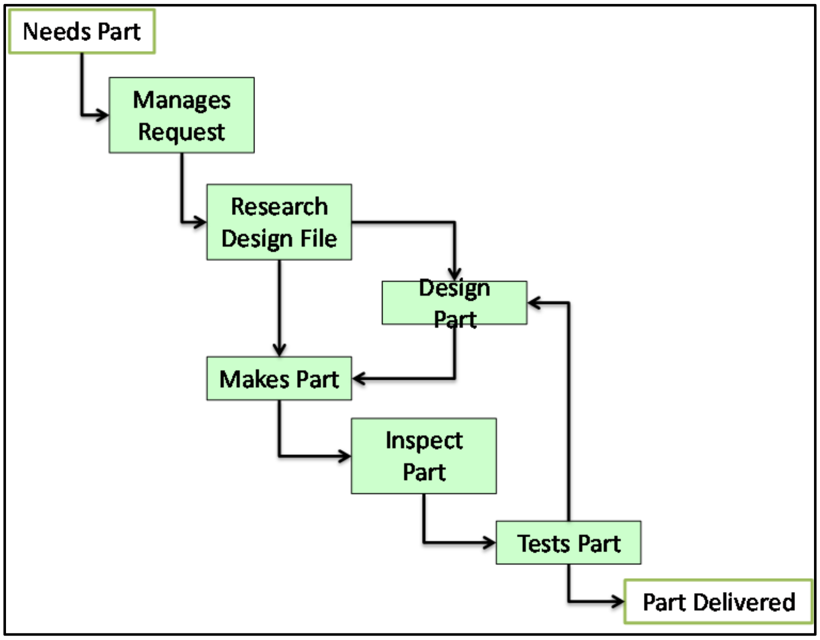


Figure 10. Depot-Level Machining Shop Process
(Kenney, 2013)

In addition to the feedback shown in Figure 10 from "Test Part" to "Design Part" and back to "Test Part" through "Makes Part" and "Inspect Part," a different feedback loop exists when parts fail inspection. In this feedback loop, parts move from "Inspect Part" to "Design Part," then to "Makes Part," and back to "Inspect Part" again. These two feedback loops are shown in Figure 11, which indicates the processes diagrammed by Kenney (2013) in Figures 9 and 10 and the similar variable used in the system dynamics model in parentheses. Figure 11 shows the reinforcing feedback loop R1, the failed testing loop described in Figure 10, and the reinforcing feedback loop R2, the failed inspection loop that is created by adding the causal link (heavy arrow) from "Inspect part (Inspection rate)" to "Design part (Complete DAC design rate)." Figure 11 also indicates the roles of the process of gathering existing conditions, which the 3DLST facilitates, and the inspection and testing failure fractions, which determine the volume of work caught in the rework cycle. These processes, including the feedback, were incorporated into the formal system dynamics model. They thereby impact the KVA model results and the performance metrics of different technology adoption and use strategies.

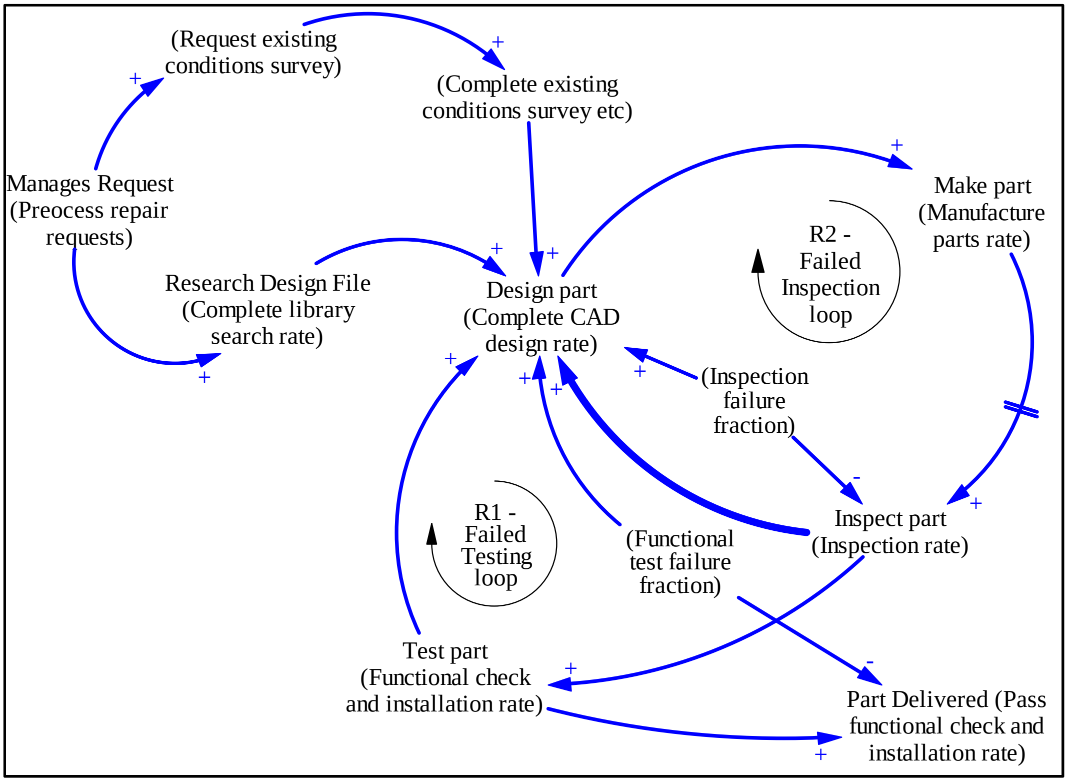


Figure 11. Partial Feedback in the Repair Part Manufacturing Process

Note. Legend of Loops:
R1—Failed Testing loop: More part testing increases designing parts, which increases making parts, inspecting parts, and thereby the testing of parts
R2—Failed Inspection loop: More part inspections increases designing parts, which increases making parts and thereby inspecting parts

A System Dynamics Model of Naval Fleet Parts Design and Manufacturing

Model Structure

The system dynamics model was based on an understanding of manufacturing processes, previous research on AM, 3DLST, and CPLM, and the data collected about the use of AM at the Fleet Readiness Center Southwest. A conceptual description of that model is provided here. Model details are available from the authors.

The core of the model structure is two sequential chains that each reflect the addition of value to either information used to manufacture a part or the material that is used to manufacture the part. The information processing structure (see Figure 12) models the flow of the parts information through the processes identified by Kenney (see Figure 9 and Figure 12, lower portion) and the collection and processing of existing conditions information (see Figure 12, top portion). More specifically, the model reflects receiving parts requests, processing parts requests, library searches, inspection failures, functional check failures, design, preparing manufacturing files, and "fixturing." These processes are depicted by pipes with arrows and valve symbols that connect the boxes in Figure 12.

These information flows are typically constrained by the workforce applied to each process and the time required to process the information for an average part. However, the "Complete CAD design rate" (see Figure 12, right) is also constrained by the rate at which "Complete existing conditions surveys, etc." (see Figure 12, top center with copy of that variable in lower right) occurs. Changing the information processing times is one of the impacts that different information technologies (i.e., 3DLST and CPLM) have on the model.

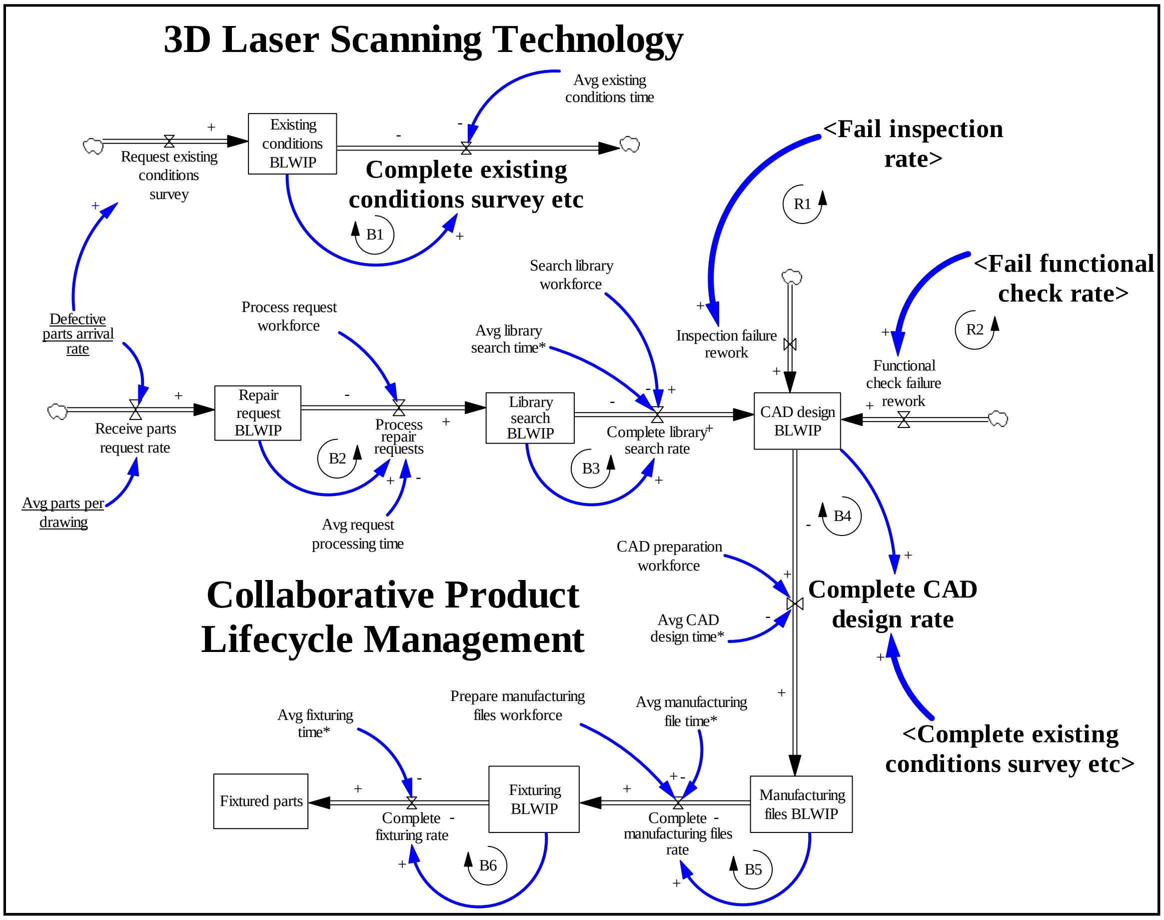


Figure 12. Information Processing Structure of the System Dynamics Model

In the system dynamics model, the information processes are separated by stocks, the accumulations of information that are waiting to be processed or that are being processed in backlogs and work-in-progress (abbreviated BLWIP in Figure 12), as depicted by the boxes in Figure 12. Separated by the processes that add value to and transform the information, this creates an aging chain, a sequence of alternating stocks and the flows in which materials or information matures over time due to processes (Sterman, 2000). These accumulations of net inflows and outflows create delays in systems, “remember” the net impact of past inflows and outflows, and provide momentum that can drive flows (Sterman, 2000). The dynamic movement of information through these accumulations is controlled directly by their inflows and outflows.[5] Those inflows and outflows (i.e., the information processes) are controlled by many feedback loops. Each feedback loop uses system components, causal links, and loop polarity to describe a series of unidirectional causal links among system components which, in combination, create closed paths of interactions. Causal links (symbolized with arrows) describe how an increase or decrease in the value of the component at the tail of the arrow impacts the value of the component at the head of the arrow. Positive causal links (“+” at the arrowhead) indicate that the values move in the same direction and negative causal links (“-” at the arrowhead) indicate that the components move in opposite directions.

Feedback loops are either balancing (B1, B2, etc., in Figure 11) or reinforcing (R1 or R2 in Figure 12). Structures dominated by balancing feedback loops generate behavior which resist continued change in a single direction and direct systems toward a goal or equilibrium conditions. In contrast, reinforcing feedback loops often generate behavior that moves component values progressively away from initial or equilibrium values or accelerate flows.

The movement of information through the basic processes identified by Kenney (2013) provided the basis for modeling the impacts of CPLM on parts replacement. In addition to the information processes identified by Kenney (2013), the information processing portion of the model reflects the collection of existing conditions information for use in parts manufacturing. This allows the explicit modeling of 3DLST, which can greatly improve this information process.

The information processing structure (see Figure 12) also includes part of the two feedback structures created by the failure of parts to pass inspection or functional checks, as described in the results of data collection above. These feedback loops pass through the CAD design and manufacturing files processes (see Figure 11), the parts manufacturing processes (described next), and back to the CAD design process when a part fails an inspection for functional test (large bold text and causal links in Figure 12).

---

[5] The role and influence of the BLWIP stocks is analogous to a bathtub. Changes in the amount of water in a bathtub are controlled by the difference between the amount of incoming water from the faucet and water leaving through the drain. The amount of water in the tub is determined by that difference and the amount of water in the tub before those flows (i.e., the net impacts of all the previous flows, or memory). The amount of water in the tub provides inertia for the outflow through the drain, in this case through the creation of static water pressure. The accumulation process requires time for the water, and the inertia it creates, to change (i.e., delays). The BLWIP in the model of parts manufacturing generate the same impacts on that system.

The manufacturing processing portion of the model structure (see Figure 13) depicts the flow of parts through the manufacturing processes, shown with pipes with arrows and valve symbols that connect the boxes in Figure 13. More specifically, the model reflects material acquisition, manufacturing, inspection, and functional checking. These flows are generally constrained by the workforce applied to each process and time required to perform the process on an average part for each process and by the fraction of parts that fail the inspection and functional tests. Changing these processing times and failure fractions are the primary means of reflecting the impacts of AM in the model.

As in the information processes aging chain, the manufacturing processes are separated by stocks, the accumulation of parts that are waiting to be processed or that are being processed in backlogs and work-in-progress (BLWIP), as depicted by the boxes in Figure 12. The flows that link those stocks (i.e., the manufacturing processes) are controlled by feedback loops. The primary balancing feedback loops (B7 through B12) are shown in Figure 12. As described above, the rate of inspection failure and functional check failure (flows in large bold type in Figure 12) form a critical part of the feedback structure of the model by recycling work back into the information processes for correction before the manufacturing and testing processes can be repeated.

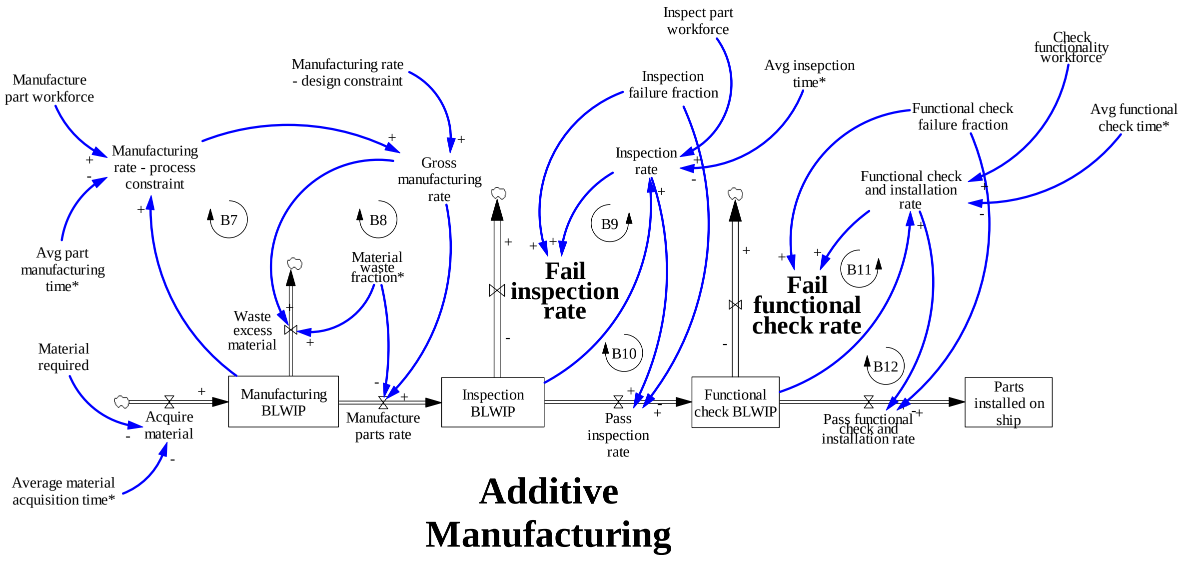


Figure 13. Manufacturing Processing Structure of the System Dynamics Model

Model Testing

The model was tested using standard tests for system dynamics models (Sterman, 2000), including tests of structural validity and behavior validity. Structural validity was increased by basing the model structure on established information about the system being modeled and data collected directly from the system operators and managers. Unit consistency checks verified that the formal model conformed to system conditions. Model behavior tests included extreme conditions testing and behavior similarity testing.

Specific model variables were set to values that allowed model behavior to be reliably predicted. As a simple example, if the fraction of parts failing inspection is zero the behavior of the flow “Fail inspection rate” should also be zero. Many tests of model behavior under extreme conditions increased the confidence that the model was simulating reasonable behavior for the same reasons that the actual system would create those behaviors. The model also created behavior patterns that are similar to those known or suspected to occur in the actual system. These and other tests indicate that the model is useful for simulating naval parts design and manufacturing for investigating the impacts of AM, 3DLST, and CPLM in ship maintenance processes. Although in the current work, the system dynamics model is used to generate input for the KVA model, in future work it can also be used to investigate reductions in parts manufacturing inventories and infrastructures with their related cost savings and the transitions from current practices to those that in which new technologies have been adopted and become standard operating procedures.

Knowledge Value Added Models of Naval Fleet Parts Design and Manufacturing

The output (flow rates) from the system dynamics model were used to build KVA models of six scenarios that reflect different strategies for the adoption and use of the three technologies (3DLST, CPLM, and AM) in naval parts production for ship maintenance:

- **As-Is:** Current processes used at the depot where data was collected
- **To-Be#1:** Immature AM in which AM is used only to create prototypes
- **To-Be#2:** Immature AM with CPLM and AM being used only to create prototypes
- **To-Be#3:** Immature AM with 3DLST, CPLM, and AM being used only to create prototypes
- **Radical#1:** Mature AM with CPLM and AM being used to create both prototypes and final parts
- **Radical#2:** Mature AM with 3DLST, CPLM, and AM being used to create both prototypes and final parts

The scenarios differ in two dimensions: the technologies used, and the scale of adoption and use of those technologies. In this way, the model results can be used to assess how these two important aspects of technology adoption impact costs.

Assumptions used in building the KVA models include the following:

- The use of 3DLST reduces the time required for gathering, preparation, and reporting of existing conditions on board the ship from 60 hours to 16 hours.
- The use of 3DLST reduces number of persons required to collect existing conditions information and transform that into CAD for design by a factor of four.
- The use of 3DLST reduces inspection failure rates by 5% (from 20% to 15%).
- The use of AM reduces the time required to manufacture a part from an average of 40 hours to five hours, including set-up time.
- The use of immature AM reduces material waste in manufacturing by 40% (from 50% to 10%), and the use of mature AM reduces material waste in manufacturing by an additional 5% (from 10% to 5%).
- The use of AM increases throughput by a factor of 30. This is based on an expert interview that includes a description of an engineer being able to complete three to four iterations of a part per year with the current technologies and processes but being able to “hundreds” of iterations per year as envisioned (Draguicevich, 2013). 100/4 = 25 times more throughput. 100/3 = 33 times more throughput. For the analysis, 30 times was assumed.
- The use of information technology in AM, collaborative lifecycle management, and 3D laser scanning technologies add new value to the processes that they impact, whereas the use of information technology in traditional technologies and processes primarily replace work that could be done by humans.
- A market comparable approach was used to estimate a surrogate revenue stream. The surrogate review stream was assumed to be the product of the unit market value of the product (from the data collected) and the volume of products generated in each scenario.

Results of Knowledge Value Added Model Simulations of Naval Fleet Parts Design and Manufacturing

The results of the KVA models of the six scenarios are shown in Tables 2–7. More detail is provided in Appendix A.

Table 2. KVA Results for As-Is (Current Technologies) Scenario

AS IS - Current Technologies		
Processes	**Benefit: Cost Ratio**	**ROI (%)**
Process request	1.28	28%
Search Library	0.71	-29%
Prep CAD	5.75	475%
Fixturing	4.17	317%
Manufacture part	1.65	65%
Inspect part	1.56	56%
Check functionality	0.25	-75%
Totals:	**1.30**	**30%**

Table 3. KVA Results for To-Be#1 (Immature AM) Scenario

TO-BE#1- Immature AM		
Processes	**Benefit: Cost ratio**	**ROI (%)**
Process request	0.09	-91%
Search Library	0.14	-86%
Prepare CAD & Add manuf	2.25	125%
Fixturing	0.83	-17%
Manufacture part	0.32	-68%
Inspect part	0.61	-39%
Check functionality	0.05	-95%
Totals:	**1.12**	**12%**

Table 4. KVA Results for To-Be#2 (Immature AM + CPLM) Scenario

TO-BE#2- Immature AM + CPLM		
Processes	**Benefit: Cost ratio**	**ROI (%)**
Process request	0.67	-33%
Search Library	0.33	-67%
Prepare CAD & Add manuf	6.57	557%
Fixturing	2.22	122%
Manufacture part	0.77	-23%
Inspect part	1.54	54%
Check functionality	0.11	-89%
Totals:	**1.92**	**92%**

Table 5. KVA Results for To-Be#2 (Immature AM + CPLM + 3DLST) Scenario

TO BE#3-Immature AM + CPLM + 3DLST		
Processes	**Cost to Benefit Ratio**	**ROI (%)**
Process request	0.78	-22%
Search Library	0.47	-53%
Prepare CAD & Add manuf	4.00	300%
Fixturing	1.27	27%
Manufacture part	0.44	-56%
Inspect part	0.88	-12%
Check functionality	0.07	-93%
Totals:	**1.40**	**40%**

Table 6. KVA Results for Radical To-Be#1 (Mature AM + CPLM) Scenario

RADICAL TO-BE#1- Mature AM + CPLM		
Processes	**Benefit: Cost ratio**	**ROI (%)**
Process request	3.13	213%
Search Library	1.27	27%
Prepare CAD & Add Manuf	26.01	2501%
Inspect part	3.08	208%
Check functionality	0.48	-52%
Totals:	**8.87**	**787%**

Table 7. KVA Results for Radical To-Be#2 (Mature AM + CPLM + 3DLST) Scenario

RADICAL TO-BE#2-MatureAM+CPLM+3DLST		
Processes	**Cost to Benefit Ratio**	**ROI (%)**
Process request	36.35	3535%
Search Library	4.82	382%
Prepare CAD & Add Manuf	104.83	10383%
Inspect part	11.68	1068%
Check functionality	1.82	82%
Totals:	**14.91**	**1391%**

Estimates of Cost Savings

The cost estimate of each of the six scenarios is the sum of four components, as shown in Table 8.

Table 8. The Four Components of Each Scenario Cost Estimate

	Prototype parts produced	**Final parts produced**
Old technologies	Prototype cost using old technologies	Final parts cost using old technologies
New technologies	Prototype cost using new technologies	Final parts cost using new technologies

The cost estimate for each cell in Table 8 was made on an annual basis using the specific benefits and ROI for the cell and the definition of ROI, as described below. Benefits were estimated using a surrogate revenue stream based on the market comparable value of the output that would be produced internally by the scenario. Each cell's surrogate revenue stream was the product of the annual production of prototype or final parts and the market comparable value of that type of part. Production rates were estimated based on information from the interview with the expert (Draguicevich, 2013), who suggested the following values for current operations (As-Is scenario):

- 2,000 prototypes per year using AM

- 3,000 prototypes each year using traditional methods
- 25,000 final parts, all using traditional methods

The market comparable value of an average prototype was also based on the interview of the expert who said, “Externally we see charges anywhere between $6,000 to $8,000 dollars and upwards of $15,000 per model” and later confirmed that $12,000 was “at the upper end of your range” (Draguicevich, 2013). Based on this, the value of an average prototype was estimated to be the mean of $6,000 and $15,000 (= $10,500/prototype). The average value of a finished part was assumed to be four times that of a prototype, or $42,000 per final part. The products of the production rates and market comparable values were summed across part type and technologies to estimate the surrogate revenue for each scenario.

Table 9 shows, the calculation of the As-Is scenario as an example calculation of a surrogate annual revenue for a scenario.

Table 9. Example Calculation of the Surrogate Revenue Streams for the Four-Part/Technology Types (As-Is Scenario)

	Prototypes			**Final Parts**		
	Production (parts/yr)	**Market comparable value** ($1,000/part)	**Surrogate revenue stream** ($1,000/yr)	**Production** (parts/yr)	**Market comparable value** ($1,000/part)	**Surrogate revenue stream** ($1,000/yr)
Old technologies	3,000	$10.5	**$31,500**	25,000	$42.0	**$1,050,000**
New technologies	2,000	$10.5	**$21,000**	0	$42.0	**$0**

The ROI values of each cell in Table 9 were derived from the KVA model results (see previous section), except for traditional processes without use of the three new technologies, for which inadequate data was available to build a KVA model. This return was estimated to be half of the ROI of the As-Is scenario (30%/2 = 15%) for all scenarios.

The benefits and ROI were combined to estimate scenario costs using the definition of return on investment

ROI = (Benefits – Costs) / Costs

which can alternatively be written as

Cost = Benefits / (ROI + 1).

The results of applying the method above are shown in Table 10.

Table 10. Estimated Annual Parts Production Costs and Cost Savings

Scenario Simulation Name	Scenario Description	Old techn. prototypes / year	New techn. prototypes / year	Old techn. final parts / year	New techn. final parts / year	ROI - old techn.	ROI - new techn.	Prototype cost (X$1,000)	Final parts cost (X$1,000)	Total Cost (X$1,000)	Cost Savings from As-Is scenario (X$1,000)
As-Is	Current technologies	3,000	2,000	25,000	0	15%	30%	$43,469	$911,801	$955,270	**$0**
To-Be #1	Immature Additive Manufacturing	0	5,000	25,000	0	15%	12%	$46,716	$911,801	$958,516	**-$3,247**
To-Be #2	Immature Additive Manufacturing + CPLM	0	5,000	25,000	0	15%	92%	$27,379	$911,801	$939,180	**$16,090**
To-Be #3	Immature Additive Manufacturing + CPLM + 3DLST	0	5,000	25,000	0	15%	40%	$37,444	$911,801	$949,245	**$6,025**
Radical To-Be #1	Mature Additive Manufacturing + CPLM	0	5,000	0	25,000	15%	787%	$5,920	$118,392	$124,311	**$830,959**
Radical To-Be #2	Mature Additive Manufacturing + CPLM + 3DLST	0	5,000	0	25,000	15%	1391%	$3,520	$70,401	$73,922	**$881,348**

The results of the modeling (Table 10) show that substantial savings (i.e., up to $881 million) can be captured in naval parts production through the widespread adoption and mature use of AM, CPLM, and 3DLST. However, the adoption of new technologies does not generate savings under all conditions. For example, adopting only one new technology (AM) without the requisite supporting technologies (e.g., CPLM) at a small scale (prototypes only) can cost more than it saves (see $3,247,000, far right column and “Ro-Be#1” row in Table 10).

The estimated savings generated by different technologies and scaling choices in Table 10 were compared to better understand the impacts of adopting different technologies at different scales (see Table 11). For example, the $19 million/year savings from adding CPLM (see Table 11, column 3, row 3) can be estimated as the difference between the savings from the small scale use of AM and CPLM (see Table 11, column 1, row 3) and the savings from the small scale use of AM only (see Table 11, column 1, row 2).

Table 11. Estimated Annual Cost Savings of AM, CPLM, 3DLST, and Scaling Up Use

			1	2	3	4	5	
	Scenario Name	**Scenario Description**	**Savings from As-Is scenario (X$1,000)**	**Savings from Additive Manufacturing (X$1,000)**	**Savings from Collaborative Product Lifecycle Management (X$1,000)**	**Savings from 3D Laser Scanning Technology (X$1,000)**	**Savings from scaling up adoption and use (X$1,000)**	**Notes on savings by specific strategies**
1	**As-Is**	Current technologies	**0**					
2	**To-Be #1**	Immature Additive Manufacturing	**-$3,247**	**-$3,247**				←(To-Be#1)-(As-Is) Small scale use
3	**To-Be #2**	Immature Additive Manufacturing + CPLM	**$16,090**		**$19,337**			←(To-Be#2)-(To-Be#1) Small scale use
4	**To-Be #3**	Immature Additive Manufacturing + CPLM + 3DLST	**$6,025**			**-$10,065**		←(To-Be#3)-(To-Be#2) Small scale use
5	**Radical To-Be #1**	Mature Additive Manufacturing + CPLM	**$830,959**				**$814,868**	←(Rad. To-Be#1)-(To-Be#2) Scale up to produce final parts
6	**Radical To-Be #2**	Mature Additive Manufacturing + CPLM + 3DLST	**$881,348**	(Rad. To-Be#2)-(Rad. To-Be#2) → Large scale use		**$50,390**	**$875,323**	← (Rad. To-Be#2)-(To-Be#3) Scale up to produce final parts

The results indicate that specific technologies can create different added costs or cost savings under different scaling assumptions. More specifically, if used on a small scale, AM alone costs $3 million/year over current technologies, but adopting AM and CPLM can save $16 million/year over As-Is processes ($19 million/year over AM alone). Similarly, adding 3DLST to small scale AM and CPLM costs $10 million/year (Table 11, column 4, row 4).

The larger cost differences are driven by the adoption and use of scaling in technologies decisions. First, all cost savings for large scale adoption and use of multiple technologies are orders of magnitude larger than savings with small scale adoption and use (see Table 11, column 1, rows 5 and 6 versus rows 2 through 4). Scaling up also greatly increases the impact of specific technologies. For example, scaling up AM and CPLM increases savings by $815 million (see Table 11, column 5, row 5) and increases the savings captured by AM, CPLM, and 3DLST by $875 million (see Table 11, column 5, row 6). Notice that scaling up adoption and mature use changes the impact of 3DLST alone from increasing costs by $10 million/year (see Table 11, column 4, row 4) to saving $50 million/year (see Table 11, column 4, row 6).

These results show the importance of scaling up the adoption and mature use of new technologies to capture large production savings. They also indicate that some technologies (e.g., 3DLST) may only add value if other technologies are in place (AM and CPLM) and widely used to make final parts as well as prototypes.

Conclusions

The cost savings estimates in this study were based on the actual use of new design and production technologies by the North Island NAVAIR maintenance depot to build two types of simulation models of ship maintenance. Given that the NAVAIR maintenance depot focused on the same kinds of legacy repair and replacement parts that are most prevalent in routine ship maintenance processes, extrapolating this actual experience with AM was appropriate for use in development of the models for the current study. The derived models were used to simulate six possible scenarios of technology adoption and use. The results were used to estimate design and production costs and thereby potential cost savings for each scenario that used the three new technologies. Comparison of potential cost savings across the scenarios provided estimates of the cost savings by mature and immature use of the three technologies. Estimated impacts on annual production costs ranged from increasing costs by $3 million if AM alone is adopted on a small scale to saving over $875 million if AM, CPLM, and 3DLST are adopted and used to create both prototypes and final parts. Scaling up adoption and use, from existing ship maintenance processes, to the widespread generation of prototypes and creation of final parts, were found to have more impact on costs than the selection of individual technologies alone.

The results of this study have several implications for naval fleet maintenance in terms of replacement part production. First, the results reinforce previous studies in forecasting substantial benefits from using AM, CPLM, and 3DLST in ship maintenance processes. Beyond this, the current study results indicated that these technologies, when incorporated with AM, provide the best results when used together and when adopted on a large scale to capture more of the potential benefits.

Despite the very large cost reductions that are available through the adoption and use of the technologies studied here, all of those benefits are not available immediately. Time and significant effort are required to achieve mature use of the technologies by incorporating them and other potentially valuable technologies into the standard operating procedures of ship maintenance. Acquisition regulations (e.g., about outsourcing) will require changes to allow and facilitate the widespread use of these technologies. It appears likely that, with some relaxation in acquisition rules that make it difficult for Navy maintenance operations to do some of the manufacturing of legacy parts, the Navy will be able to hire more personnel to perform these duties and reduce costs substantially in spite of the increased personnel costs. This will require a new way of thinking about labor costs and overall costs in acquisitions and operations that currently are primarily focused on reducing head count. By focusing on the potential value that these three technologies add to ship maintenance processes, this study provides an alternative option to head count reduction simply for the purpose of reducing costs. These challenges will require a degree of patience on the part of leadership to obtain the very substantial cost savings possible when the use of these three technologies becomes a mature aspect of ship maintenance processes.

The current work also has implications for future research. Next steps in this line of research include investigating the impacts of these technologies on the outsourcing of fleet maintenance, estimating the impacts of these technologies on manufacturing infrastructures and material inventory costs, the continued documentation of the current use of these technologies within some Naval maintenance processes for ships and NAVAIR, and the investigation of costs and savings during adoption and scaling up. This study's results were purposefully conservative and based on only two levels of ship maintenance operations. Future research will need to estimate the total cost savings possible when the technologies become routine aspects of all Navy maintenance processes. The continued research of new technology adoption and use for naval fleet maintenance issues will accelerate an improved understanding of how advanced technologies can be effectively and efficiently adopted to generate enormous cost savings while improving fleet operational availability.

THIS PAGE INTENTIONALLY LEFT BLANK

References

Abdel-Hamid, T. (1988). Understanding the “90% syndrome” in software project management: A simulation-based case study. *Journal of Systems and Software*, *8*, 319–330.

ASTM. (2013). *Annual book of ASTM standards* (Vol. 10.04). West Conshohocken, PA: Author.

Bakken, B. E. (2004). The Atlantic defense technology gap: Will it be closed? In *Proceedings of the 22nd International Conference of the System Dynamics Society*. Oxford, England: System Dynamics Society.

Bakken, B. E., & Gilljam, M. (2003). Dynamic intuition in military command and control: Why it is important, and how it should be developed. *Cognition, Technology and Work*, *5*, 197–205.

Bakken, B. T., Gilljam, M., & Haerem, T (2004). Perception and handling of complex problems in dynamic settings: Three cases of relevance to military command and crisis management. In *Proceedings of the 22nd International Conference of the System Dynamics Society*. Oxford, England: System Dynamics Society.

Bakken, B. T., Ruud, M., & Johannessen, S. (2004). The system dynamics approach to network centric warfare and effects based operations: Designing a “learning lab” for tomorrow. In *Proceedings of the 22nd International Conference of the System Dynamics Society*. Oxford, England: System Dynamics Society.

Bakken, B. T., & Vamraak, T. (2003). Misperception of dynamics in military planning: Exploring the counter-intuitive behaviour of the logistics chain. In *Proceedings of the 21st International Conference of the System Dynamics Society*. New York, NY: System Dynamics Society.

Bartolomei, J. (2001). A system dynamics model of government engineering support during the development phase of a military acquisition program. In *Proceedings of the 19th International Conference of the System Dynamics Society*. Atlanta, GA: International System Dynamics Society.

Bell, J. W., Jr., & Liphard, R. E. (1978). A system dynamics model of the Department of Defense enlisted force for investigation of alternative retirement proposals (GPO Report Number: ADA065970). Wright-Patterson AFB, OH: Air Force Institute of Technology.

Chayka, K. (2013). 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/

CIMdata. (2007a). All about PLM. Retrieved from http://www.cimdata.com/PLM/plm.html

Cooper, K. G. (1980). Naval ship production: A claim settled and a framework built. *Interfaces*, *10*(6), 20–36.

Cooper, K. G. (1993a). The rework cycle: Benchmarks for the project managers. *Project Management Journal*, *14*(1), 17–21.

Cooper, K. G. (1993b). The rework cycle: How it really works … and reworks. *PM Network*, 25–28.

Cooper, K. G. (1993c). The rework cycle: Why projects are mismanaged. *PM Network*, 5–7.

Copper, K. G. (1994). The $2,000 hour: How managers influence project performance through the rework cycle. *Project Management Journal*, *15*(1), 11–24.

Coyle, R. G. (1996, August). System dynamics applied to defense analysis: A literature survey. *Defense & Security Analysis*, *212*(2), 141–160.

Coyle, R. G., & Gardiner, P. A. (1991). A system dynamics model of submarine operations and maintenance schedules. *Journal of the Operational Research Society*, *42*(6), 453–462.

Duczynski, G. (2000). Profiler: An “effects-based” military capability manager. In *Proceedings of the 18th International Conference of the System Dynamics Society* (p. 59). Bergen, Norway: System Dynamics Society.

Flood, R. L., & Jackson, M. C. (1991). *Creative problem solving: Total systems intervention*. Chichester, UK: Wiley.

Ford, D. (2002). Achieving multiple project objectives through contingency management. *ASCE Journal of Construction Engineering and Management, 128*(1), 30–39.

Ford, D. N., & Dillard, J. T. (2008). Modeling the integration of open systems and evolutionary acquisition in DoD programs. In *Proceedings of the Fifth Annual Acquisition Research Symposium*. Monterey, CA: Naval Postgraduate School.

Ford, D. N., & Dillard, J. T. (2009a). Modeling open architecture and evolutionary acquisition in ARCI with applications to RCIP. In *Proceedings of the Sixth Annual Acquisition Research Symposium*. Monterey, CA: Naval Postgraduate School.

Ford, D. N., & Dillard, J. T. (2009b). Modeling the performance and risks of evolutionary acquisition. *Defense Acquisition Review Journal*, *16*(2), 143–158.

Ford, D. N., Housel, T., & Mun, J. (2012, November 30). *Naval ship maintenance: An analysis of Dutch shipbuilding industry using the knowledge value added, system dynamics, and integrated risk management methodologies* (NPS-AM-12-053). Monterey, CA: Naval Postgraduate School, Acquisition Research Program.

Ford, D., & Sterman, J. (1998). Modeling dynamic development processes. *System Dynamics Review*, *14*(1), 31–68.

Ford, D., & Sterman, J. (2003a). The liar's club: Impacts of concealment in concurrent development projects. *Concurrent Engineering Research and Applications*, *111*(3), 211–219.

Ford, D., & Sterman, J. (2003b). Overcoming the 90% syndrome: Iteration management in concurrent development projects. *Concurrent Engineering Research and Applications*, *111*(3), 177–186.

Forrester, J. W. (1961). *Industrial dynamics*. Portland, OR: Productivity Press.

Gibson, I., Rosen, D. W., & Stucker, B. (2010). *Additive manufacturing technologies: Rapid prototyping to direct digital.* New York, NY: Springer Science+Business Media, LLC.

Greaves, T., & Jenkins, B. (2007). 3D laser scanning market red hot: 2006 industry revenues $253 million, 43% growth. SparView, 5(7). Retrieved from http://www.sparllc.com/archiveviewer.php?vol=05&num=07&file=vol05no07-01

Halpern, M., & Smith, M. (2004, December 29). *Total value of opportunity analysis exposes value of PLM* (Gartner Group Report).

Homer, J. B., & Somers, I. (1988). Defense program lifecycle management: A dynamic model for policy analysis. In *Proceedings of the 1988 International System Dynamics Conference*. La Jolla, CA: International System Dynamics Society.

Housel, T. J., & Kanevsky, V. (1995). Reengineering business processes: A complexity theory approach to value added. *INFOR, 33*, 248–262.

Jackson, M. C. (2003). *Systems thinking: Creative holism for managers*. Chichester, UK: Wiley.

Joglekar, N., & Ford, D. (2005). Product development resource allocation with foresight. *European Journal of Operational Research*, *160*(1), 72–87.

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. Naval Postgraduate School thesis.

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* (NPS-AM-06-003). Retrieved from Naval Postgraduate School, Acquisition Research Program website: http://www.acquisitionresearch.net

Kronsberg, M. (2013, October 20). 3-D printing for all. *Wall Street Journal*, p. D14.

Lane, D. C., & Jackson, M. C. (1995). Only connect! An annotated bibliography reflecting the breadth and diversity of systems thinking. *Systems Research, 12*, 217–228.

Lee, Z., Ford, D., & Joglekar, N. (2007). Effects of resource allocation policies for reducing project durations: A systems modeling approach. *Systems Research and Behavioral Science, 24*(6), 551–566.

Lipson, H., & Kurman, M. (2013). *Fabricated: The new world of 3D printing.* Somerset, NJ: Wiley.

Lyneis, F., Cooper, K., & Els, S. (2001). Strategic management of complex projects: A case study using system dynamics. *Systems Dynamics Review*, *17*(3), 237–260.

Lyneis, J. M., & Ford, D. N. (2007). System dynamics applied to project management: A survey, assessment, and directions for future research. *System Dynamics Review*, *23*(4), 157–189.

McLucas, A. C., Lyell, D., & Rose, B. (2006). Defence capability management: Introduction into service of multi-role helicopters. In *Proceedings of the 24th International Conference of the Systems Dynamics Society* (p. 92). Nijmegen, The Netherlands: Systems Dynamics Society.

Melhuish, J., Pioch, N., & Seidel, A.. (2009). Improving military strategy using predictive agents with embedded mental simulation models. In *Proceedings of the 27th International Conference of the System Dynamics Society*. Albuquerque, NM: System Dynamics Society.

National Shipbuilding Research Program Advanced Shipbuilding Enterprise (NSRP ASE). (2007a). *Integrated Shipbuilding Environment (ISE).* Retrieved from http://www.nsrp.org/projects/ise.pdf

National Shipbuilding Research Program Advanced Shipbuilding Enterprise (NSRP ASE). (2007b). *NSRP ASE ship check data capture follow-on project results.* Retrieved from http://www.nsrp.org/projects/deliverables/ase_505001.pdf

National Shipbuilding Research Program Advanced Shipbuilding Enterprise (NSRP ASE). (2006). *NSRP ASE ship check project* (Technical No. NSRP 04-01-08). http://www.nsrp.org/panels/bpt/downloads/ShipCheck1205.pdf

Reuters. (2013). World in nano [Presentation slides]. Retrieved from http://www.reuters.com/news/pictures/slideshow?articleId=USRTR304C2#a=1

Schindler, C. (2010). *Product lifecycle management: A collaborative tool for defense acquisitions* (Master's thesis). Monterey CA: Naval Postgraduate School.

Sterman, J. S. (2000). *Business dynamics: Systems thinking and modeling for a complex world*. New York, NY: Irwin McGraw-Hill.

Taylor, T. R., & Ford, D. N. (2006). Tipping point dynamics in development projects. *System Dynamics Review*, *22*(1), 51–71.

Taylor, T. R., & Ford, D. N. (2008, June). Managing tipping point dynamics in development projects. *ASCE Journal of Construction Engineering and Management*, *134*(6), 421–431.

Watts, K. M., & Wolstenholme, E. F. (1990). The application of a dynamic methodology to assess the benefit of a logistics information system in defense. In *Proceedings of the 1990 International System Dynamics Conference: System Dynamics '90* (p. 1286). Chestnut Hill, MA: International System Dynamics Society.

Wohlers Associates, Inc (2010) "What is Additive Manufacturing?" http://wohlersassociates.com/additive-manufacturing.html. Accessed December 10, 2013.

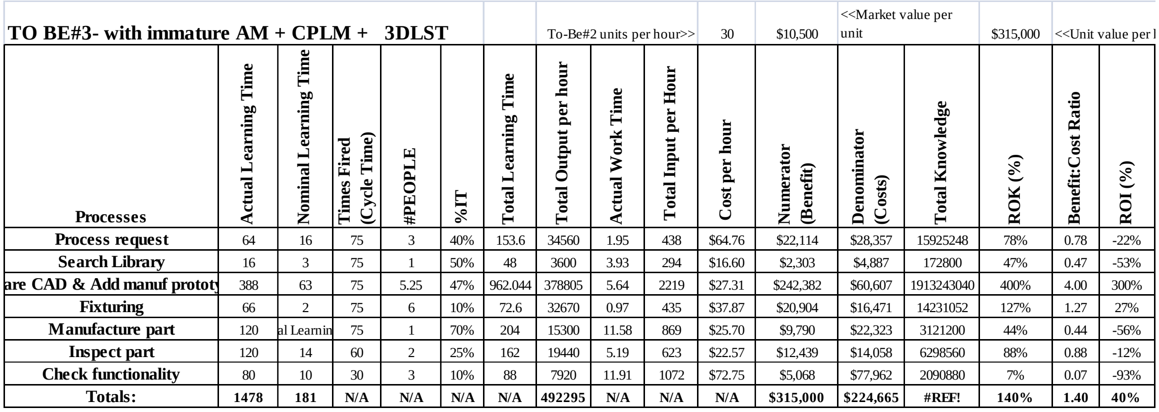
THIS PAGE INTENTIONALLY LEFT BLANK

Appendix: KVA Model Results

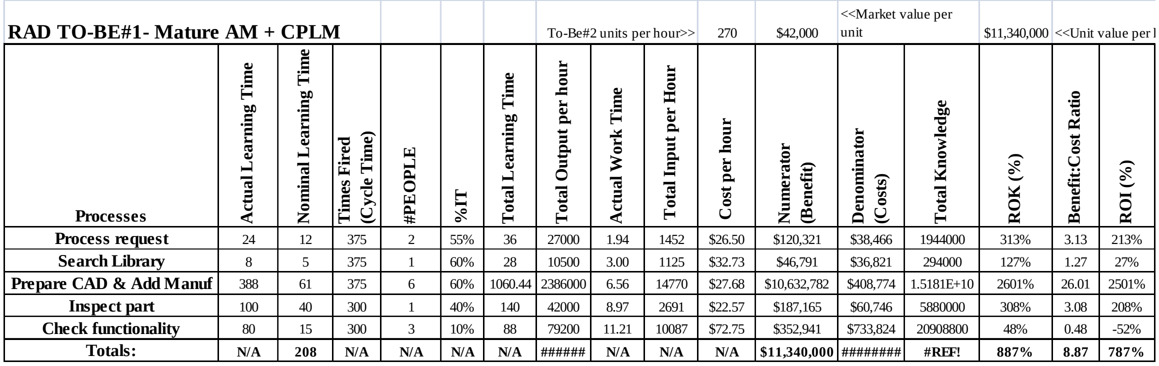
AS IS - Current Technologies							As Is units per hour>>			0.25	$10,500	<<Market value per prototype unit		$2,625	<<Unit value per l	
Processes	Actual Learning Time (hour, cuo)	Nominal Learning Time	Times Fired per hour	#People required per firing	%IT	Total Learning Time (cuo)	Total Output per hour (cuo / hour)	Actual Work Time (hours)	Total Input per Hour (man-hrs)	Cost per hour ($ / man-hour)	Benefits (numerator) ($/hr)	Costs (denominator) ($/hr)	Total Knowledge	ROK (%)	Benefit:Cost Ratio	ROI (%)
Process request	58	11	2.5	3	17%	68	510	2.04	15	$64.76	$1,270	$989	104040	1%	1.28	28%
Search Library	16	2	2.5	1	20%	19.2	48	4.06	10	$16.60	$119	$168	921.6	13%	0.71	-29%
Prep CAD	322	41	2.5	4	28%	434.4	4344	6.89	69	$27.31	$10,814	$1,881	7548134.4	575%	5.75	475%
Fixturing	25	8	2.5	2	10%	27.5	137.5	0.62	3	$26.51	$342	$82	7562.5	417%	4.17	317%
Manufacture part	120	14	2.5	1	70%	204	510	11.96	30	$25.70	$1,270	$768	104040	165%	1.65	65%
Inspect part	100	14	0.5	1	40%	140	70	9.92	5	$22.57	$174	$112	9800	156%	1.56	56%
Check functionality	80	10	0.25	3	10%	88	66	12.05	9	$72.75	$164	$657	17424	25%	0.25	-75%
Totals:	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**1054**	**N/A**	**N/A**	**N/A**	**$2,625**	**$2,014**	**591185**	**130%**	**1.30**	**30%**

TO-BE#1- Immature AM							To-Be#1 units per hour>>			22.5	$10,500	<<Market value per unit		$236,250	<<Unit value per l	
Processes	Actual Learning Time	Nominal Learning Time	Times Fired (Cycle Time)	#PEOPLE	%IT	Total Learning Time	Total Output per hour	Actual Work Time	Total Input per Hour (man-hr per hour)	Cost per hour	Numerator (Benefit, $/hr)	Denominator (Costs, $/hr)	Total Knowledge	ROK	Benefit: Cost ratio	
Process request	64	10	75	3	17%	75.2	11.28	2.12	1	$64.76	$6	$61	405.888	9%	0.09	-91%
Search Library	16	3	75	1	20%	19.2	1440	4.18	313	$16.60	$713	$5,198	27648	14%	0.14	-86%
CAD drawings & Add manuf pr	388	47	75	6	37%	905.6	407520	7.30	3284	$27.31	$201,643	$89,694	2214300672	225%	2.25	125%
Fixturing	66	2	75	6	10%	72.6	32670	1.15	516	$37.87	$16,165	$19,527	14231052	83%	0.83	-17%
Manufacture part	120	10	75	1	70%	204	15300	12.41	930	$25.70	$7,571	$23,913	3121200	32%	0.32	-68%
Inspect part	120	14	45	2	25%	162	14580	5.78	520	$22.57	$7,214	$11,742	4723920	61%	0.61	-39%
Check functionality	80	10	22.5	3	10%	88	5940	12.24	826	$72.75	$2,939	$60,085	1568160	5%	0.05	-95%
Totals:	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**477461**	**N/A**	**N/A**	**N/A**	**$236,250**	**$210,220**	**#VALUE!**	**112%**	**1.12**	**12%**

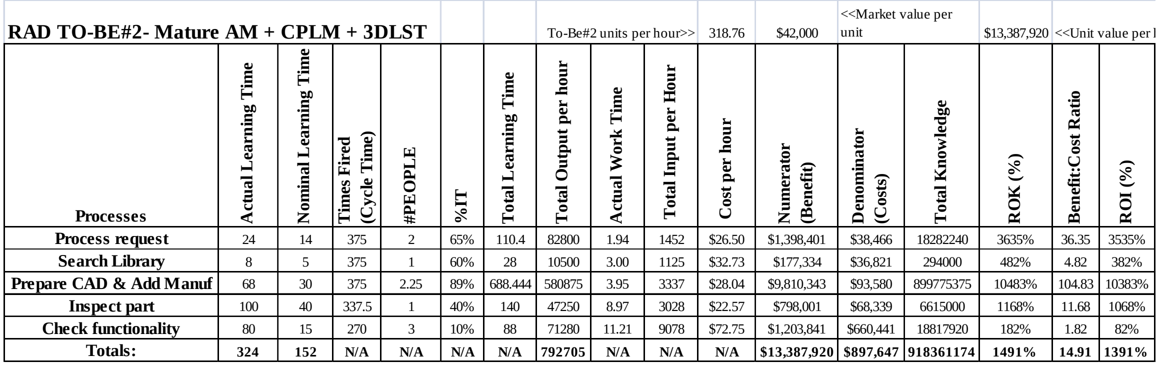
TO-BE#2- Immature AM + CPLM							To-Be#2 units per hour>>			54	$10,500	<<Market value per unit		$567,000	<<Unit value per l	
Processes	Actual Learning Time	Nominal Learning Time	Times Fired (Cycle Time)	#PEOPLE	%IT	Total Learning Time	Total Output per hour	Actual Work Time	Total Input per Hour	Cost per hour	Numerator (Benefit)	Denominator (Costs)	Total Knowledge	ROK	Benefit: Cost ratio	
Process request	64	10	75	3	17%	75.2	16920	1.95	438	$64.76	$18,902	$28,357	3817152	67%	0.67	-33%
Search Library	16	3	75	1	20%	19.2	1440	3.93	294	$16.60	$1,609	$4,887	27648	33%	0.33	-67%
CAD drawings & Add manuf pr	388	47	75	6	37%	905.6	407520	5.64	2536	$27.31	$455,257	$69,265	2214300672	657%	6.57	557%
Fixturing	66	2	75	6	10%	72.6	32670	0.97	435	$37.87	$36,497	$16,471	14231052	222%	2.22	122%
Manufacture part	120	0	75	1	70%	204	15300	11.58	869	$25.70	$17,092	$22,323	3121200	77%	0.77	-23%
Inspect part	120	14	60	2	25%	162	19440	5.19	623	$22.57	$21,717	$14,058	6298560	154%	1.54	54%
Check functionality	80	10	54	3	10%	88	14256	11.91	1929	$72.75	$15,926	$140,332	3763584	11%	0.11	-89%
Totals:	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**507546**	**N/A**	**N/A**	**N/A**	**$567,000**	**$295,693**	**#VALUE!**	**192%**	**1.92**	**92%**



TO BE#3- with immature AM + CPLM + 3DLST							To-Be#2 units per hour>>			30	$10,500	<<Market value per unit		$315,000	<<Unit value per l	
Processes	Actual Learning Time	Nominal Learning Time	Times Fired (Cycle Time)	#PEOPLE	%IT	Total Learning Time	Total Output per hour	Actual Work Time	Total Input per Hour	Cost per hour	Numerator (Benefit)	Denominator (Costs)	Total Knowledge	ROK (%)	Benefit:Cost Ratio	ROI (%)
Process request	64	16	75	3	40%	153.6	34560	1.95	438	$64.76	$22,114	$28,357	15925248	78%	0.78	-22%
Search Library	16	3	75	1	50%	48	3600	3.93	294	$16.60	$2,303	$4,887	172800	47%	0.47	-53%
are CAD & Add manuf prototy	388	63	75	5.25	47%	962.044	378805	5.64	2219	$27.31	$242,382	$60,607	1913243040	400%	4.00	300%
Fixturing	66	2	75	6	10%	72.6	32670	0.97	435	$37.87	$20,904	$16,471	14231052	127%	1.27	27%
Manufacture part	120	al Learnin	75	1	70%	204	15300	11.58	869	$25.70	$9,790	$22,323	3121200	44%	0.44	-56%
Inspect part	120	14	60	2	25%	162	19440	5.19	623	$22.57	$12,439	$14,058	6298560	88%	0.88	-12%
Check functionality	80	10	30	3	10%	88	7920	11.91	1072	$72.75	$5,068	$77,962	2090880	7%	0.07	-93%
Totals:	**1478**	**181**	**N/A**	**N/A**	**N/A**	**N/A**	**492295**	**N/A**	**N/A**	**N/A**	**$315,000**	**$224,665**	**#REF!**	**140%**	**1.40**	**40%**



RAD TO-BE#1- Mature AM + CPLM							To-Be#2 units per hour>>			270	$42,000	<<Market value per unit		$11,340,000	<<Unit value per l	
Processes	Actual Learning Time	Nominal Learning Time	Times Fired (Cycle Time)	#PEOPLE	%IT	Total Learning Time	Total Output per hour	Actual Work Time	Total Input per Hour	Cost per hour	Numerator (Benefit)	Denominator (Costs)	Total Knowledge	ROK (%)	Benefit:Cost Ratio	ROI (%)
Process request	24	12	375	2	55%	36	27000	1.94	1452	$26.50	$120,321	$38,466	1944000	313%	3.13	213%
Search Library	8	5	375	1	60%	28	10500	3.00	1125	$32.73	$46,791	$36,821	294000	127%	1.27	27%
Prepare CAD & Add Manuf	388	61	375	6	60%	1060.44	2386000	6.56	14770	$27.68	$10,632,782	$408,774	1.5181E+10	2601%	26.01	2501%
Inspect part	100	40	300	1	40%	140	42000	8.97	2691	$22.57	$187,165	$60,746	5880000	308%	3.08	208%
Check functionality	80	15	300	3	10%	88	79200	11.21	10087	$72.75	$352,941	$733,824	20908800	48%	0.48	-52%
Totals:	**N/A**	**208**	**N/A**	**N/A**	**N/A**	**N/A**	**######**	**N/A**	**N/A**	**N/A**	**$11,340,000**	**########**	**#REF!**	**887%**	**8.87**	**787%**



RAD TO-BE#2- Mature AM + CPLM + 3DLST							To-Be#2 units per hour>>			318.76	$42,000	<<Market value per unit		$13,387,920	<<Unit value per l	
Processes	Actual Learning Time	Nominal Learning Time	Times Fired (Cycle Time)	#PEOPLE	%IT	Total Learning Time	Total Output per hour	Actual Work Time	Total Input per Hour	Cost per hour	Numerator (Benefit)	Denominator (Costs)	Total Knowledge	ROK (%)	Benefit:Cost Ratio	ROI (%)
Process request	24	14	375	2	65%	110.4	82800	1.94	1452	$26.50	$1,398,401	$38,466	18282240	3635%	36.35	3535%
Search Library	8	5	375	1	60%	28	10500	3.00	1125	$32.73	$177,334	$36,821	294000	482%	4.82	382%
Prepare CAD & Add Manuf	68	30	375	2.25	89%	688.444	580875	3.95	3337	$28.04	$9,810,343	$93,580	899775375	10483%	104.83	10383%
Inspect part	100	40	337.5	1	40%	140	47250	8.97	3028	$22.57	$798,001	$68,339	6615000	1168%	11.68	1068%
Check functionality	80	15	270	3	10%	88	71280	11.21	9078	$72.75	$1,203,841	$660,441	18817920	182%	1.82	82%
Totals:	**324**	**152**	**N/A**	**N/A**	**N/A**	**N/A**	**792705**	**N/A**	**N/A**	**N/A**	**$13,387,920**	**$897,647**	**918361174**	**1491%**	**14.91**	**1391%**

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

www.acquisitionresearch.net