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Additive Manufacturing Laboratories at Sea and their Value to the Navy's Seagoing Warfighter

December 2019

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ABSTRACT

The purpose of this MBA report is to analyze and evaluate the added-value of additive manufacturing laboratories (AMLs) installed on seagoing vessels and to provide lessons learned from the U.S. Navy's first Additive Manufacturing Shop at Sea, onboard USS John C. Stennis (CVN 74), in the manufacturing (printing) of replacement parts on-demand for immediate use. This project seeks to make three contributions. First, a cost-benefit analysis (CBA) utilizing a selected part manufactured through AM procedures to determine value, cost, and time savings that AMLs installed aboard ships would offer. Second, a comprehensive analysis utilizing the Knowledge Added-Value Methodology (KVA) to determine the KVA of the Surface Navy's 3D printing AM program. Third, a compilation of lessons learned to support or reject the installation and viability of these shops and their equipment installed across the fleet, by utilizing data gathered from firsthand accounts and experiences of the sailors who operated the first AML at sea onboard USS John C. Stennis. At the end of the report, the research team provides general recommendation(s) for the future installation of AMLs across the fleet to maximize benefits, cost savings, and value added to the U.S. Navy as well as for future research.

Keywords: additive manufacturing (AM), 3D printing (3DP), Knowledge Value Added (KVA), return on knowledge (ROK), return on investment (ROI), cost-benefit analysis (CBA), manufacturing on demand, value-added, additive manufacturing laboratory (AML), USS John C. Stennis (CVN 74).

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ABOUT THE AUTHORS

Lieutenant Commander Eduardo Nicholls enlisted in the US Navy in 1999 as a Gas Turbine Systems Technician (GSM). He served onboard USS LABOON (DDG 58) and USS MAHAN (DDG 72). In 2007, while on active duty, he completed a Bachelor of Science in Management and received his Commission from Navy Officer Candidate School in August 2007. Lieutenant Commander Nicholls' operational assignments include Supply Officer onboard USS COWPENS (CG 63), Fuels Officer at Camp LEMMONIER, Djibouti, Africa, and Assistant Supply Officer onboard USS BENFOLD (DDG 65). His shore duty assignments include Naval Postgraduate School where he earned his MBA and Assistant Chief of Staff J8 (ACOS J8) and Financial Controller for Naval Striking and Support Forces NATO (STRIKFORNATO) in Lisbon, Portugal. Additionally, he completed an internship as Operations Logistics-Petroleum at Fleet Logistics Center, Point Loma, San Diego.

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— Eduardo A. Nicholls LCDR, SC

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LIST OF ACRONYMS AND ABBREVIATIONS

3DP	3D Printing
3M	Maintenance and Material Management
ABS	Acrylonitrile Butadiene Styrene
AI	Artificial Intelligence
ALT	Actual Learning Time
AM	Additive Manufacturing
AML	Additive Manufacturing Laboratory
AOR	Area of Operation
CAD	Computer Aided Drafting
CBA	Cost-Benefit Analysis
CHENG	Chief Engineer
CNC	Computer Numerically Controlled
COSAL	Coordinated Ship's Allowance
COTS	Commercial-Off-the-Shelf
DFAS	Defense Finance and Accounting Service
DLA	Defense Logistics Agency
DOD	Department of Defense
DoN	Department of the Navy
EM	Electrician Mate
EXMAN	United States Marine Corps Expeditionary Manufacturing
FCU	Fan Coil Unit
FDM	Fused Deposition Modeling
FEDLOG	Federal Logistics Data
FLC	NAVSUP Fleet Logistics Center
GDP	Gross Domestic Product
GSA	General Services Administration
hazmat	Hazardous Material
IP	Intellectual Property
IT	Information Technology

KVA	Knowledge Added-Value Methodology
LS	Logistics Specialist
LT	Learning Time
ML	Machine Learning
MR	Machinery Repairmen
NAVSEA	Navy Sea Systems Command
NAVSUP	Naval Supply Systems Command
NIIN	National Identification Number
NSN	National Stock Number
OECD	Organization for Economic Cooperation and Development
OJT	On the Job Training
OMB	Office of Management and Budget
OOC	Out of Commission
OPNAV	Office of the Chief of Naval Operations
OSO	Other Supply Officer
P-485	Naval Supply Procedures Publication 485 Vol. 1
PQS	Personnel Qualification Standards
PTG	Polyethylene Terephthalate Glycol
QA	Quality Assurance
RLT	Relative Learning Time
ROK	Return on Knowledge
ROI	Return on Investment
RPPO	Repair Parts Petty Officer
R-Supply	Relational Supply
R&D	Research and Development
SIM	Selected Item Management
SME	Subject Matter Expert
SOP	Standard Operating Procedures
SQ	Status Quo
USMC	United States Marine Corps
WSS	NAVSUP Weapons Systems Support

EXECUTIVE SUMMARY

As the Department of the Navy (DoN) moves into adopting additive manufacturing (AM) technology across its surface fleet, it is important to measure the value it adds to the warfighter. The purpose of this MBA research project is to analyze and evaluate whether the installation of additive manufacturing laboratories (AMLs) across the surface fleet is beneficial to the Navy. Specifically, this thesis assesses whether there is any value added to the Navy by manufacturing (3D printing) replacement parts on-demand for immediate use.

This project seeks to make three contributions. First, by gathering data from firsthand experiences of the men and women who operated the first AML at sea, it produces a comprehensive analysis utilizing the Knowledge Added-Value Methodology (KVA) to determine the return on investment (ROI) and the return on knowledge (ROK) of the Surface Navy's existing 3D Printing (3DP) AM program. As a result, this project will likely change the AML process in adopting the AML on future ships. Second, this report analyzes a selected part manufactured through AM procedures utilizing a cost-benefit analysis (CBA) to determine value added with cost, and time savings by having it manufactured onboard surface ships. The CBA and KVA results produced an assessment whether it is viable to keep the AML onboard or scrape it. Lastly, the research team compiled a list of lessons learned and recommendations to adopt the AML on future ships.

Keywords: additive manufacturing (AM), 3D printing (3DP), Knowledge Value Added (KVA), return on knowledge (ROK), return on investment (ROI), cost-benefit analysis (CBA), manufacturing on demand, value-added, additive manufacturing laboratory (AML), USS John C. Stennis (CVN 74*)*.

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I. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing technology, in the U.S. Navy has overcome the testing phase ashore and is entering an implementation stage. The existing plan to install additive manufacturing laboratories (AMLs) would allow AM to reach most surface combatants' vessels by 2025 (Arcano et al., 2017). Despite this existing plan, there has been no assessment of the value of AM technology in a real-life setting at sea. AM will continue to grow and mature in the military; however, to optimize this growth through adequately allocating funding and resources in support of the Navy's mission, the potential benefits and costs need to be quantified with accuracy.

A. PURPOSE OF RESEARCH

The purpose of this MBA research project is to evaluate the viability of AML installed on surface ships in the manufacturing (printing) of replacement parts on-demand for immediate use. It also attempts to determine whether implementing 3D printers on surface ships would be cost-beneficial or whether the Navy should continue utilizing the conventional supply system for procuring parts while accepting all implications and delays in a deployed, and likely contested, environment. In addition, this research attempts to provide all the lessons learned from an interview with the AML crew from USS John C. Stennis (CVN 74). The research team compiled a list of lessons learned and recommendations to adopt the AML on future ships.

B. BACKGROUND

Deployed operations require and expect maintenance personnel to return any down equipment to readiness condition safely and expeditiously. For this to happen, maintenance crews should have "ready to install" repair parts at their disposal or have the certainty that they will receive the needed spare parts in a timely manner. Failure to have replacement parts available would result in prolonged equipment downtime and potentially fatal mishaps. There are various methods utilized in theater to procure and issue a required repair part to maintenance crews in order to minimize the negative impact on readiness of the down equipment. The primary method is to utilize the established supply chain procedures (status quo) delineated in the Naval Supply Systems Command (NAVSUP) Publication P-485 (2015). Additional methods include contract awards to private companies for expeditious manufacturing and delivery (off-the-shelf type scenario), and lastly “cannibalization,” which is removing a part, or parts, from another asset that is not being utilized or that is out of commission.

It is not uncommon for the military to have a multimillion-dollar asset out of commission or otherwise deemed unserviceable. Sometimes this downtime of equipment is caused by lack of a part or parts worth a few cents—causing thousands of dollars in delays, failure to train, and possibly failure to execute the mission. In light of this, the Department of Defense (DOD) has been researching the utilization of 3D printing, also known as additive manufacturing (AM). This DOD initiative’s primary objective is to reduce the time it takes to issue a spare part (from a predetermined list of approved parts) to maintenance personnel. The status quo (SQ) supply chain system remains available, but the ability to print a part becomes a new preferred procurement procedure, reducing the downtime of an asset or system (Brown, Davis, Dobson, & Mallicoat, 2014).

AM technology was initially developed as a system for creating product prototypes using random material samples (Gibson, Rosen, & Stucker, 2015). It has continually evolved to include the development of advanced technologies to create more capabilities, as well as the emergence of new materials and processes.

AM is a process that joins material, layer on a layer, in the form of a three-dimensional model to make objects, utilizing data and raw materials as input to print the required part (Gibson et al., 2015). It is also called additive processes or additive layer manufacturing. Companies first adopted it in aerospace to save on weight and in healthcare to customize solutions for the manufacturing of medical implants, repairing of dental malformations, and manufacturing of hearing aids (Dietrich, Kenworthy, & Cudney, 2019). AM uses different technologies and materials such as metal, polymers, and ceramics (Gibson et al., 2015). Overall, the major benefits and value to industry for adopting AM are shortened product development lead-time due to the absence of tooling fabrication and quick physical prototypes; design performance gains such as weight and cost reduction and multifunctionality; and logistical savings due to simplification of assemblies through design integration (Dietrich et al., 2019).

There are several variations of the technology, which have different energy systems and feedstock types. The most popular category of AM is powder bed fusion because of the ability to make designs that are intricate and have high mechanical property and structural integrity on polymers as well as metals (Gibson et al., 2015). According to Dietrich et al. (2019), powder bed fusion is a widely used technology that uses two lasers and electron beam energy. It is commonplace to find it in the automotive racing sector, aerospace, and healthcare. Additionally, according to a study conducted by Ford and Despeisse (2016), AM is considered more environmentally friendly when compared to conventional manufacturing, which is mainly subtractive and generally has higher levels of waste, consumption of energy, and emission of carbon. While there are savings of energy consumed using AM, under certain conditions and applications there is also the potential for AM to use high levels of energy (Dietrich et al., 2019; Li, Jia, Cheng, & Hu, 2017).

Over the last several years, AM has become one of the most influential trends in technology combining machine learning (ML) and artificial intelligence (AI), transforming a sector of the manufacturing industry worldwide. There are several reasons why AM is becoming a powerful tool. Some of them include the reduction in product development lead-time since it does not involve the fabrication of tools and creates physical prototypes quickly. Another factor is the variety of designs with a reduction of the product's weight and the cost of production while ensuring multi-functionality. AM also simplifies the assembly of products by integrating designs that allow easy assembly within the parts produced, leading to savings of the costs of logistics. Lastly, AM customizable material solutions take advantage of physics in the print process and use enhanced technology to verify the design, aspect, and final build (Dietrich et al., 2019).

AM has unique characteristics that have considerable implications for the delivery of the supply chain of spare parts, allowing manufacturers to produce spare parts on demand, thus reducing the stages involved within the supply chain. The on-demand production of spare parts can lead to a reduction in operating costs while satisfying customers. This aspect allows suppliers to overcome the unpredictability of demand, enabling decision-makers to trade off staging and storage costs, for on-demand delivery, further reducing operating costs (Li et al., 2017) Due to the development of AM over time, objects can be created using unique resources such as paper, plastic, metal, earthenware, and glass, as well as living cells, which can be input in the form of powder, liquids, sheets, or filaments (Huang, Leu, Mazumder, & Donmez, 2015).

AM is now used in the production of high-quality precision parts for select applications such as aircraft parts, prosthesis equipment, and even hearing aids (Gibson et al., 2015). Hence, it is no longer a technology solely for producing prototypes, but it also has the potential to affect supply chains by revolutionizing complete manufacturing operations. Advancements in speed, affordability, precision, and range of materials are some of the qualities and inherent capabilities of this new technology. As a result, manufacturers can produce customized parts at any time and in various locations, which can alter complete configurations in any given supply chain (Dietrich et al., 2019).

However, AM is not free of controversy. Intellectual property (IP) and AM seem to go hand in hand, and discussion about their relationship is a recurrent subject (Yampolskiy, Andel, McDonald, Glisson, & Yasinsac, 2014). As AM technology develops, more fields demanding high quality and precision at a lower cost, such as the space industry, military weaponry, and vehicles, are making large investments in research and development (R&D). This is causing concerns about plagiarism and piracy (Ford & Despeisse, 2016). It is imperative to protect U.S. patents and intellectual property and discoveries. As the technology becomes widespread, the possibilities for other individuals, companies, and even nations to try to replicate parts by successfully operating AM equipment increases (Dietrich et al., 2019). Failure to protect IP could have a profound financial ripple in the manufacturing industry.

C. RESEARCH QUESTIONS

The following are the research questions guiding this project:

- What is the value added to the U.S. Navy from having AMLs onboard Navy surface ships?
- What are the lessons learned and recommendations for ship maintenance operations that can be facilitated by the use of AMLs onboard a U.S. Navy warship?

D. SCOPE

This research project attempts to discover whether there is an added value to the U.S. Surface Navy by having AMLs or capabilities onboard its vessels. It also focuses on gathering the lessons learned and best practices from the initial installation of these laboratories on U.S. Navy warships.

Within the context of U.S. Naval warships spare parts, AM has the potential to ensure equipment remains in operational conditions. It provides the ability to fabricate essential parts on demand and on station, thereby reducing downtime costs. Furthermore, the use of AM in the U.S. Navy operations ensures a reduced number of stages within the conventional chain of supply. This implies that the transportation of various products does not have to pass through retailers and distributors, thus reducing costs and increasing time savings.

The study employs the Knowledge Value Added (KVA; Housel & Bell, 2001) methodology to calculate a return on investment (ROI) and a return on knowledge (ROK). This research focuses on calculating the ROI and ROK from the use of AM in Navy vessels. It also discusses some of the implications this new technology will have in the repair parts supply chain and other upcoming opportunities.

Additionally, the study performs a cost-benefit analysis (CBA) on a random spare part that has been produced by the USS John C. Stennis' AML. The process is compared against the status quo process to acquire the same part. The CBA follows the guidelines of the U.S. Army Cost-Benefit Analysis Guide 2010 and formulates not only possible recommendations but also possible additional opportunities.

Lastly, the research team provides lessons learned and general recommendations for the future installation of AMLs across the surface fleet to maximize benefits (if any), cost savings (if any), and of course, value-added to the Navy (if any).

Additional research should highlight potential savings associated with AM technologies as well as approaches via waste reduction, enhanced readiness of operations, error reductions, enhanced execution precision on logistics undertakings and potential savings due to reduced manning.

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II. LITERATURE REVIEW

A. ADDITIVE MANUFACTURING IN THE NAVY

AM in the Navy can be viewed from two perspectives: increased readiness and sustainability, and enhanced warfighting capabilities. Regarding increased readiness and sustainability, the Department of Navy (DoN) has used AM for more than 20 years in the production of various items such as fixtures, molds, prototypes, and tooling. The use of AM has allowed production processes to become more cost effective and efficient. Therefore, the evolution of AM could be a critical component in producing end-use items or components, leading to a resolution of obsolescence and long lead-time issues currently experienced within the Navy supply chain. Better yet, the capability of producing components or requirements on demand could drastically decrease excessive lead-times and create a level of independence from the conventional delivery supply chain. Also, the production of components on-demand leads to vigorous supply and scalable delivery sequence allowing an innovative age of independence in the delivery chain (Gibson et al., 2015).

By enhancing the capabilities of warfighting, the implementation of AMLs afloat could possibly eliminate constraints that accompany traditional design methods, which allows for unique design characteristics previously unattainable or impossible. Assembly of multiple components can be merged into single or multiple lattice-like formations, which produces parts that are light yet rigid, of superior quality, and with increased functionality. AM provides widespread modification capability, which enables results that are tailored and precise to every assignment or even every warfighter (Arcano et al., 2017).

The implementation of AMLs afloat has great potential to positively affect the configuration and effectiveness of the conventional Navy supply chain, due to the added AM capability, which virtually eliminated various phases of the SQ supply chain procedures. Although AM technology, as of yet, has not fully matured to the point of conventional manufacturing (Huang et al., 2015), interesting comparisons in terms of costs can be made, because cost is a critical aspect of decision-making and greatly influences the decisions made for supply and manufacturing. In particular, the elimination of the required delivery time of spare parts or requirements can lead to reductions in operating costs, such as transportation costs.

According to Housel and Bell (2001), one approach in which AM could affect the supply chain is by centralizing AM capabilities to replace the inventory holdings. This way, the placement of a machine is done at the centralized distribution centers to assist in the production of slow-moving spare parts on demand.

If the delivery and transportation of spare parts are removed from the equation, that can lead to the reduction of operating costs. It can also satisfy customers when the suppliers are able to mitigate and overcome unpredictable demand. Lastly, the supplier is eased-up on whether to trade off inventory level, delivery time, or operating costs. Although the technology of AM has not yet matured to the conventional manufacturing, there is an interesting comparison in terms of cost between AM and conventional supply chain (from raw material to delivery of goods). Cost is a critical aspect of decision-making and highly influences the decisions made for manufacturing technologies.

AM capability can also reduce required inventory space and storage, which ultimately reduces inventory holding costs. Furthermore, the use of AM also reduces the safety stock inventory requirements for spare parts for aircraft in the supply chain (Li et al., 2017). These cost savings are most evident when a high demand exists for the parts being produced using AM, thus justifying the capital investment. Furthermore, the use of AM reduces the safety inventory required, for instance spare parts for aviation in the supply chain (Li et al., 2017).

When analyzing the cost of using AM in conventional centralized and decentralized supply chains, it is apparent that the costs are significantly higher in conventional supply chains in comparison to AM production capabilities. Additionally, transportation cost is the overriding aspect in the conventional supply chain of delivery, accounts for about 60% of its supply chain costs, and is also the overriding aspect in delivery chains using centralized AM (Gibson et al., 2015). The circumstance also differs when it comes to AM, where manufacturing cost accounts for almost half of the total cost. AM supply chains only hold inventory at the site of manufacturing, which drastically lowers transportation delays and ultimately leads to the elimination of excessive inventory and administration costs. The adoption of AM is therefore an economical advantage, not only in relation to transportation, but also in regard to management and cost of production, given that AM requires use of fewer phases or stages than the conventional supply chain (Gibson et al., 2015).

The current supply chain, due to its many stages and steps, increases the chances of a spare part being unavailable or not delivered on time. It forces manufacturers and distributors to have larger quantities of inventory at hand to avoid running out of stock. Also, the current supply chain further increases overhead costs such as administration and inventory control (Guo & Leu, 2013). Inversely, the AM supply chains hold inventory only at the site of manufacturing, shortening the delay in transportation which ultimately leads to lower overhead costs, reduced inventory and less administration (Li et al., 2017).

There is, however, a significant proportional increase in cost of materials for AM supply chains in contrast to the conventional supply chains. Increased costs of materials and labor translate to overall higher manufacturing costs. According to Arcano et al. (2017), a decentralized AM supply chain structure is preferable for its limited number of services locations, hence reducing costs. Another consideration is that the full price of the AM chain of delivery in its entirety is lower than that of the conventional delivery chain (Li et al., 2017). Lastly, in the case of the Navy, it is important to produce components on demand, thereby allowing independence.

An AM supply chain is superior when it comes to variable costs because its characteristics allow for a decrease in the number of phases or stages found in the chain of delivery, consequently reducing the overall costs by providing spare parts that are cost effective, while at the same time offering flexibility in manufacturing (Arcano et al., 2017; Li et al., 2017).

B. THE NAVY SUPPLY SYSTEM: STATUS QUO

The following section details the SQ procurement procedures that an afloat operational command would utilize to order parts or materials. The process begins with the afloat command recognizing and validating a requirement for a part or material. The material in this section follows the guidelines set by the Naval Supply Procedures (Navy

Supply Systems Command [NAVSUP], 2015), hereafter referred to as the P-485, and standard practices by supply officers afloat.

1. Part or Material Initially Available

Once a requirement has been validated and identified, a logistics specialist (LS) will research the Navy Supply System Relational Supply (R-Supply) database utilizing the associated National Stock Number (NSN) for the part or material. After successfully retrieving the necessary information and the current status for the part (for brevity, the research team refers only to “part” hereafter), the LS will subsequently submit a requisition for the part. The R-Supply database will cross-reference and survey the ship’s supply inventory to verify whether the part is currently onboard and in stock. If the requested part is onboard, it will be retrieved from the respective supply storeroom, processed through Supply Support, and delivered to the requesting division/customer.

If R-Supply reports that the part is currently not onboard or in stock, the LS will then conduct a search for the current location of the desired part, surveying the supply inventories of all afloat and ashore naval commands. If R-Supply discovers that the part is currently in stock at another command and available, an “Other Supply Officer” (OSO) transfer will be initiated and executed. The requesting afloat command will then request and retrieve the part from the OSO command and deliver the material to the division/customer.

If R-Supply reports that the part cannot be located in the R-Supply database or if the part location has been found but an OSO transfer is unavailable, the ship will then forward the requisition to a Navy supply activity. The Navy supply activity will be the nearest NAVSUP Fleet Logistics Center (FLC) that has been regionally assigned to the ship’s area of operation (AOR). The NAVSUP FLC will then screen the inventories and stocks of their requirement sources to determine whether the required part is on hand. Common requirement sources for NAVSUP FLCs are Defense Logistics Agency (DLA), General Services Administration (GSA), and local contracting. If the required part is on hand and available, the part is pulled from the respective source’s inventory, packaged for shipping, and forwarded to the requesting ship. The requesting ship will track the delivery status of the part, process the material through Supply Support upon receipt, and deliver the part to the division/customer.

If after screening its stocks the Supply Activity (FLC) concludes that the requested material is not carried or available, the requisition will be forwarded and referred to the NAVSUP Weapons Systems Support (NAVSUP WSS), which is designated as the cognizant inventory manager and Supply Planner (NAVSUP, 2015, p. 1–31). After surveying and researching master records and verifying that the part is unavailable, NAVSUP WSS will then initiate the contracting process for manufacturing of the required part. The requesting afloat operational command will then track the completion and anticipated delivery date of the part, and upon delivery to the ship, deliver the material to the requesting division/customer.

2. Part or Material Initially Unavailable

Once a requirement has been validated and identified, the LS will research the NAVSUP R-Supply database utilizing the associated NSN for the part or material. If the LS cannot retrieve information on the current status of the material, he will subsequently attempt to identify suitable substitutions for the part and continue with the ordering process. If a substitute is successfully identified and located, the LS will proceed with the normal ordering process to procure the part or material.

If a suitable substitute part is not available, the LS will attempt to identify the next upper level assembly and location. If the next higher-level assembly is successfully identified and located, the LS will proceed with the normal ordering process to procure the part or material.

If the next higher-level assembly cannot be located or is not available, the LS will forward the requisition to the respective item manager, who will then initiate the contracting process for manufacturing of the required part. The requesting afloat operational command will then track the completion and anticipated delivery date of the part, and upon delivery to the ship, deliver the material to the requesting division/customer (see Figure 1).

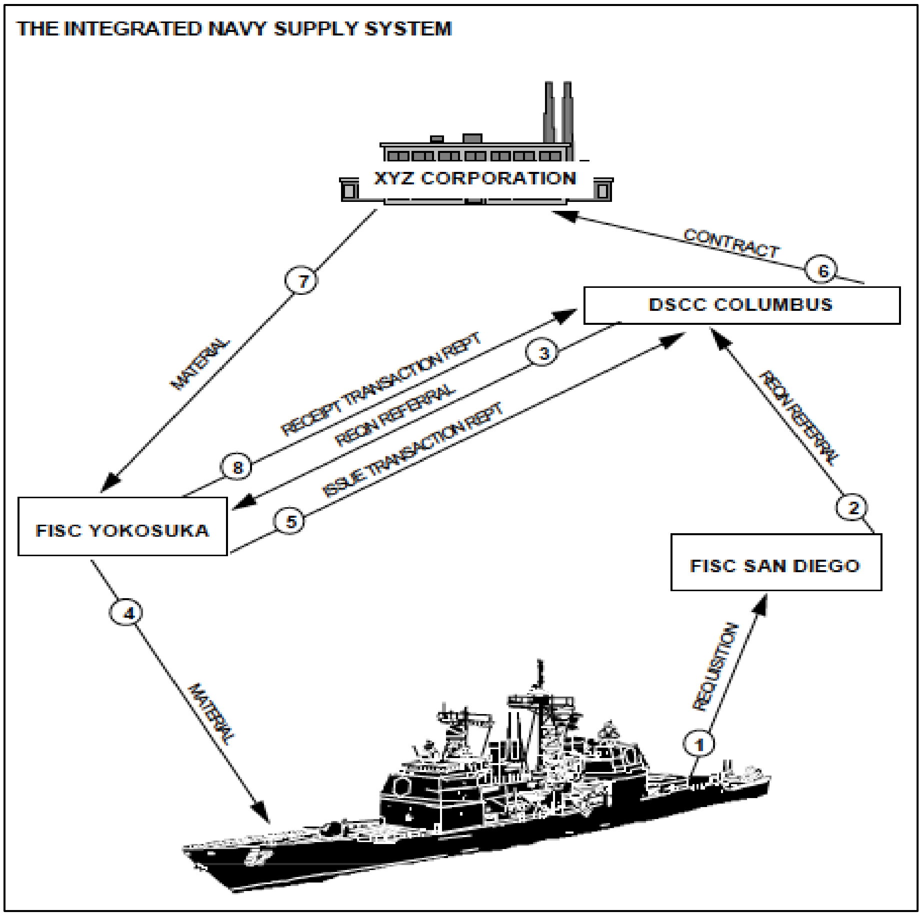

Figure 1. The Navy Supply System. Source: NAVSUP (2015).

C. COST-BENEFIT ANALYSIS (CBA)

A cost-benefit analysis is an instrument for supporting decisions and contains facts, data, and the necessary analysis critical to making informed decisions (U.S. Army, 2010). According to the guide (U.S. Army, 2010), a CBA offers a prediction of the actions that would be effective in solving problems or fully taking advantage of available opportunities. A CBA is structural proposal for decision-making by organizations. Due to being structural, it firstly defines the solutions, which are aimed at attaining goals specific to the Army, Navy, or any other organization. A CBA quantifies both financial and other impacts to the business.

According to the 2010 *U.S. Army Cost-Benefit Analysis (CBA) Guide*, a CBA enables decision-makers to make informed and unbiased decisions based on facts and data. It is therefore an analysis designed for decision-making by an organization's leadership.

Some of its most important aspects include focusing on maximizing savings and reducing or avoiding costs, enhancing revenue or improving the flow of cash, improving performance, and reducing or eliminating the gap in capabilities (U.S. Army, 2010). Second, a CBA takes into consideration all factors whether they are financial or not, as well as those benefits that are not easily quantified regarding a course of action that is preferred or other alternatives. Third, a CBA analyzes the problems and the risk and recommends alternative solutions to those problems, which ultimately leads to a recommended solution before having to invest funds. Fourth, a CBA is tailor-made to unique “problems” to produce the optimal solution and supports the process of decision-making although the decisions are made by leadership. Finally, a CBA is not regarded as a substitute for making a judgment call, common sense, or management that is sound. It should, however, be updated regularly because it is a live document that assists in informed decision-making (U.S. Army, 2010).

Several stakeholders are involved in the construction of a CBA because stakeholders are the owners of the functional process and the ones who use the end products or services from the CBA (Li et al., 2017). Selecting the members of the team that will draft a CBA should be done based on their knowledge and skillsets (U.S. Army, 2010). Although it is clear that decision-makers in a CBA are the most important stakeholders, it is important to identify stakeholders on whom the CBA will have the greatest impact, so that they can act as consultants in the development process of the CBA (Schmid, 2019). This way, the CBA will meet most requirements, expectations, and needs (U.S. Army, 2010).

According to the *U.S. Army Cost-Benefit Analysis Guide*, a CBA includes cost estimation, equipment, personnel, facilities, and logistics. Personnel drafting a CBA need to come up with the size, scope, schedule, and timelines in which the CBA is expected to be completed based on the clear expectations laid out in terms of the outcomes and performance. Therefore, the proposed recommendation should be supported by clear statements that outline the benefits that outweigh the risks, costs, and trade-offs. The value proposition should establish the expected results or value that is tangible to a decision-maker. The value proposition therefore tells the decision-maker the achievements that can be made from implementing the recommended course of action.

While deployed, a great portion of the duties and responsibilities of maintenance personnel is to maintain a 100% readiness condition of all maintenance equipment onboard. The inability to achieve this goal could have a great negative impact on the mission, leading to excessive equipment downtime and possibly fatal mishaps. Over the course of its existence and through trial and error, the U.S. Navy has tried and implemented several procurement and supply methods and procedures to decrease the lead-time associated with required repair parts for maintenance personnel. Examples of these methods include the NAVSUP supply chain procedures or SQ, procuring the part from older/out-of-service equipment (which is known as cannibalization), and outsourcing or contracting to civilian private companies that are authorized to manufacture or procure the part.

In recent years, the Navy decided to analyze and test yet another procurement and manufacturing method in attempt to enhance and improve warfighting capabilities. The DoN established the AM Implementation Plan, with the goal of increasing readiness and sustainment. The AM Implementation Plan identifies several important initiatives and outlines an overall strategy for AM implementation across the DoN, with a primary initiative being to continue the development and exploration of the use of AM in afloat, subsurface, and expeditionary operational environments (Arcano, et al., 2017). To address the deployed afloat environment initiative, the Navy installed an AML onboard the USS John C. Stennis (CVN 74). Our CBA attempts to analyze and assess the economic viability of AMLs onboard naval vessels, ultimately making a recommendation as to whether it is cost beneficial for the DoN to install AMLs on all naval ships.

D. KNOWLEDGE VALUE ADDED (KVA)

The book *Measuring and Managing Knowledge* by Thomas Housel (2001) explains,

> The knowledge-value-added (KVA) methodology addresses a need long recognized by executive and managers by showing how to leverage and measure the knowledge resident in employees, information technology, and core processes. KVA analysis produces a return-on-knowledge (ROK) ratio to estimate the value added by given knowledge assets regardless of where they are located. The essence of KVA is that knowledge utilized in corporate core processes is translated into numerical form. This translation allows allocation of revenue in proportion to the value added by the

> knowledge as well as the cost to use that knowledge. Tracking the conversion of knowledge into value while measuring its bottom-line impacts enables managers to increase the productivity of these critical assets. (p. 91)

According to Housel, it would be impossible to quantify knowledge or to define the quantity of it, although he explains that the following actions are needed to produce knowledge. First, it is necessary to conduct gathering, as it is the process of bringing together data and information into a system. Second, dissemination of the information is the process of getting information to people who are supposed to use it. Third, organization of said information and how it is related to the associations of the items establishes context and provides easy access to items. Finally, refinement is the added value that is acquired through discovery of relationships, synthesis, abstraction, and sharing (Housel & Bell, 2001, p. 12).

The question that ultimately needs to be answered is what was the quantity of knowledge that was utilized and deemed beneficial for the organization and if attempts to obtain and disclose knowledge put more of it to profitable application (Cohen, 2016). KVA is used to determine the amount of existing knowledge residing under an activity or knowledge imbedded in assets (technology) within a core process. Based on this ratio, a ROK is generated (Housel & Bell, 2001). Additionally, the KVA methodology also generates an ROI calculation output (Komoroski, 2006).

Table 1. Explanation of the Two Different Metrics Produced by KVA: ROK and ROI. Source: Housel and Bell (2001).

Metric	**Description**	**Type**	**Calculation**
Return on Knowledge (ROK)^2	Basic productivity, Cash-flow ratio	Sub-corporate, process-level performance ratio	Outputs-benefits in common units/cost to produce the output
Return on Investment (ROI)	Same as ROI at the sub-corporate, process level	Traditional investment finance ration	(Revenue-investment)/investment cost

Knowledge management in an economy that relies on information means more than just the supply of knowledge because all organizations in business or in other fields build, create, and distribute products and services using knowledge. As a result, the management of knowledge must be designed in a way that is applicable to businesses in the creation or building of services and products that customers are willing to buy. Acquisition of knowledge therefore focuses on knowledge that is entrenched in processes that are core and that eventually create competitive advantage. The knowledge economy is thus the leverage for leadership to use knowledge assets to create a competitive advantage as well as add value (Housel & Bell, 2001). Leadership and management teams at different organizations use management techniques that focus on efficiency in operations, development of skills, and distribution and production of services. However, the economic order based on knowledge is a threat because skills are no longer guaranteed to be successful because there are new challenges and opportunities (Housel & Bell, 2001).

Additionally, any industry that utilizes the electronic economy is forced to create strong positions with the use of transformation tools as it would allow them to capitalize on new opportunities for growth. However, there are challenges due to the rapid changes in the marketplace, which means that leadership needs to ensure that employees have access to knowledge, which is a critical component in the support and sustenance of results.

As Housel and Bell (2001) stated, knowledge needs to consequently lead to services, products, and features that are enhanced in order to create and sustain value. In order to thrive in the new markets that are competitive, companies will be required to invest in knowledge tools that can address the gaps in knowledge and impact strategic decisions. The future of companies is therefore centered on automatic manufacturing and services that are dependent on information in the industry.

Over half of the gross domestic product (GDP) in the Organization for Economic Cooperation and Development (OECD) has been estimated to be based on knowledge and heavily relies on information technology resources (Housel & Bell, 2001). They are therefore referred to as knowledge-based economies, which are involved directly in the producing, distributing, and the use of information and knowledge in designing, producing, and distributing products and services (Housel & Bell, 2001). Although systems that have been entrenched with knowledge in the form of brains and technology have been the key components of the development of the economy, the importance of technology has greatly increased in the past years. Housel and Bell (2001) observed that knowledge is especially more important for OECD economies in the use, production, and distribution of knowledge because there is an expansion in the industries using high technology such as communications, electronics, computers, and aerospace. It results in the doubling of the share of the high technology of OECD in manufacturing through exports reaching up to 25% of the market share (Housel & Bell, 2001). Additionally, industries that use high technology, especially in information technology and cutting-edge electronics, are the major drivers of the economy in the world, with an estimated growth of communications and computer market hardware and software to above one trillion U.S. dollars (Housel & Bell, 2001). KVA follows a common-sense rule: "The harder the task, the longer it takes to learn" (see Figure 2).

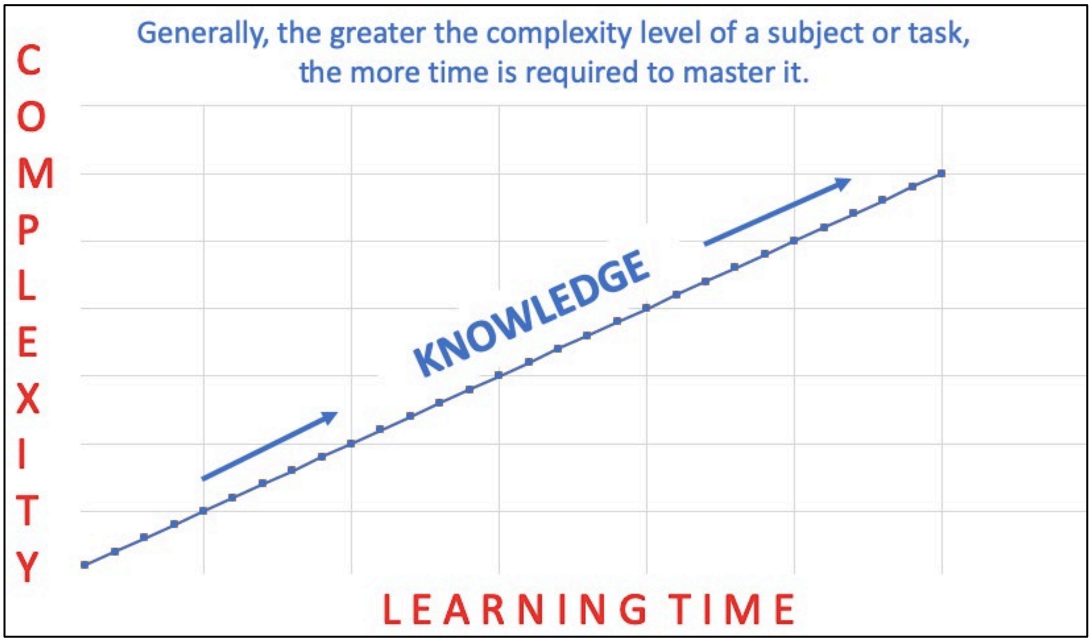

Figure 2. Complexity versus Learning Time. Source: Housel and Bell (2001).

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III. METHODOLOGY

A. PURPOSE

The purpose of this chapter is to introduce and apply the methodologies used to analyze and produce the results of this study. The KVA process developed by Housel and Bell (2001) and the Cost-Benefit Analysis (CBA) guide produced by the U.S. Army (2010) are the supporting pillars in the construction of this analysis.

The AML installed onboard USS John C. Stennis is the foundational basis for our research. The AML is the first of its kind and will serve as the source of lessons learned, and adaptation and implementation procedures for future labs installed on other surface vessels. Due to its infancy state, several aspects may improve as processes mature. Some of the areas that currently need improvement include the tracking, storing, and, most importantly, sharing of information between the different stakeholders for parts manufactured. This failure to share information presents a significant challenge when attempting to obtain parts data from either the Supply department or the AML personnel, including NSN, National Identification Number (NIIN), part numbers, correct nomenclature, and procurement information for items that the ship has already manufactured in its own AML.

This failure to share information, and the resulting lack of communication, is an issue that could become a major problem if it is not addressed, specifically for Supply departments. For instance, say that an electrician mate (EM) onboard a ship needs to replace a part in a critical piece of equipment or component, so he or she orders it via the supply system, only to find out that the part is not onboard and will take three months to arrive. Because of the urgency of the repairs, the EM requests that the AML personnel fabricate the part needed. The AML personnel designs, manufactures, and delivers the part to the EM a few hours later. The EM receives a perfectly suitable part (assuming it is) and installs it, completing the critical repairs to the down component and returns it to readiness condition.

Although this scenario sounds exactly like the reason why AMLs are being installed on ships, this new “solution” could alter the Navy’s supply frequency of demand and with it, the Navy's supply chain structure. Let's use another scenario to briefly explain one of the issues. The Supply system refers to those items that have a predictable demand or frequency of demand of two or more within six months as selected item management (SIM; NAVSUP, 2015). SIM items are supposed to be carried onboard at all times, but let's say that the EM in our previous example asks the AML to make this part and avoids ordering it through the supply system first. Because this part is now being produced by the AML and no longer demanded, then this part will be re-designated as a NON-SIM item and will no longer be carried onboard, affecting the coordinated ship's allowance (COSAL) or ship's parts inventory (NAVSUP, 2015). This same scenario could happen to hundreds of parts across the ship.

Once maturity is reached and processes become more stable, these kinks are expected to be fixed and become a part of the past. However, in the current process, communication between the end user (customer ordering a part), the manufacturer (AML technicians), and the logisticians onboard (Supply department) is not fully established, and in more than one instance, is not existent. In order to maximize the value (if any) the AMLs provide to the Surface Navy, it is imperative for the communication to flow freely, among all three stakeholders, as represented in Figure 3.

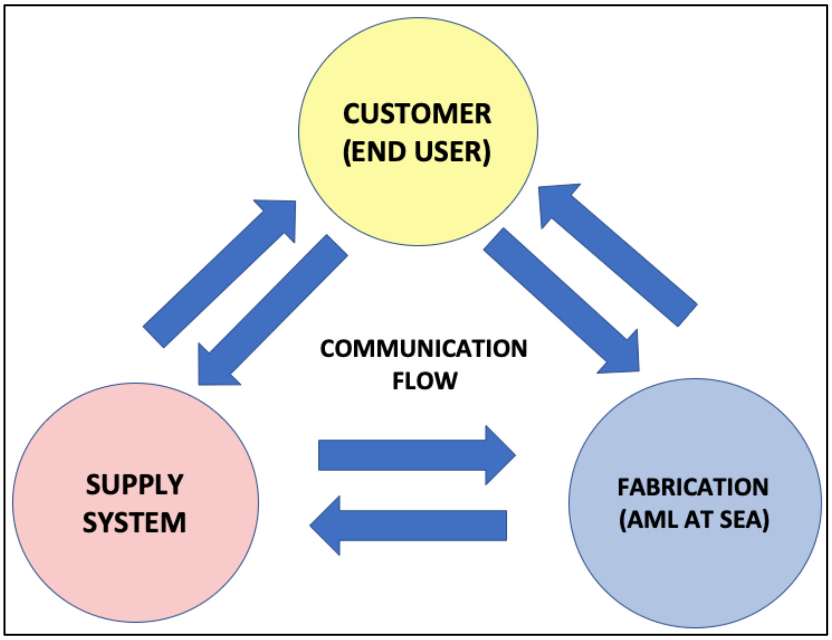


Figure 3. Communication Flow Between Stakeholders.

Because of the infancy state of the AML onboard the USS John C. Stennis (CVN 74), there is not enough information to produce a thorough CBA on the parts produced onboard. Therefore, for the purpose of this research, the research team utilized a part already printed by the military in a more mature and robust process executed by the U.S. Marine Corps (USMC). The part is a vane-axial impeller fan for the M1A1 Abrams Tank. The purpose of the part is to expel dust from the tank's engine keeping its filters clean and ensuring proper engine function (USMC, 2019).

> **NOTE:** When developing a CBA, it is of the utmost importance to remember that value does not equal cost, just as cost does not equal value. Equating cost (of any kind) to value is fundamentally and logically incorrect. Cost savings are useful when the value of the part being compared is exactly the same or very similar in quality and performance, which it is the presumption with AM during our analysis. Lowering costs of a process while maintaining the intended output and performance, or increasing output and performance without affecting costs, it is a true measure to value generation.

B. CBA PROCESS

AM technology in the Navy is moving past the testing phase and entering an implementation stage. The existing plan would allow AM to reach most surface combatants' vessels by 2025 (Arcano et al., 2017). Despite the existing plan, there has been no assessment of the value added in AM in a real-life shipboard setting. The purpose of this MBA research project is to analyze and evaluate the potential value-added of AMLs installed on surface ships. It also attempts to determine whether it would be more cost beneficial to implement AMLs on surface ships in order to obtain and issue a spare part to the maintenance personnel faster or to acquire the part through the regular supply system.

1. Data Collection and Analysis

Deployed operations require and expect maintenance personnel to return any down equipment back to readiness condition in a safe and expeditious manner. In order for this to occur, maintenance crews should either have "ready to install" repair parts at their disposal or have the certainty that they will receive the needed spare part within a timely manner. The failure to do so could result in prolonged equipment downtime and potentially fatal mishaps. In order to minimize the negative impact on personnel in theater, organizations utilize various methods of procurement and issue the required repair part to maintenance crews. Some methods include established supply chain procedures, or what the research team calls the status quo (SQ), additional contract awards to civilian companies for expeditious manufacturing and/or delivery (off-the-shelf type scenario), and cannibalization of other equipment. It is not uncommon to have a multimillion-dollar asset grounded, out of commission, tagged out, or simply deemed unserviceable (NAVSUP, 2015). But what it is of concern is that an insignificant "commercial off the shelf" part could "down" a piece of equipment for an unknown amount of time due to the lack of immediate availability of said part.

In light of this, the DOD has been researching the utilization of AM. This DOD initiative has as a primary objective to reduce the time it takes to issue a spare part (from a predetermined list of approved parts) to maintenance personnel. Overall, this would reduce the downtime of an asset or system, regardless of whether the component was procured through the SQ established procedure or if it was manufactured at sea on demand (Brown et al., 2014). Last, it is important to reiterate that the goal of this CBA is to find the best value for the cost, but cost reduction is not the primary goal.

2. Assumptions

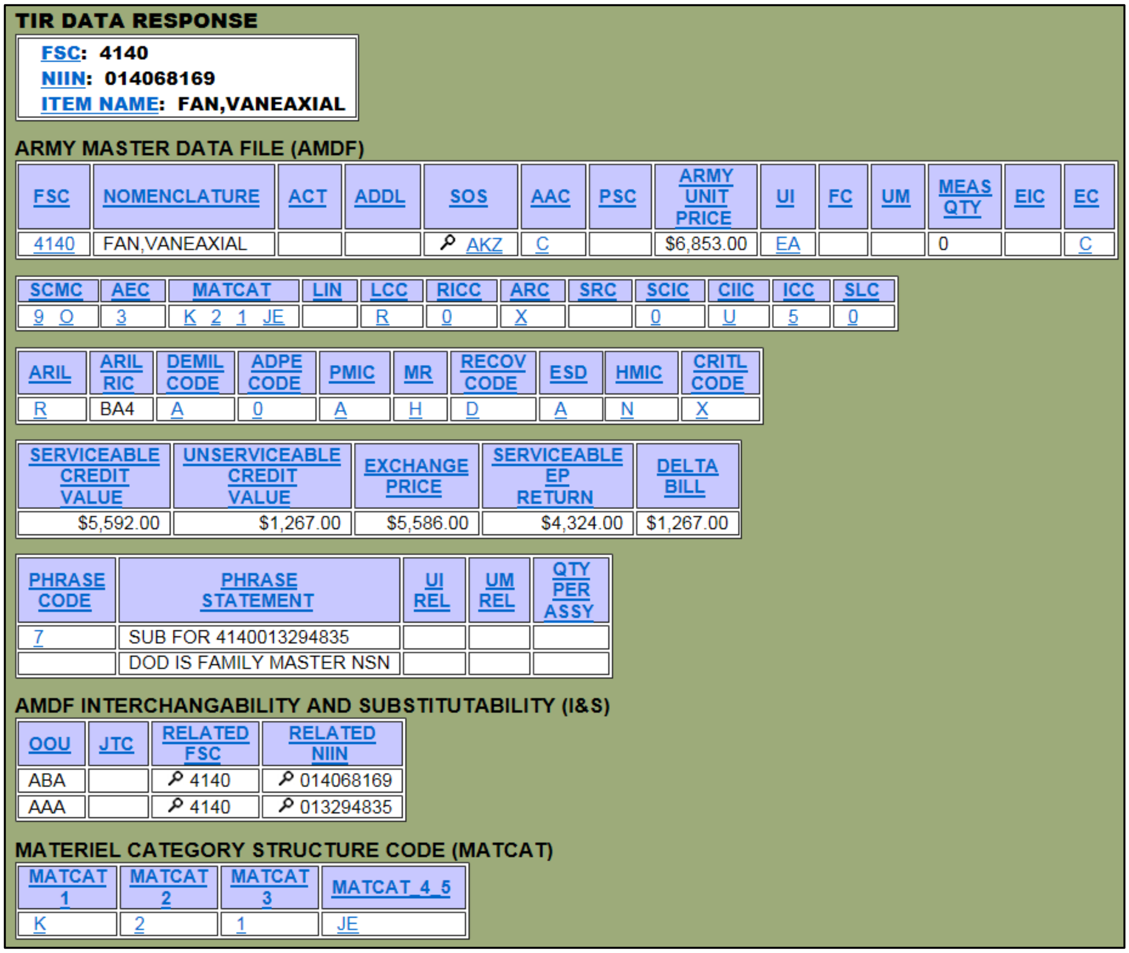
The following assumptions have been made in order to conduct this analysis: First, the manufactured part produces the same operational benefits and performs exactly as the part purchased through the established supply chain. Second, the cost of the 3D printers and other equipment involved in the AML is irrelevant because this cost is being treated as a sunk cost. Third, the AM technology is mature. Fourth, the Navy is legally authorized to reverse engineer spare parts and that there will be no patent or licensing issues. Fifth, there are no recurring fees associated with obtaining the legal rights to print spare parts. Sixth, there are trained, capable technicians and personnel available to operate the printer. Seventh, the technology necessary to print the spare parts is assumed to be at a full and complete maturation level, and an approved list of spare parts able to be printed exists. Eighth, there are no funding issues; the monetary cost to purchase the printers has been allocated to the appropriate budget appropriation line and is a sunk cost. Finally, AM will not be the primary source by which to procure spare parts; instead, it will be an alternate solution that will allow units to receive a part faster.

3. Course of Action

There are two courses of action being considered in this analysis. The SQ is purchasing the spare part through the DOD supply system. The alternate course of action is using 3D printing to print the spare part. Procuring the spare part through the supply system tends to result in longer wait times for the parts than if the parts were printed. This aspect of the analysis will provide information that could be used in determining whether 3D printing is beneficial for the Navy.

4. Guidelines

The following guidelines are in use for the purpose of this analysis: (1) the U.S. Navy procurement procedures (supply system) are followed as the status quo, and (2) the standard sample spare part being used in this analysis is a vane-axial impeller fan for the M1A1 Abrams Tank used for both the Army and the Marine Corps. The purpose of this part is to remove debris from the air filter of the Abrams, allowing for its safe operation. Data has been obtained from DLA's Federal Logistics Data (FEDLOG) regarding the impeller fan (FEDLOG, 2017). The price to purchase a brand-new impeller fan is \$6,853.00. The price to purchase this part if a serviceable part is turned in is \$1,261.00, which is the full unit price minus the unserviceable credit value for the part turned in (\$6,853.00 – \$5,592.00). The price to purchase the part if an unserviceable part is turned in is \$5,586.00, which is the full unit price minus the unserviceable credit value for the part turned in (\$6,853.00 – \$1,267.00). See Figure 4, which reports all information for the primary customers, the U.S. Army and U.S. Marine Corps. The research team added an additional assumption that prices would not change for the Navy.



TIR DATA RESPONSE

FSC: 4140
NIIN: 014068169
ITEM NAME: FAN,VANEAXIAL

ARMY MASTER DATA FILE (AMDF)

FSC	NOMENCLATURE	ACT	ADDL	SOS	AAC	PSC	ARMY UNIT PRICE	UI	FC	UM	MEAS QTY	EIC	EC
4140	FAN,VANEAXIAL			AKZ	C		$6,853.00	EA			0		C

SCMC	AEC	MATCAT	LIN	LCC	RICC	ARC	SRC	SCIC	CIIC	ICC	SLC
9 O	3	K 2 1 JE		R	0	X		0	U	5	0

ARIL	ARIL RIC	DEMIL CODE	ADPE CODE	PMIC	MR	RECOV CODE	ESD	HMIC	CRITL CODE
R	BA4	A	0	A	H	D	A	N	X

SERVICEABLE CREDIT VALUE	UNSERVICEABLE CREDIT VALUE	EXCHANGE PRICE	SERVICEABLE EP RETURN	DELTA BILL
$5,592.00	$1,267.00	$5,586.00	$4,324.00	$1,267.00

PHRASE CODE	PHRASE STATEMENT	UI REL	UM REL	QTY PER ASSY
7	SUB FOR 4140013294835			
	DOD IS FAMILY MASTER NSN			

AMDF INTERCHANGABILITY AND SUBSTITUTABILITY (I&S)

OOU	JTC	RELATED FSC	RELATED NIIN
ABA		4140	014068169
AAA		4140	013294835

MATERIEL CATEGORY STRUCTURE CODE (MATCAT)

MATCAT 1	MATCAT 2	MATCAT 3	MATCAT_4_5
K	2	1	JE

Figure 4. FEDLOG Data Product. DLA NSN 4140–01-406-8169.
Source: FEDLOG, Defense Logistics Agency Database, (2017).

5. Inventory of Impacts

In order to compare the benefits of 3D printing the part, it is necessary to monetize the different time factors affecting the decision to stay with the SQ. The first factor is time, and it is the average waiting time for the impeller fan to be purchased and received using the current supply system. The following process is used to purchase a part through the supply system: (1) a technician identifies the part, including the NSN; (2) the technician develop a work request and submit the request via the supply system; (3) the request goes to a Navy Supply Fleet Logistics Center (NAVSUP FLC) for action (issue, local purchase, or submitted to a local supplier on an existing contract); (4) if the request cannot be filled by the NAVSUP FLC, it is sent to Naval Supply Systems Command—Weapons Systems Support (NAVSUP WSS) for procurement, which could take anywhere from a few days to several months based on whether the part has to be contracted out for manufacturing; finally, (5) once the part is acquired, it is sent to the local supply center for delivery to the unit (NAVSUP, 2015). See Figure 5 for a diagram of the supply procedures.

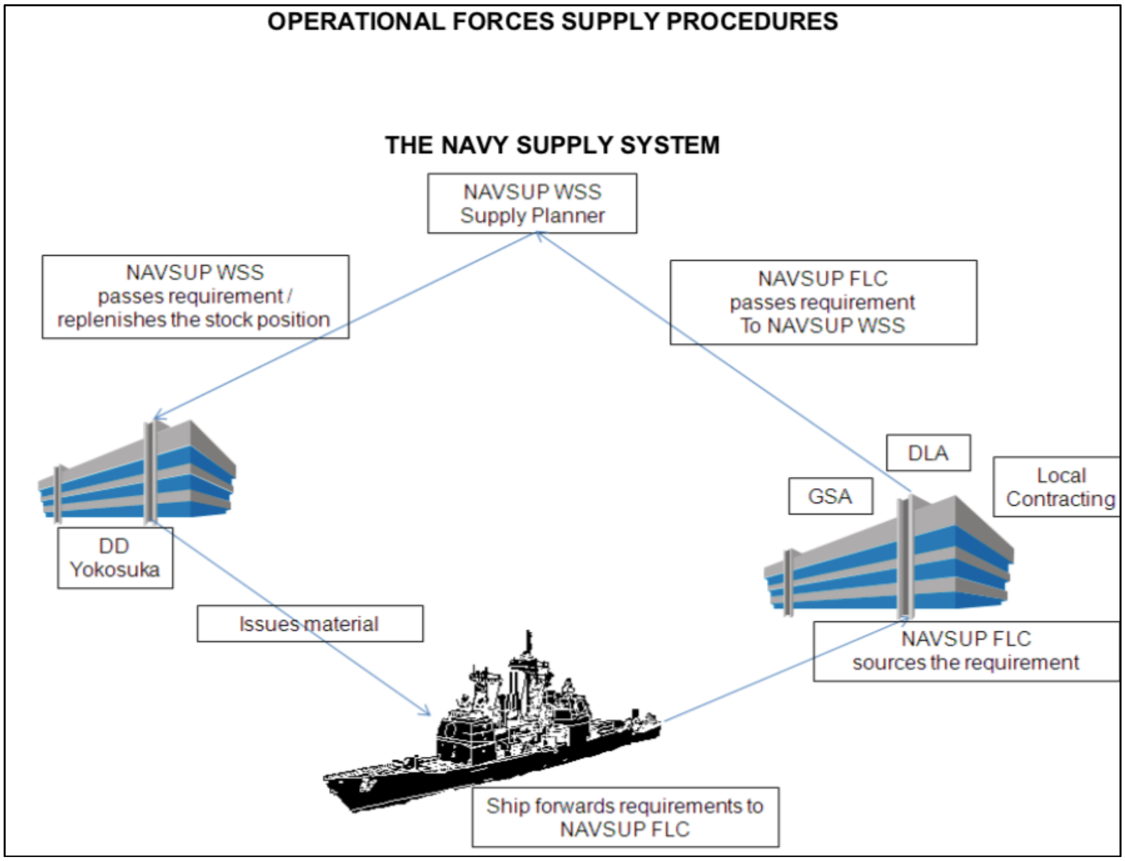


Figure 5. NAVSUP Operational Forces Supply Cycle. Source: NAVSUP (2015).

6. Forces Supply Procedures

Currently the impeller fan has an estimated field delivery time of approximately 120 days unless its priority is changed due to requirements. (This estimation was obtained informally through Marine Corps personnel currently working with 3D printing.)

The second SQ factor is the time the equipment is out of commission (OOC). This time needs to be kept under consideration since troops will be spending time and resources to obtain a new asset (replacement fan or even replacement tank) from any available source (e.g., another unit or home base). Other non-monetary factors related to the time the equipment is out of commission are unit readiness, unit morale, and unit training time loss. Additionally, the status quo forces maintenance crews to improvise and use non-traditional methods such as cannibalization of equipment. It is important to also consider the impact on resources and maintenance crew time that cannibalization causes. In this case, another OOC M1A1 Abrams tank must provide the part to fix the down tank; however, cannibalization should be used only as a last resort due to the intensive monitoring required in order to ensure the process is accomplished in accordance with standard procedures (NAVSUP, 2015).

The cost associated with the impeller fan is $6,853; however, this part is a depot-level repairable part, so the cost can be reduced to $1,261 if the carcass of the old serviceable part is turned in. Conversely, the current cost to print an impeller—accounting only for raw material without taking into consideration other costs such as manpower—is less than $50. For the purpose of this analysis, the research team assumed the cost of manufacturing the impeller utilizing AM is $50.

7. Projection of Impacts

Currently, naval forces are distributed or deployed across the globe. To receive timely repair parts for the platforms required to keep the readiness of any unit is challenging. The associated risks of not having the needed repair parts can be detrimental, especially if the required part affects readiness during a combat situation or any other mission. It is clear that the status quo of utilizing the supply chain process does not always provide the timeliest support to all the units around the world. This analysis focuses on three different areas to determine whether an impeller fan for the M1A1 Abrams Tank should be printed or purchased through the regular supply channels. The areas to consider are delivery time, downtime, and actual costs. Considering the above factors, the length of time that an M1A1 Abrams Tank is out of service will have the following impacts: (1) the crew receives pay without performing their primary duties due to the tank being down and unavailable for training or mission use, and (2) extra man-hours will be spent attempting to cannibalize another tank.

In a regular economy, the supply and demand of products shift constantly based on the inputs of the market. The graph in Figure 6 represents the impact in the market due to the internal production of parts. Since the Navy will produce its own impeller fans, the government will decrease the demand for the part; The research team expects the demand curve to shift to the left, which will cause a price reduction for the impeller fan (see Figure 6).

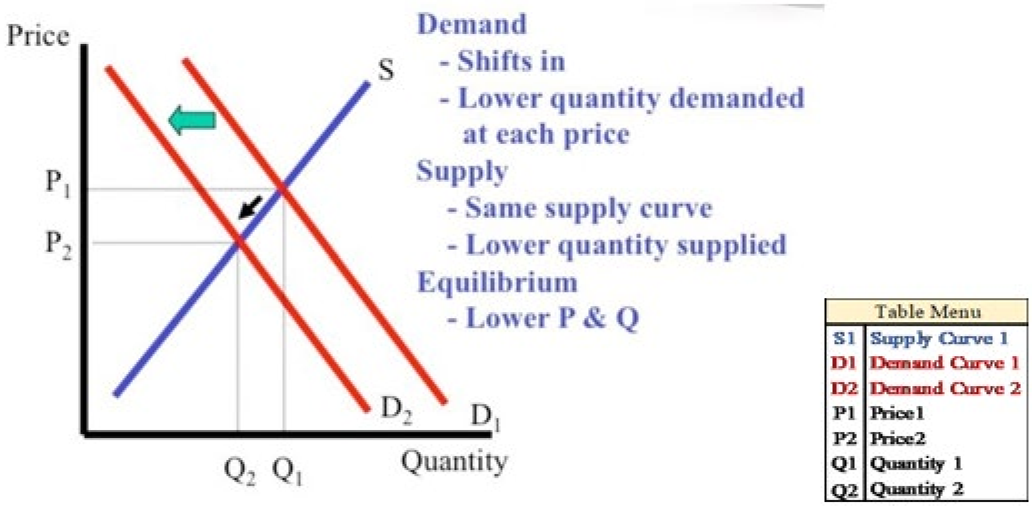


Figure 6. Behavior of the Demand Curve in the Market. Adapted from Mankiw (2016).

8. Calculation of Benefits and Costs

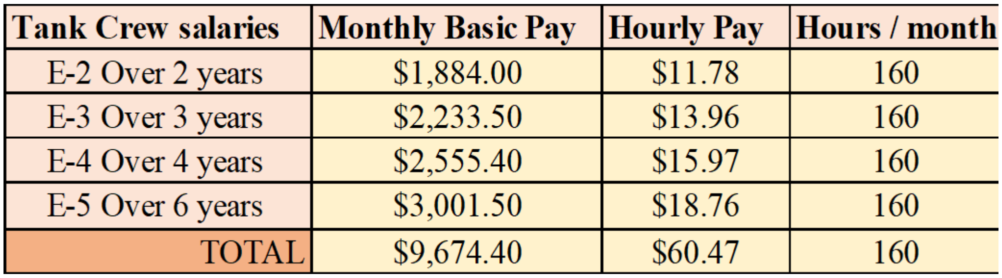
This analysis attempts to monetize the cost of waiting for the parts to be sourced from current sources of supply and the time of a down piece of equipment in order to add those to the actual cost of purchase or AM production. The time frame for this analysis is four years, which is the expected useful life of most 3D printers being purchased by the Navy (Arcano et al., 2017). The material and delivery costs can be determined by identifying the NIIN or NSN to price the part via the conventional supply sources. Utilizing the 2019 military pay table, the basic salary of a service member broken down to working-hours and its dollar value is utilized as the common unit (see Table 2).

Table 2. Enlisted Members (Active) Monthly Rates of Basic Pay. Source: Defense Finance and Accounting Service (DFAS, 2019).

Pay Grade (Years)	**2 or less**	**More than 2**	**More than 3**	**More than 4**	**More than 6**	**More than 8**
E-7	3,020.70	3,296.70	3,423.30	3,590.10	3,720.90	3,945.00
E-6	2,612.70	2,875.20	3,002.10	3,125.40	3,254.10	3,543.30
E-5	2,393.40	2,554.80	2,678.10	2,804.40	3,001.50	3,207.00
E-4	2,194.50	2,307.00	2,431.80	2,555.40	2,664.00	2,664.00
E-3	1,981.20	2,105.70	2,233.50	2,233.50	2,233.50	2,233.50
E-2	1,884.00	1,884.00	1,884.00	1,884.00	1,884.00	1,884.00
E-1	1,680.90	1,680.90	1,680.90	1,680.90	1,680.90	1,680.90

As shown in Table 3, for the purpose of this analysis, the research team assumed the following specific pay grades, years of service, and workhours per month.

Table 3. Selected Paygrades and Their Hourly Pay. Source: DFAS (2019).



Tank Crew salaries	**Monthly Basic Pay**	**Hourly Pay**	**Hours / month**
E-2 Over 2 years	$1,884.00	$11.78	160
E-3 Over 3 years	$2,233.50	$13.96	160
E-4 Over 4 years	$2,555.40	$15.97	160
E-5 Over 6 years	$3,001.50	$18.76	160
TOTAL	$9,674.40	$60.47	160

When purchasing the impeller fan through the supply system, two factors were considered: the downtime of the tank (due to part unavailability), and the cost of the part including delivery costs. It is estimated that delivery of the part could potentially take up to 10 months (USMC, 2019), but for the purpose of this research, the research team chose a random delay-time of just four months to be delivered; hence, in our calculations, the tank is down for four months. Another assumption is that a month has 160 workhours or 40 workhours per week, and the research team did not account for the weekends. To monetize the downtime, it is necessary to multiply the four months by the total monthly crew salary rate of $9,674.40. There are no identified benefits to the period of time it will take the part to be delivered, so there are no benefits, only costs. Therefore, the associated net cost of downtime is -$38,697.60 or ($0 – $38,697.60). The monetary cost to procure the part through the supply system is $6,853.00. This actual cost was found via FEDLOG from the DLA (FEDLOG, 2017). There are no associated benefits with the monetary purchase of the part through the supply system, so the associated net benefit is -$6,853.00. The total net value of purchasing the impeller fan through the supply system is -$45,550.60, which represents the downtime for the tank crew and the cost of purchasing the part (-$38,697.60 + -$6,853.00). See Table 4.

Table 4. Total Net Value with Full Value Replacement Part and Four-Month Downtime.

Purchase Costs SQ (Via Supply System)	Acquisition Costs	Benefits	Net Value (Benefits – Costs)
Delivery time/Down-time (120 days)	$38,697.60	$0.00	$ (38,697.00)
Part Cost (Including delivery)	$ 6,853.00	$ 6,853.00	$ -
TOTAL	$45,550.60	$0.00	$ (45,550.60)

The following factors are considered when calculating the total net value of using 3D printing to manufacture the impeller fan:

- the downtime of the equipment or the time it takes to print the part and
- the monetary cost of manufacturing the part.

For the downtime cost, it is estimated (assumption) that it will take three days to print the impeller fan. The cost of the printing time/downtime was monetized by multiplying three days by the total crew hourly rate of $60.47 for a cost of $1,451.16.

8 hours per day × 3 days = 24 hours

$60.47 × 24 hours = $1,451.16

The cost of the downtime if the required part was acquired through the regular supply chain was calculated by subtracting the 24 hours (three days) it would take to print the part from the 640 working hours (four months) it would take to receive the part if it were purchased through the supply system, then multiplying the resulting 616 hours by the total hourly crew salary rate of $60.47. This results in a downtime cost of $37,246.44 as follows:

160 hours/month × 4 months = 640 hours

640 hours - 24 hours = 616 hours

616 hours × $60.47 = $37,246.44

However, if the part was 3D printed, the savings are estimated as follows: $37,246.44 of downtime costs, minus $1,451.16, which is the labor-cost of printing the part, for a total net savings of $35,795.28 as follows:

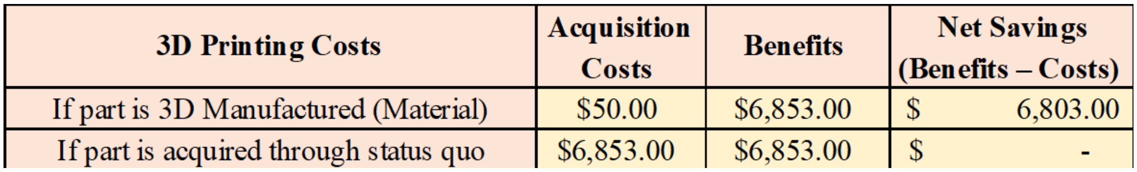
$37,246.44 - $1,451.16 = $35,795.28.

> **NOTE:** It is very important to remember that these costs are accounting only for the unit's personnel basic pay unless it is specified otherwise. These costs do not include equipment costs, overhead, or any other pay or allowances to the personnel involved.

The cost to print the part is approximately $50.00. This cost was determined by informal methods, including personal conversations, from data tracked at the Marine Corps Expeditionary Manufacturing (EXMAN) lab located in Camp Pendleton. The benefit of printing the impeller fan was calculated by subtracting the monetary cost of printing the part from the monetary cost of purchasing it through the supply system. This resulted in a net savings of $6,803.00 as follows:

$6,853.00 - $50.00 = $6,803.00. See Table 5.

Table 5. Net Savings AM vs. Using Full Cost Replacement Part.



3D Printing Costs	Acquisition Costs	Benefits	Net Savings (Benefits – Costs)
If part is 3D Manufactured (Material)	$50.00	$6,853.00	$ 6,803.00
If part is acquired through status quo	$6,853.00	$6,853.00	$ -

So, the total economic benefit associated with printing the impeller fan when accounting for downtime and material costs is $42,598.28 as follows:

$35,795.28 + $6,803.00 = $42,598.28. See Table 6.

Table 6. Total Economic Benefit with Four-Month Downtime.

	If 3D printed	Status Quo (616 Work hours)	Net Cost
Cost of downtime	$ 1,451.16	$ 37,246.44	$35,795.28
Part manufacturing cost	$ 50.00	$ 6,853.00	$6,803.00
So, total Costs and Benefits	$ 1,501.16	$ 44,099.44	$42,598.28

After monetizing the costs and benefits associated with both printing the impeller fan and purchasing it through the supply system, it is important to determine the present value of the total net benefit of printing the part across the useful life of the printer. To do this, the present value equation was used:

$$\boldsymbol{PV = \frac{1}{(rate)^n}}$$

where PV is the present value, divided by the rate and elevated to *n*, signifying the number of periods; in this case, the periods will be years. The present value at year zero is $42,598.28, as calculated in the previous paragraph. The discount rate of 1.07 is being used and is the standard discount rate used by the government (Office of Management and Budget [OMB], 2018). The present value for year 1 was determined to be $39,811.48 as follows:

$$\boldsymbol{PV = \frac{42,598.28}{1.07^1} = \$39,811.48}$$

After substituting 2 years into the equation for *n* and keeping everything else the same, the present value for year 2 was determined to be $37,206.99 as follows:

$$\boldsymbol{PV = \frac{42,598.28}{1.07^2} = \$37,206.99}$$

The same method was used to determine the present value of the total net benefit of printing for year 3. This value is $34,772.89 as follows:

$$\boldsymbol{PV = \frac{42,598.28}{1.07^3} = \$34,772.89}$$

After adding up the net present value of printing the impeller fan for years 0 through 3, the total net present value of printing the part over a period of four years was calculated to be $154,389.63. See Table 7.

Table 7. Net Present Value of AM Part.

Net Present Value	Year	Printing Net Value
	0	$ 42,598.28
	1	$ 39,811.48
	2	$ 37,206.99
	3	$ 34,772.89
Total	4 Yrs	$154,389.63

9. Sensitivity Analysis

Two factors were altered in order to perform a sensitivity analysis on the previously discussed data for the impeller fan. Those two factors are the cost of the part and the number of days it takes the part to be delivered.

First, the cost of the part was reduced from the full replacement value ($6,853.00) to the amount the part would cost if a serviceable part is turned in ($1,261.00) and all other factors remained the same. This resulted in a change in the cost of the part in year 0 if the part was to be purchased through the supply system from $45,550.60 to $39,958.60. If the part was printed, the net value changed from $42,598.28 to $37,006.28 in year 0.

The total change after four years (n=4) between buying a brand-new part or receiving the discount from a suitable turn-in replacement is only $20,267.18, from $154,389.63 - $134,122.45 = $20,267.18, which indicates that the most important factor in the analysis is not the cost of the part, but instead the cost of the downtime. Therefore, the research team adjusted the times to see the impacts. See Table 8.

Table 8. Using Suitable Turn-In Price (Lower Part Cost Only) and Same Four-Month Downtime.

Purchase Costs SQ (serviceable turn-in)	**Acquisition Costs**	**Benefits**	**Net Value (Benefits – Costs)**
Delivery time/Down-time (120 days)	$38,697.60	$0.00	($38,697.60)
Part Cost (Including delivery)	$ 1,261.00	$ 1,261.00	$ -
TOTAL	$39,958.60	$0.00	($39,958.60)

With the new suitable turn-in price of $1,261, the research team makes the calculation keeping the same costs for downtime. See Table 9.

Table 9. Using Suitable Turn-In Price (Lower Part Cost Only).

3D Printing Costs (serviceable turn-in)	**Acquisition Costs**	**Benefits**	**Net Savings (Benefits – Costs)**
Material cost if part is 3D Manufactured	$50.00	$1,261.00	$1,211.00
Part cost if status quo	$1,261.00	$1,261.00	$0.00

The total economic benefit associated with printing the impeller fan when accounting for downtime but utilizing suitable turn-in price of $1,261 is as follows: $35,795.28 + $1,211.00 = $37,006.28. See Table 10.

Table 10. Using Suitable Turn-In Price (Lower Part Cost Only) vs. AM.

	If 3D printed	**Status Quo (616 Work hours)**	**Net Cost**
Cost of downtime	$ 1,451.16	$ 37,246.44	$35,795.28
Part manufacturing cost	$ 50.00	$ 1,261.00	$1,211.00
So, total Costs and Benefits	$ 1,501.16	$ 38,507.44	$37,006.28

Last, the research team accounted again for the net present value using the suitable turn-in price (lower part cost only). See Table 11.

Table 11. Net Present Value Using Suitable Turn-In Price (Lower Part Cost Only).

Net Present Value (serviceable turn-in)	Year	Printing Net Value
	0	$ 37,006.28
	1	$ 34,585.31
	2	$ 32,322.72
	3	$ 30,208.15
Total	4 Yrs	$134,122.45

Because it has been determined that the cost of the part is not as critical as the downtime of the equipment, the research team changed the four-month time frame used in our original calculation accounting for 640 working hours:

160 hours / month × 4 months = 640 hours

to account for the second factor in our sensitivity analysis—the number of days it takes the part to be delivered. The research team reduced the delivery of the part down to half the time or just two months. The research team used the original cost of the part $6,853.00 as follows:

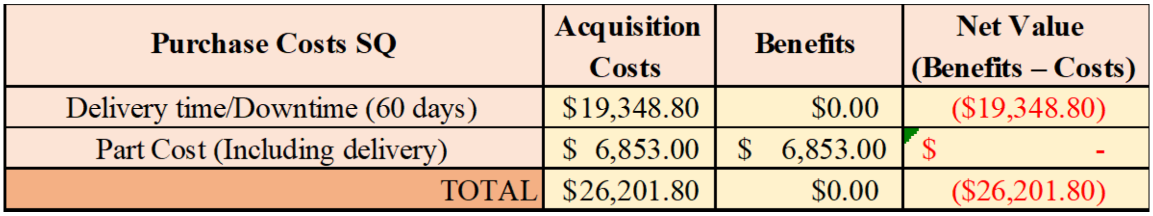
160 hours / month × 2 months = 320 hours

Procuring the part through the supply system but reducing the delivery time and of course, the downtime of the tank from four months down to two months, results in an increase in value of $19,348.80, as follows:

(-$45,550.60) - (-$26,201.80) = -$19,348.80

and an overall net value of -$26,201.80, as indicated in Table 12.

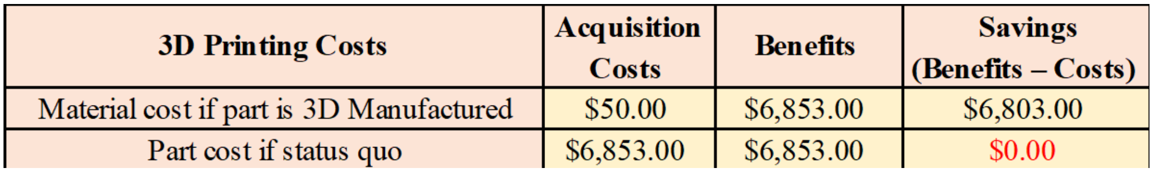
Table 12. Total Net Value with Full Value Replacement Part and Two-Month Downtime.



Purchase Costs SQ	Acquisition Costs	Benefits	Net Value (Benefits – Costs)
Delivery time/Downtime (60 days)	$19,348.80	$0.00	($19,348.80)
Part Cost (Including delivery)	$ 6,853.00	$ 6,853.00	$ -
TOTAL	$26,201.80	$0.00	($26,201.80)

The savings associated with AM the part remain the same, as seen in Table 13.

Table 13. Net Savings AM vs. Using Full Cost Replacement Part.

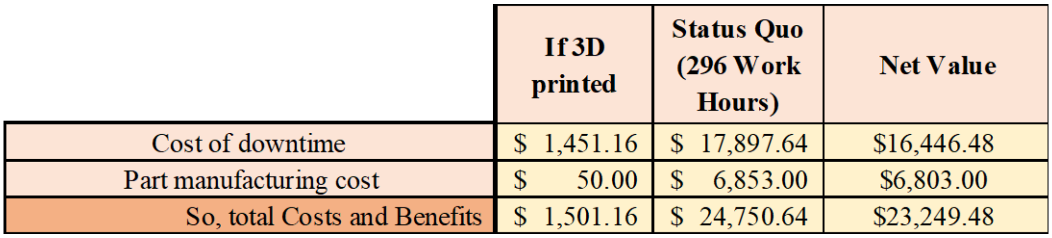


3D Printing Costs	Acquisition Costs	Benefits	Savings (Benefits – Costs)
Material cost if part is 3D Manufactured	$50.00	$6,853.00	$6,803.00
Part cost if status quo	$6,853.00	$6,853.00	$0.00

So, the total economic benefit associated with printing the impeller fan when accounting for downtime but utilizing the part's original price of $6,853.00 is as follows:

$16,446.48 + $6,803.00 = $23,249.48. See Table 14.

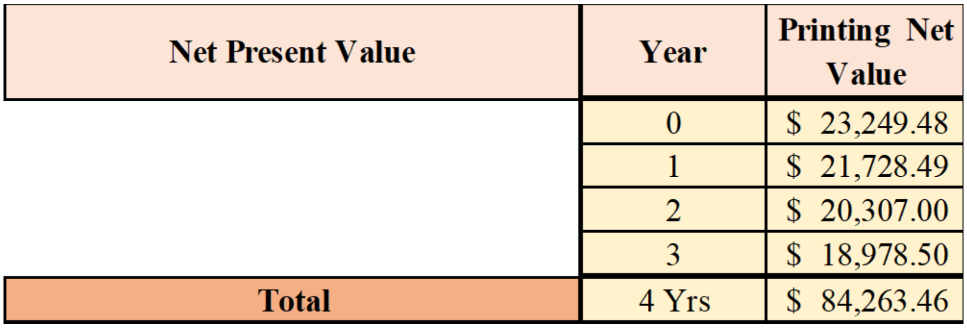
Table 14. Using Full Value Replacement Part and Two-Month Downtime.



	If 3D printed	Status Quo (296 Work Hours)	Net Value
Cost of downtime	$ 1,451.16	$ 17,897.64	$16,446.48
Part manufacturing cost	$ 50.00	$ 6,853.00	$6,803.00
So, total Costs and Benefits	$ 1,501.16	$ 24,750.64	$23,249.48

Lastly, the research team accounted again for the net present value using original price of the part and the two-month downtime. See Table 15.

Table 15. Net Present Value Using Full Value Replacement Part and Two-Month Downtime.



Net Present Value	Year	Printing Net Value
	0	$ 23,249.48
	1	$ 21,728.49
	2	$ 20,307.00
	3	$ 18,978.50
Total	4 Yrs	$ 84,263.46

Continuing with our sensitivity analysis next, the research team further reduced the downtime from four months to just one month:

So, from 160 hours / month x 4 months = 640 hours

to:

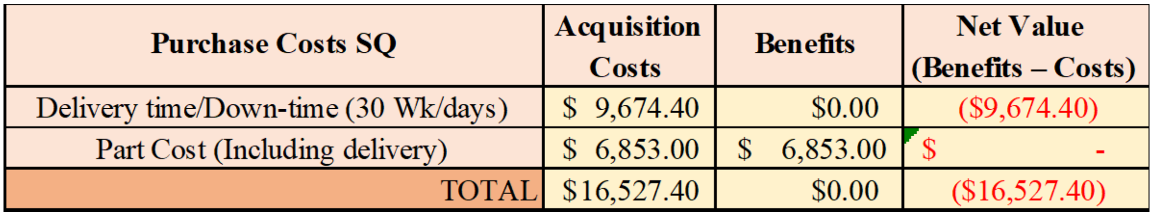
160 hours / 1 month = 160 hours

Procuring the part through the supply system but reducing the delivery time and of course the downtime of the tank from four months down to just one month, results in an increase in value of $29,023.20, as follows:

(-$45,550.60) - (-$16,527.40) = -$29,023.20

and an overall net value of -$16,527.40, as indicated in Table 16.

Table 16. Total Net Value with Full Value Replacement Part and One-Month Downtime.



Purchase Costs SQ	Acquisition Costs	Benefits	Net Value (Benefits – Costs)
Delivery time/Down-time (30 Wk/days)	$ 9,674.40	$0.00	($9,674.40)
Part Cost (Including delivery)	$ 6,853.00	$ 6,853.00	$ -
TOTAL	$16,527.40	$0.00	($16,527.40)

The savings associated with AM the part remain the same, as seen in Table 17.

Table 17. Net Savings AM vs. Using Full Cost Replacement Part AM Benefit.

3D Printing Costs	Acquisition Costs	Benefits	Savings (Benefits – Costs)
Material cost if part is 3D Manufactured	$50.00	$6,853.00	$6,803.00
Part cost if status quo	$6,853.00	$6,853.00	$0.00

The total economic benefit associated with printing the impeller fan when accounting for downtime but utilizing the part original price of $6,853.00 is as follows:

$6,772.08 + $6,803.00 = $13,575.08. See Table 18.

Table 18. Using Full Value Replacement Part and One-Month Downtime.

	If 3D printed	Status Quo (296 Work Hours)	Net Value
Cost of downtime	$ 1,451.16	$ 8,223.24	$6,772.08
Part manufacturing cost	$ 50.00	$ 6,853.00	$6,803.00
So, total Costs and Benefits	$ 1,501.16	$ 15,076.24	$13,575.08

Last, the research team accounted again for the net present value using original price of the part and the two-month downtime. See Table 19.

Table 19. Net Present Value Using Full Value Replacement Part and One-Month Downtime.

Net Present Value	Year	Printing Net Value
	0	$ 13,575.08
	1	$ 12,686.99
	2	$ 11,857.00
	3	$ 11,081.31
Total	4 Yrs	$ 49,200.38

The previous data shows the cost of the part does not have much effect on the net present value (NPV). However, when the number of days for the part to be delivered is reduced, there is a significant impact on NPV. This reveals that as the number of days for the impeller fan to be delivered through the supply chain is reduced, 3D printing the impeller fan becomes less beneficial.

10. CBA Results and Recommendations

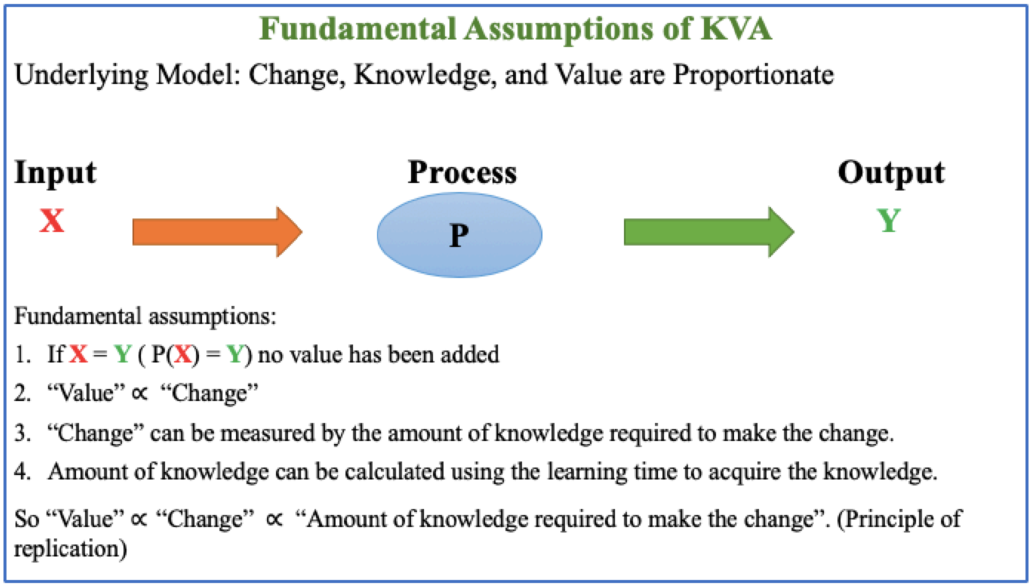
The results of this CBA and its sensitivity analysis point out that having the ability to print on demand via an AML greatly reduces downtime for any unit and subsequently reduces costs, improves the benefits, and, most importantly, saves taxpayer dollars. However, it also shows that for parts that are readily available via the status quo of utilizing the supply chain, printing is the best approach. In simple terms, the analysis points out that AM does not have the current capacity to supplant the Navy supply chain but instead supplement it.

The value provided by 3D printing technology by reducing downtime is undeniable, and it is what AMLs onboard ships could help resolve. The Navy could handsomely benefit from having these AMLs in all of their deployable units as they are impacted by delivery times, primarily due to their various and random geographical locations at any given moment. Units forward deployed should definitely have their own AML and trained personnel. A complete AML is recommended onboard Navy vessels, if possible, in order to reduce the downtime of equipment in deployed environments where the current supply system is slow to deliver or alternative solutions for spare parts are not feasible.

C. KVA ANALYSIS PROCESS

The purpose of this section is to introduce the KVA methodology used to complete the findings of our research presented in the following analysis. Together with the CBA, the KVA process developed by Housel and Bell (2001) is the basis for estimating the results based on how much value is provided to the Surface Navy by having AMLs at sea and manufacturing repair parts on demand. It is important to reiterate that supply storerooms aboard ships do not always have the capacity to carry the necessary parts for making repairs at sea. Hence, if a part is unavailable in the storerooms, resulting in long lead-time to procure, the maintenance team will request the part through the AML printing process to reduce the downtime of the equipment.

KVA is a methodology that measures the value of knowledge by converting it into common units, enabling its users to quantify it. The acceptance of KVA as an analytical tool and its popularity are growing due to its practicality and ease of use (Walsh, 1998). But in order to clearly understand KVA, it is necessary to know that the fundamental assumption of KVA demonstrates how knowledge, calibrated in common units of learning time (LT), can be used as a surrogate for common units of value (i.e., output).[1] This is better explained in Figure 7.



Fundamental assumptions:

1. If X = Y (P(X) = Y) no value has been added
2. "Value" ∝ "Change"
3. "Change" can be measured by the amount of knowledge required to make the change.
4. Amount of knowledge can be calculated using the learning time to acquire the knowledge.

So "Value" ∝ "Change" ∝ "Amount of knowledge required to make the change". (Principle of replication)

Figure 7. Defining KVA. Source: Housel and Bell (2001).

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[1] Housel and Bell (2001) explained this further:

"The principle of replication states that given that we have the knowledge necessary to produce the change, then we have the amount of change introduced by the knowledge. By definition, if we have not captured the knowledge required to make the changes necessary, we will not be able to produce the output as determined by the process, these tests to determine if the amount of knowledge required to produce an output has been accurately estimated."(pp.94)

1. Data Collection and Analysis

The main purpose of KVA is to transform the knowledge required to produce an output into common units such as money or LT to calculate to overall amount of knowledge in an activity, procedure, or organization. Housel and Bell (2001) explained:

> The essence of KVA is that knowledge utilized in corporate core processes is translated into numerical form. This translation allows allocation of revenue in proportion to the value added by the knowledge as well as the cost to use that knowledge. Tracking the conversion of knowledge into value while measuring its bottom-line impacts enables managers to increase the productivity of these critical assets. (p. 91)

2. Process Identification

The identification of the inputs and outputs of the organization’s core processes is crucial to begin formulating the KVA process. By understanding the amount of knowledge in each process and subprocess, the value that each element of the process contributes to the entire process can be identified. For this thesis, USS John C. Stennis (CVN 74) subject matter experts (SMEs) provided the procedures used to manufacture a part in-house using AM in their own AML. Via a business flow chart, the research team was able to identify eight sub-processes from this core process. See Figure 8 to understand the sequence of steps.

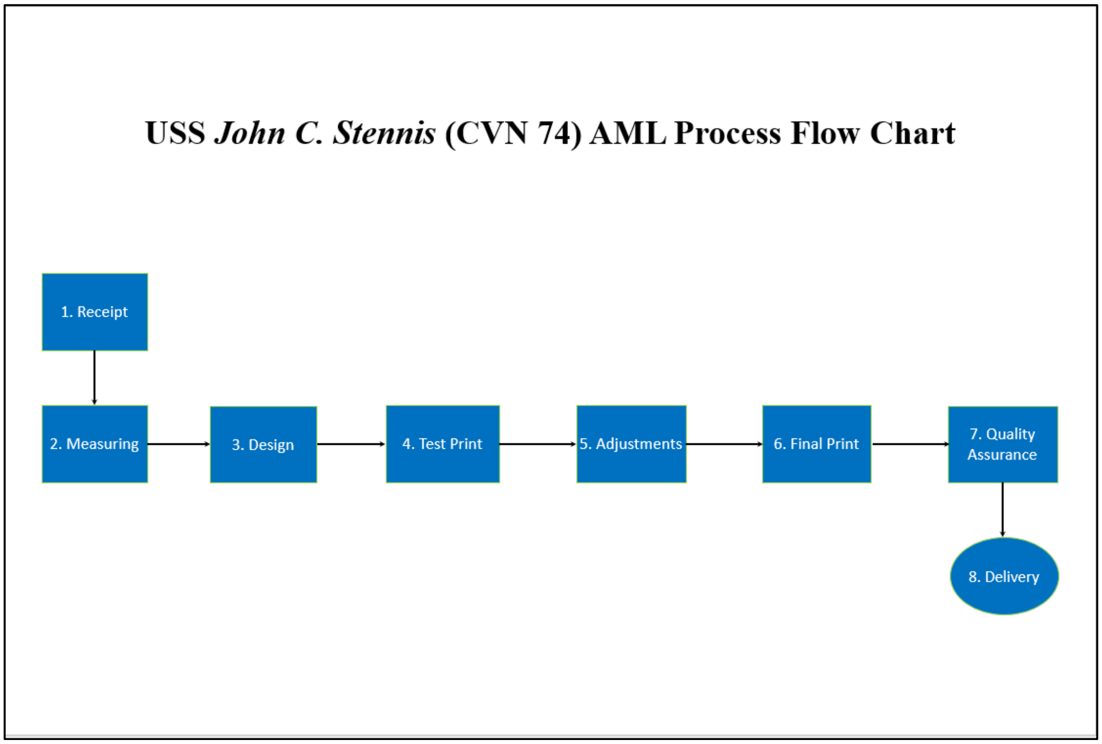

Figure 8. USS John C. Stennis (CVN 74) Repair Part Manufacturing Process. Source: USS John C. Stennis (2019).

The flow chart in Figure 8 illustrates the scope of the entire process, establishing boundaries to determine the finished output (Housel & Bell, 2001). When an information technology (IT) product contributes to a certain process, it needs to be segregated to effectively measure its knowledge effect on that particular process (Komoroski, 2006).

3. Knowledge Value Added Approaches

The knowledge of each process can be broken down into LT, process instructions, or binary query method. In this thesis, the LT approach is utilized but not the process instructions or the exception of binary query method. The correlation between the estimates of LT is used to ensure there is an accurate estimate of outputs for the model. Table 20 shows the three LT estimates to KVA and identified the process for each step (Housel & Bell, 2001).

Table 20. Three Approaches to KVA. Source: Housel and Bell (2001).

Steps	Learning	Process description	Binary query method
1	Identify core process and its subprocesses		
2	Establish common units to measure learning time.	Describe the products in terms of the instructions required to reproduce them and select unit of process description.	Create a set of binary yes/no questions such that all possible outputs are represented as sequence of yes/no answers.
3	Calculate learning time to execute each subprocess.	Calculate number of process instructions pertaining to each subprocess.	Calculate length of sequence of yes/no answers for each subprocess.
4	Designate sampling time period long enough to capture a representative sample of the core process's final product/service output.		
5	Multiply the learning time for each subprocess by the number of times the subprocess executes during sample period.	Multiply the number of process instructions used to describe each subprocess by the number of times the subprocess executes during sample period.	Multiply the length of the yes/no string for each subprocess by the number of times this subprocess executes during sample period.
6	Allocate revenue to subprocesses in proportion to the quantities generated by step 5 and calculate costs for each subprocess.		
7	Calculate ROK, and interpret the results.		

4. Learning Time Approach

In the LT approach, knowledge is measured by the approximate amount of time that a common reference point learner takes to learn to execute each process output. When conducting KVA calculations, knowledge is "counted" only when it is in use and it is required to complete the output for each process (Komoroski, 2006). Therefore, the proportion of the knowledge, in LT units, taken to complete entire process is measured in terms of common units of output, which in this analysis will be LT.

In the context of this thesis, the KVA team interviewed the SMEs, made observations, and talked with the sailors in charge of the AML from USS John C. Stennis (CVN 74) to get the estimated Actual Learning Time (ALT) for each process. After identifying the ALT, SMEs ranked the level of difficulty to learn for each process from easiest to the most difficult. In a KVA process, high correlation between the level of difficulty to learn and ALT is important in successfully analyzing the ROK. If the correlation is more than 80%, the estimated LT is deemed reliable. If it is less than 80%, the data provided is not reliable and the SME-provided data will need to be reassessed. Once the reliability is established, Relative Learning Time (RLT) can be established. RLT is calculated by assuming that the knowledge required to produce all outputs can be assumed to take 100 units of LT. It is understood that 100% of the knowledge can be allocated across the process (Housel & Bell, 2001).

5. Total Learning Time

The LT captures the time it takes to learn each process in addition to the amount of automation executed by IT products. Therefore, the percentage of the ALT for each process and the automation estimates by the AM IT products are captured in a spreadsheet to properly allocate the proportion of learning knowledge and automation (Komoroski, 2006).

6. Measuring Knowledge and Utility Executions

The number of total learned time or knowledge units of each process are common units surrogate for value, and the total amount of time required to use each resource to produce each process output is the cost for the process. Both value and cost serve as inputs for the ROK (Komoroski, 2006). Finally, value and cost are multiplied to produce a flow-based estimate of the total benefits/costs (Kennedy, 2013).

7. Return on Knowledge

In calculating the ROK ratio, the numerator represents the allocation of the market comparable revenue to the proportion of the total amount of knowledge in a given. The denominator for ROK represents the knowledge resource execution cost. If there is a high ROK percentage, the KVA utilization for that particular process is high. If the ROK percentage is low, then the knowledge utilization is low.

An additional benefit of KVA is that being able to convert the knowledge into a value enables the decision-makers to measure how effective the investment in training and knowledge utilization are, thereby enabling the decision-makers to allocate the utilization of knowledge assets in the area where it can produce better returns (Kennedy, 2013).

8. Data Collection and Analysis

a. Introduction

The USS John C. Stennis (CVN 74), currently stationed in Norfolk, VA, successfully completed a 2019 deployment with the first AML installed aboard an operational Surface Navy ship and is our test subject. The research team, also referred to as the KVA team, collected data from the CVN-74 Engineering Department, specifically from Machinery Repairmen (MRs) belonging to the Repair Division who have operated the AML since its inception. By conducting an interview with these two SMEs, the KVA team was able to acquire the average learning-time estimates required to complete each subprocess and therefore the necessary information to conduct our analysis.

This research dissects the "as-is" or status quo business processes currently being conducted at the Stennis AML. It is done through the estimates provided by the SMEs of the AM program aboard CVN-74. KVA was the methodology chosen to analyze the AM process onboard a naval vessel to find out how much value is added by the "as-is" process for the ship, and more importantly, to determine how much value added there is that could eventually affect the entire Navy.

Currently, a first-class petty officer (MR1) and a second-class petty officer (MR2) are responsible for the operation of the AML. These two SMEs have less than 18 months of experience in dealing with AM onboard a naval vessel, although they have several years of experience fabricating and manufacturing parts on-demand via subtractive manufacturing.

The SMEs have a total combined training time of four days of formal instruction in AM and in the use of the equipment that makes up the AML. This class training and the instruction manuals to the equipment were given to them before going on their 2018–2019 deployment. In a one-year period, they manufactured approximately 60 different types of actual repair parts, many of them still in-place and being used today with only their two days of training. On the job training (OJT), as well as trial-and-error via self-learned lessons, were sufficient for these two to become the tip of the spear in 3D printing at sea in the Navy. Additional explanation regarding the analysis of each person cost, actual LT, value added, and assumptions are outlined following the KVA process.

b. As-Is Manufacturing Process

Based on the interviews, the KVA team was able to break down the AML operation to eight core processes required to manufacture a repair part requested by a customer, from initial order receipt to delivery of final product. These processes are receipt, measurement, design, test print, adjustments, final print, quality assurance (QA), and delivery. They are shown in Figure 9.

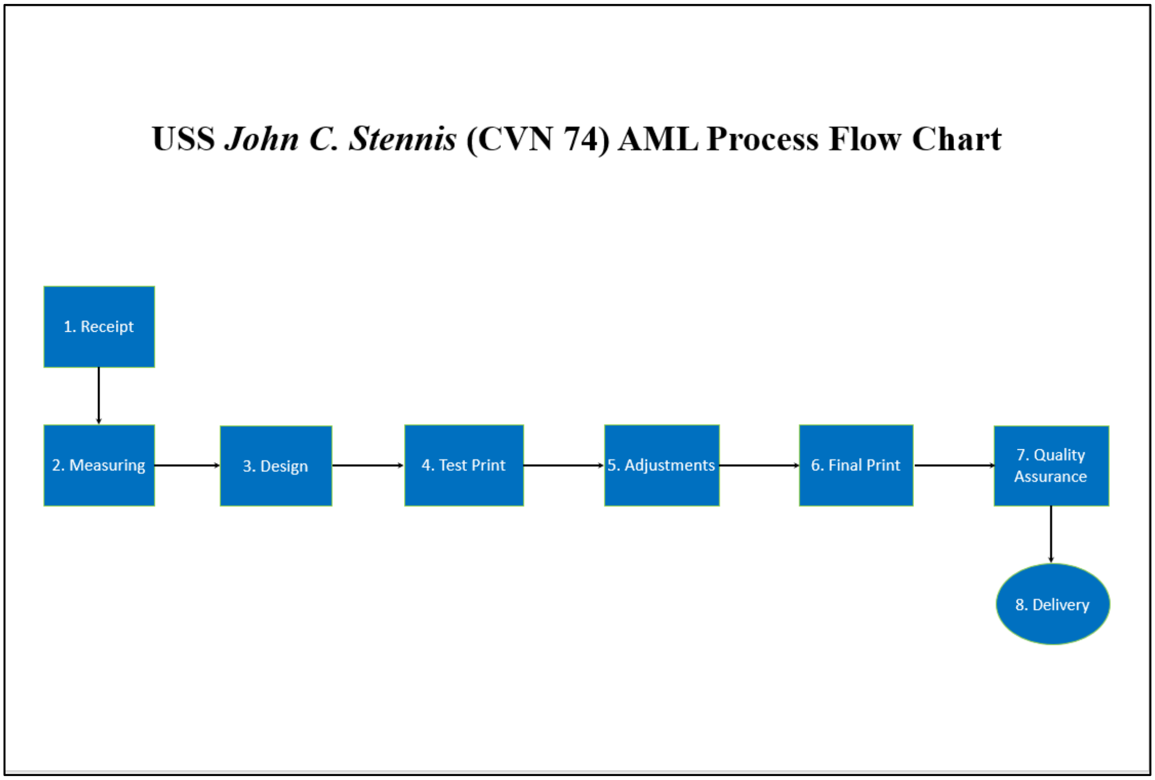

Figure 9. USS John C. Stennis (CVN 74) Repair Part Manufacturing Process. Source: USS John C. Stennis (2019).

(1) Receipt

The AML personnel receives a request to print a repair part from customers from any division on the ship. Personnel in the AML will review the paperwork for completeness and determine the feasibility of manufacturing the part being requested against current knowledge, capabilities, and resources onboard. Next, the AML personnel sends the request to the chief engineer (CHENG) for approval or disapproval with their recommendations (yes/no) to print the requested part onboard based on the criticality, capability, and capacity of the shop. If the request is disapproved, the request is sent back by the AML to the customer for procurement via the supply department; otherwise the process to manufacture moves forward.

It normally takes the CHENG approximately two hours to evaluate the recommendation from the AML personnel, but it only takes 12 minutes to receive the request, so only 12 minutes are being taken into consideration.

2.2 hours × \$24.21 = \$53.26

The output for this step is a receipt to the customer, indicating whether the AML is taking on the job requested. The LT for this step is one hour.

(2) Measurement

Once the CHENG's approval is attained, the personnel from the AML perform a detailed measurement of the part to input into the design software. Equipment such as a laser scanner could prove to be very valuable in this stage. Time for measurement could take up to four hours depending on the complexity of the part.

4 hours × \$17.52 = \$70.08

The output for this step is the measurements needed to proceed to the next step, which is design. The LT for this step is 1,000 hours.

> **NOTE:** In some instances, some parts have been previously manufactured and the required measurements as well as the designs are readily available in their own database. As more and more parts continue to be produced, the database will continue to grow and will eventually become a source of extreme value to the shop and other ships utilizing this technology.

(3) Design

Once the measurements are taken, AML personnel have the option to scan the part with the handheld scanner or design the drawings of the part using computer-aided drafting (CAD) software on a provided laptop. The handheld scanner provided by Navy Sea Systems Command (NAVSEA) was designed to scan large objects and the printer capabilities are to print small projects (6" × 6" × 6" dimensions). The printing software can reduce the size of the object scanned. However, due to the compatibility of the software and the scanner, the reduced size never came out in a right proportion of the printed and original part. Therefore, AML crew designed the part by drawing it themselves with CAD software during their deployment.

This process normally takes between five and 24 hours, depending on the complexity of the part design.

5 to 24 hours × $17.52 = $87.60 to $420.48

The output for this step is a completed designed for the part needed to proceed to the next step, which is test print. LT for this step is 2,020 hours.

(4) Test Print

The time of the test-print phase of the process varies based on the amount of raw material required to produce the part. Although the printers are doing all the work at this stage and the technicians are able to do other functions, a person still must constantly monitor the printers during the manufacturing process as problems may arise. One of the most common problems is caused by the air-conditioning in the AML, as it disrupts the heating temperature required by the printer to melt the raw material for printing the part.

This process normally takes between two and 12 hours depending on the complexity of the part design.

2 to 12 hours × $17.52 = $35.04 to $210.24

The output for this step is a manufactured part that will serve as a test print. LT for this step is four hours.

(5) Adjustments

An AML technician will thoroughly check the fabricated part for details and measurements to ensure that the part was printed correctly and that all measurements conform with the size and details required. If there is any deviation from the expected size, shape, and quality, the technician will make adjustment in the CAD software to test print again. Although proficiency of the technicians reduces the number of times this step is to be performed, this process may have to be done several times along with the test print. It takes approximately 30 minutes to two hours to complete this process per part.

0.5 to 2 hours × \$17.52 = \$8.76 to \$35.04

The output for this step is all the adjustments made to the original design needed to proceed to the next step, which is final print. LT for this step is 720 hours.

(6) Final Print

When the test print meets the standard required as expected, the AML personnel will do the final print of the part. It takes approximately the same amount of time as the test print process. Again, the printers are doing all the work at this stage, and the technicians are able to do other functions; however, it is recommended that a person constantly monitor the printers during the manufacturing process as problems may arise.

This process normally takes between two and 12 hours depending on the complexity of the part design.

2 to 12 hours × \$17.52 = \$35.04 to \$210.24

The output for this step is a final manufactured part. The LT for this step is four hours.

(7) Quality Assurance (QA)

When the part is finally printed, it is the responsibility of the most qualified of the technicians to perform a full and final check of all the specifications required and expected of the final printed part. Quality assurance includes not just the oversight of shape, hardness, or appearance, but also the use of more technical tools such as micro-meters for quality control. Many times, customers provide a sample of the part being requested to be printed; because of this, sometimes a simple naked-eye check is all that is needed.

This process takes 30 minutes to check all the specifications provided by the customer.

0.5 hours × \$24.21 = \$12.10

The output for this step is the final product ready to be delivered to the customer or rejected back to the AML technician. The LT for this step is 336 hours.

(8) Delivery

After the final print passes the QA phase, the AML technician will send an email to the customer for part pick-up by the customer. Once the customer receives the part, the customer will sign the receipt paperwork for the AML technician who will record the transaction electronically as completed. The design drawing for the part is saved on the local hard drive and added to the library for future use. In addition, the file is sent to NAVSEA within seven days for future information sharing with other ships.

It normally takes the personnel 12 minutes to deliver and record and save all information about the part.

$$0.2 \text{ hours} \times \$24.21 = \$4.84$$

The output for this step is a receipt signed by the customer, as well as a finalized digital file for the part produced. The LT for this step is one-half hour.

c. As-Is Process Analysis

The following is the breakdown of steps for the KVA process analysis as described by Housel and Bell (2001) in their book *Measuring and Managing Knowledge.* The steps are broken down and identified by "Column number" to make it easy for the reader to follow.

Column 1. The process areas of AML are as follows:

1. Receipt
2. Measurement
3. Design
4. Test print
5. Adjustments
6. Final print
7. Quality assurance
8. Delivery of final part

Column 2. The processes are ranked in terms of the level of relative difficulty to learn, from level one (1) being the easiest to learn to level eight (8) being the hardest to learn. As shown in Table 22, "delivery" has been identified as the easiest area to learn, earning a rank of one, and "design" is the hardest to learn and execute earning a rank of eight.

Column 3. The purpose of column 3 is to assign an RLT estimate to each activity to determine a percentage of how long it would take to learn each step. The research team assumed that it takes 100 hours for an average person to learn all eight processes correctly. The Stennis SMEs were asked to break down and divide the 100 hours of LT among those eight areas with a typical learner in mind. For instance, the delivery process is perhaps the simplest, but it requires one hour to learn out of the 100 hours provided. This approach keeps the leadership aligned with the conceptual context for quantification of knowledge within each respective event. This amount ultimately relates to the rank classification in column 2, given they are different ways to measure the same thing. If the two figures do not correlate highly (i.e. >0.80) then most likely an estimate is incorrect. The level of correlation should be high, for the KVA to be accurate. In this case, the correlation is over 90%, which is acceptable. Housel and Bell (2001) explained:

> Based on the fundamental assumption of KVA, the correlation between any two or more estimates should be at a high level to ensure an accurate estimate. This simple matched correlation measures the reliability of an estimate. (p. 95)

Column 4. This is the number of personnel executing each core process for manufacturing a part. The majority of steps take only one person, but designing the part is difficult and requires two personnel. Although this is not always the case, the research team assumes that it is.

Column 5. The estimated amount of knowledge contained in the IT systems that support these processes is the percentage of automation (Housel & Bell, 2001, p. 100). This percentage is an assumption of the amount of time required for the average person to learn and execute the knowledge manually that is currently being completed by IT. With the elimination of automation, the total is the sum of knowledge used to generate the same yield that would result from utilizing automation (Housel & Bell, 2001, p. 100).

Column 6. This column measures the quantity of knowledge fixed in automation. The LT (column 3) is multiplied by the total number of employees (column 4). That result is then multiplied by the percentage of automation the result as shown in column 5 (Housel & Bell, 2001, p. 100).

Column 7. This column calculates the amount of knowledge per one execution of the manufacturing process. It is calculated by multiplying the RLT in column 3 by the number of personnel in column 1, and the research team added the amount of knowledge embedded in automation in column 6.

Column 8. This column calculates the total amount of knowledge utilized in a year by multiplying the amount of knowledge per one manufacturing process (column 7) by the number of times the process was performed in a year (column 16).

Column 9. It calculates the percentage of knowledge of allocation to each process. This is done by dividing the amount of RLT of each individual process (column 7) by the sum of all the process RLT on the same column (column 7), which in this case is 198.

Column 10. This column is labeled "Market Comparison Annual Revenue Allocation." It calculates the revenue necessary to estimate an ROI. However, government projects generate benefits instead of revenue; thus, it is necessary to use a market comparable to obtain a revenue input. The research team used a revenue surrogate and assign it a value of 1.5 times the annual expense to create the market comparison. This is an assumption that the market would pay at least 1.5 times for the use of the ROK. Therefore, this column is calculated by multiplying the annual expense or "denominator" (column 11) by 1.5 (Housel, Little, & Rodgers, 2007).

Column 11. It indicates the annual expense of producing each core process during the process. In this step, it is important to account for the cost incurred in each firing of the process. It is calculated by the personnel cost; therefore, it is necessary to calculate the hourly cost of the employee performing the job and how many employees participate in completing each step. To obtain this number, the hourly rate of the employee is multiplied by the number of employees involved in the core process (column 4) times the time it takes to complete the said step (column 15), and finally multiply this number by how many times this occurred, or the number of firings (column 16). This column is also designated as our "Denominator." This denominator is used in our ROK and ROI equations.

Column 12. The revenue column, as it is name would indicate, is the estimated revenue. However, as explained above, in a government entity it is extremely difficult, impossible, or unnecessary to determine revenue as well as profit. The research team used this row as our "Numerator" in the equations used to determine ROK and ROI. To find this number, it is necessary to divide the knowledge per each process (column 7) by the total sum of all these process (column 7) and then multiply this number by the sum of all the market comparative annual revenue allocation (column 10).

Column 13. This column is our final product and main answer to our analysis. This column produces the ROK for each core process. This is obtained by a simple equation similar to the one of productivity that states, "Output over Input." In this case, the research team used our numerator in column 12, which is the allocated revenue, and it will be divided by the cost to use this knowledge or our denominator in column 11 (Housel & Bell, 2001, p. 101).

Column 14. Another benefit of KVA is that it allows for the calculation of ROI as described previously via the market comparable revenue estimate. For knowledge management to be taken seriously, investors, stakeholders, or, in this case, taxpayers must be able to determine the ROI (Housel & Bell, 2001, p. 81). Because ROI is a more common and acceptable valuation methodology than ROK, this column produces the kind of number that a financial analyst can understand. The research team obtained this number by utilizing the standard ROI formula:

$$\boldsymbol{ROI = \frac{Profit\ (Benefit)}{Investment\ (Cost)}}$$

or in this case,

$$\boldsymbol{ROI = \frac{Revenue - Annual\ Expense}{Annual\ Expense}}$$

The equation would look like this: revenue (column 12) minus cost (column 11) divided by cost (column 11). It is important to know that the correlation between ROK and

ROI will always equal 1 if all numbers and calculations are correct because the estimates are drawn from the same base numbers.

Column 15. The number entered in this column utilizing hours as unit of measure indicates how long on average each step takes to complete.

Column 16. This is the number of times each process was completed in a year. It is important to know that the SMEs of the USS John C. Stennis (CVN 74) executed many firings of each core process and produced several parts and pieces throughout their time with the AML. However, during this time period, they have manufactured approximately 60 documented repair parts or pieces. See Table 23.

Column 17. This column approximates the number of hours that Stennis AML SMEs have undergone either formal training or OJT to execute all core processes necessary to manufacture a part. OJT is a form of self-learning. This column is not used specifically to obtain KVA; however, the data in this column are used to calculate correlations between the different aspects of the process and to obtain an idea of the time consumed to achieve this desirable level of knowledge. See Table 21.

Table 21. Column 17, Training Time/Self-Learning/On-the-Job Time Spent Learning.

Col. 17
Training Time / Self-Learning / OJT (hrs)
1
1000
2020
4
720
4
336
0.5
60

Table 22 and Table 23 represent the annualized high-level aggregate view of USS John C. Stennis (CVN 74) AML performance.

Table 22. Columns 1–8 Inputs Required to Execute the KVA Methodology for AML Process.

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
Core Process	**Rank in terms of difficult to learn (1= easiest, 8=hardest)**	**Relative learning time (RLT) (total=100 hours)**	**No. of personnel**	**Percentage of automation**	**Amount of knowledge embedded in automation**	**Amount of knowledge per one manufacturing process**	**Total amount of knowledge**
Receipt	2	1	1	20%	0.2	1.2	72
Measuring	7	20	1	0%	0	20	1200
Design	8	40	2	50%	40	120	7200
Test print	4	6	1	80%	4.8	10.8	648
Adjustments	6	16	1	50%	8	24	1440
Final Print	3	6	1	80%	4.8	10.8	648
Q/A	5	10	1	0%	0	10	600
Delivery	1	1	1	20%	0.2	1.2	72
Total		100				198	11880

Table 23. Columns 9–16 Results from Applying the KVA Methodology to the USS John C. Stennis (CVN 74) AML Process.

Col. 1	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14	Col. 15	Col. 16
Core Process	**Percentage of knowledge allocation**	**Market comp annual revenue allocation**	**Annual expense (Denominator)**	**Revenue (Numerator)**	**ROK**	**ROI**	**Time to complete**	**Number of times performed in a year**
Receipt	1%	$ 435.78	$ 290.52	$ 757.28	261%	161%	0.2	60
Measuring	10%	$ 6,307.20	$ 4,204.80	$ 12,621.35	300%	200%	4	60
Design	61%	$ 75,686.40	$ 50,457.60	$ 75,728.13	150%	50%	24	60
Test print	5%	$ 18,921.60	$ 12,614.40	$ 6,815.53	54%	-46%	12	60
Adjustments	12%	$ 3,153.60	$ 2,102.40	$ 15,145.63	720%	620%	2	60
Final Print	5%	$ 18,921.60	$ 12,614.40	$ 6,815.53	54%	-46%	12	60
Q/A	5%	$ 1,089.45	$ 726.30	$ 6,310.68	869%	769%	0.5	60
Delivery	1%	$ 435.78	$ 290.52	$ 757.28	261%	161%	0.2	60
Total		$ 124,951.41	$ 83,300.94	$ 124,951.41	1.5	0.5	54.9	60

Table 24 shows the following: hourly wage, process number for which each person in the shop is mostly responsible, their individual monthly base pay, and the number of hours per year they work. See Table 24.

Table 24. Calculation of Assigned Military Personnel Hourly Wage for Each Process. Source: DFAS (2019).

Pay Grade	**Hourly Wage**	**Process number responsible for**	**Monthly base pay**	**Work hours per year 40hrs*48Wks**
Machinery Repairmen Second Class with more than 4 years	$ 17.52	2, 3, 4, 5, and 6	$ 2,804.00	1920
Machinery Repairmen First Class with more than 12 years	$ 24.21	1, 7, and 8	$ 3,874.00	1920

Each firing in the process has its own individual cost. See Table 25.

Table 25. Price Per Firing.

Price per firing	**$10.52**

Table 26 shows the correlation between the different areas of the KVA processes to include training time/OJT. The level of correlations should have a minimum of 85% to be acceptable in order for the KVA to be effective.

Table 26. Correlation between KVA Processes of USS John C. Stennis (CVN 74) AML Performance.

Col. 2	Col. 3
Rank in terms of difficult to learn (1= easiest, 8=hardest)	**Relative learning time (RLT) (total=100 hours)**
2	1
7	20
8	40
4	6
6	16
3	6
5	10
1	1
	100
Correlation between Difficulty and RLT	**0.90**

Col. 2	Col. 17
Rank in terms of difficult to learn (1= easiest, 8=hardest)	**Training time / Self-learning / OJT (hrs)**
2	1
7	1000
8	2020
4	4
6	720
3	4
5	336
1	0.5
	60
Correlation between Difficulty and Self learning	**0.88**

Col. 3	Col. 17
Relative learning time (RLT) (total=100 hours)	**Training time / Self-learning / OJT (hrs)**
1	1
20	1000
40	2020
6	4
16	720
6	4
10	336
1	0.5
100	60
Correlation between RLT and Self learning	**0.99**

Col. 3	Col. 8
Relative learning time (RLT) (total=100 hours)	**Total amount of knowledge**
1	72
20	1200
40	7200
6	648
16	1440
6	648
10	600
1	72
100	11880
Correlation between RLT and Total knowledge	**0.94**

(1) Assumptions

The following key assumptions were made to standardize the calculation for this particular KVA analysis:

- The common unit of measurement is hours.
- The common currency used is U.S. dollars.
- Time calculation for KVA is based on 40 working hours per week, 160 working hours per month, 48 weeks per year, and a total of 1,920 working hours per year.
- The work year consists of 48 weeks, taking into consideration four weeks or 30 days of leave. (52 weeks per year) - (4 weeks of leave) = 48 working weeks/year.
- There are only two employees working at the AML.
- Current assigned members' paygrade and years of service were utilized to calculate the hourly wage based on their base pay only in this analysis.
- Calculation for hourly wage is based on basic pay only. No other pay or allowances were accounted for in this analysis.
- The hourly wage calculation is based on the 2019 basic pay chart from Defense Finance and Accounting Service (DFAS) and is calculated by dividing the basic pay by the number of working hours per month (160 working hours).
- In the public sector, an ROI calculation is based on the ratio of how much profit or loss (net income) in a given period of time expressed in terms of an invested capital. In the DOD, there is no revenue to calculate the profit. In the commercial sector, the expense incurred to hire contractor to do the job is one and one half times more than hiring the Navy's own employees. Therefore, expense is multiplied utilizing a factor of 1.5 to estimate the revenue utilizing market comparable approach (Housel et al., 2007).
- Because only 60 documented parts had been manufactured by the time the KVA team conducted their initial research, this is the number of parts utilized in this analysis for calculations.
- All measurements and design were fully done by the Stennis's SMEs to produce all 60 parts. No saved designs, blueprints, or measurements previously stored in a database were used for the manufacturing of any of these 60 parts.

(2) Limitations

Because the USS John C. Stennis (CVN 74) is the first ship to have been suited with a formal AML, and it still is a testing platform, a training program for AM at sea has currently not matured. NAVSEA provided only two days of formal training to the Stennis AML crew, which led to extensive self-learning hours. Therefore, current calculation of training and LT might be overstated. When the training process reaches its maturity, it is presumed that RLT, ALT, and training time will be drastically reduced.

Calculation of the hourly wages are based on the current paygrades of the service members with their respective years of service assigned to the Stennis and will vary in different ships with technicians in different paygrades. Current pay calculations are based on the 2019 Basic Pay Chart from DFAS and do not include subsistence and housing allowance. Housing allowance varies depending on where the parent command is currently stationed, and it will skew the data in determining the hourly wage. Subsistence allowance also varies between the personnel living on the ship or off ship and can also skew the data if it is included in hourly wage computation.

Since calculations are based on the 40-hour work week, the maximum hours per year is 1,920 hours. However, service members usually work more than 40 hours per week especially during deployment. Therefore, the time calculation could be understated.

USS John C. Stennis (CVN 74) AML personnel manufactured 60 new parts without the help of an established design database. Once there is a mature and robust database with tested and approved designs, it is presumed that design, testing, and overall fabrication time will be drastically reduced.

d. KVA Results Findings

The KVA analysis results produced an average ROK of 334% as well as ROI of 234% and a correlation between them of 1. This confirms that there is a value added from having an AML onboard the USS John C. Stennis (CVN 74) and subsequently having AMLs across the Surface Navy. Currently, the Stennis AML is an added capability to the supply chain SQ in the Navy. However, the analysis points out that although the process is not fully mature, it provides a significant value added to the warfighter. The research team can estimate from the analysis conducted that as the AML process matures along with a more robust training, an established database, and more experience in the field and the Navy, LT will only get shorter, and it will significantly improve the ROK and ROI.

IV. LESSONS LEARNED

One of the objectives of this research was to provide the Navy's leadership with a comprehensive list of lessons learned from the initial installation of the AML onboard USS John C. Stennis (CVN 74). The lessons learned were gathered from maintenance personnel onboard the USS John C. Stennis (CVN 74), and subject matter experts (SMEs) at Naval Sea Systems Command (NAVSEA) and the Office of the Chief of Naval Operations (OPNAV). These lessons learned addressed different areas such as equipment, training, and operation of the AML.

A. EQUIPMENT

The AML onboard the USS John C. Stennis currently has four AM printers, one 3D scanner, one laser cutter, and one computer-controlled milling machine (CNC Mill) as follows:

- Stratasys uPrint SE Plus (AM printer)
- Artec Eva (AM printer)
- LulzBot taz-6 (AM printer)
- MakerGear M3 (AM printer)
- Boss Laser Engraver LS-1630 (Laser Scanner)
- Tormach PCNC 400 (CNC Mill)

1. Stratasys uPrint SE Plus (AM printer)

Figure 10. Stratasys uPrint SE Plus 3D printer. Source: Stratasys (2019).

The Stratasys uPrint SE Plus 3D printer manufactures “prototypes that are durable, stable and accurate items” (Stratasys, 2019). The uPrint uses Fused Deposition Modeling (FDM) technology to build parts, models, and functional prototypes utilizing ABSplus thermoplastic as the raw material. The ABSplus thermoplastic soluble support material is available in different colors, and it comes conveniently spooled, making it easy to load into the material bay of the printer (GoEngineer, 2019). Its average cost is $32,000.00 (Treatstock, 2019).

Inside the 3D printer, the raw material in the form of plastic strands is fed to a print head. The print head’s job is to heat up the plastic filament enough to turn it into a semi-liquid form allowing the head to lay the material in layers to initiate the manufacturing process. A prefabricated base provides the surface on which the models are manufactured.

Once the part is manufactured, the recyclable base is taken out of the 3D printer and snapped off the model (GoEngineer, 2019). The Stennis's AM technicians have deemed the Stratasys uPrint SE Plus 3D printer as the most versatile and useful piece of equipment in the entire lab. They described it as reliable, effective, and easy to use and maintain.

NAVSEA, however, installed the uPrint over a custom base foundation with attached shock-absorbent coils. The Stennis's SMEs discovered that such an intricate platform base is not necessary. They demonstrated this phenomenon while printing a sample piece. The technicians pretended to replicate the most drastic of sea state conditions the machine could possibly endure by vigorously and continuously shaking the machine, and yet, the printer still manufactured a high-quality product. This demonstration suggested that eliminating the shock-absorbent mounts or simplifying them might reduce costs while providing the same value.[2]

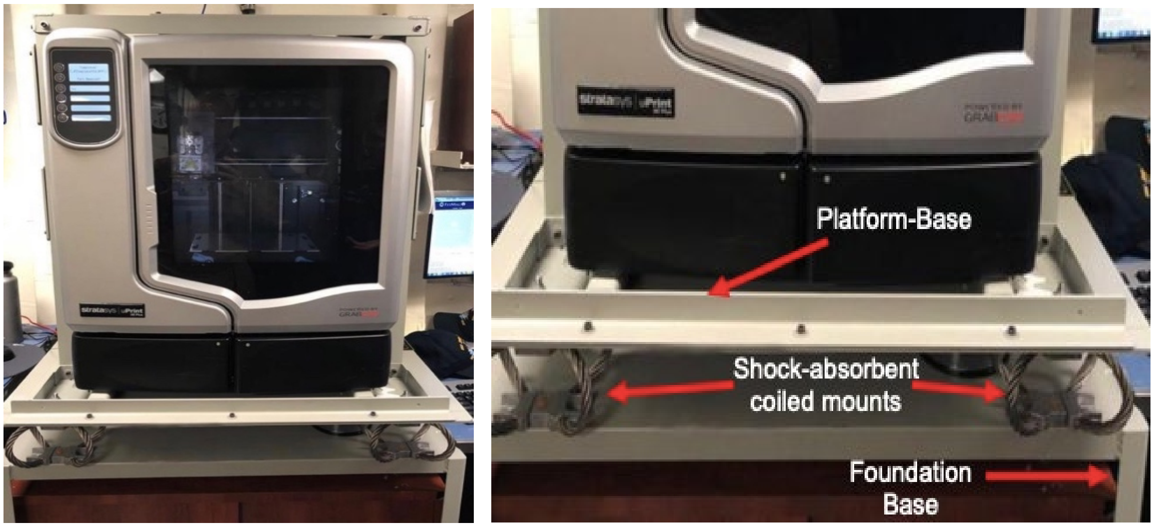

Figure 11. USS John C. Stennis (CVN 74) AML Stratasys uPrint printer installation. Source: USS John C. Stennis (2019).

One of the weaknesses of this printer is the size of the parts it can manufacture. It can manufacture parts not to exceed eight-inch by six-inch by six-inch sizes (8” × 6” × 6”)

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[2] It is important to note that while the test mentioned above was very helpful to demonstrate the sturdiness and the capability of the uPrint to manufacture parts under any sea-state, the test is definitely not considered an actual field test.

(GoEngineer, 2019). Overall, the technicians running the AML onboard the Stennis gave the uPrint the highest marks.

2. LulzBot TAZ 6 3D Printer

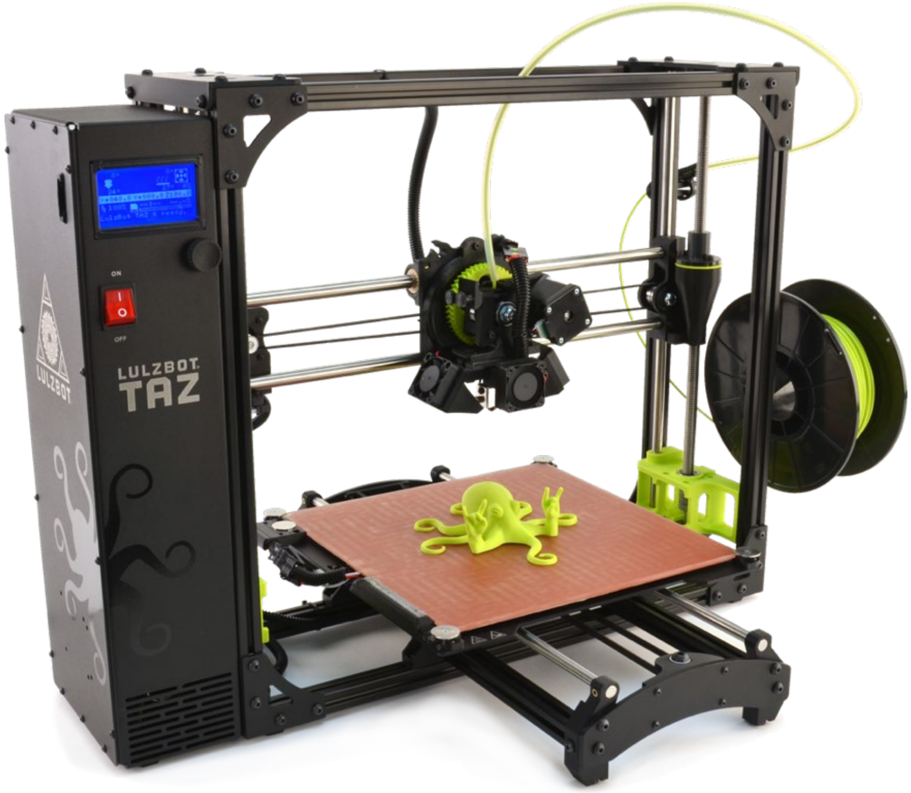

Figure 12. LulzBot TAZ 6 3D Printer. Source: LulzBot (2019).

The LulzBot TAZ 6 is probably the easiest-to-use desktop 3D printer in the lab and currently operates as a larger extruder. Its open design provides one of the largest print volumes in its class (11.02” × 11.02” × 9.80”) and costs approximately $3,500.00 (LulzBot, 2019).

Two of these printers are installed in the Stennis AML. However, the Stennis’s SMEs do not rely on them as much, because the TAZ 6 printer requires dedicated monitoring and the attention of technicians during the entire printing process. According to the SMEs, even the smallest of AM jobs takes at least a couple of hours to be fully printed.

Additionally, when NAVSEA initially installed the AML, the Stennis's SMEs reported numerous problems trying to manufacture parts utilizing the TAZ 6. Parts continued to have defects, and the TAZ 6 could not execute the models ordered through the computer to completion. However, it was discovered that both of the TAZ 6 printers had been installed directly in front of the space fan coil unit (FCU) that provides the space with its air-conditioning. This constant flow of cold air blowing directly towards the machine (the TAZ 6 has an open design) prevented the TAZ 6 from achieving proper temperatures to execute the extruding process; therefore, the parts printed were prone to defects.

Due to this issue, the technicians aboard the Stennis relocated the printers to an area in the lab where air did not blow directly at the machines. The SMEs reported a substantial improvement in performance as well as a reduction of rework for test prints as well as final prints. This incident is a valuable lesson learned for future installations of AMLs. Additionally, the technicians recommend fabricating or purchasing enclosures for the TAZ 6, as its open design does not allow the filters installed on printers to reduce what the SMEs mentioned as "possibly hazardous fumes," a byproduct of manufacturing parts.

Despite the need for workarounds to address its open design and the "possibly hazardous fumes," and because of its ability to print large parts, the TAZ 6 is recommended to remain as part of the AML set-up until a better printer is identified to replace it.

3. MakerGear M3-SE

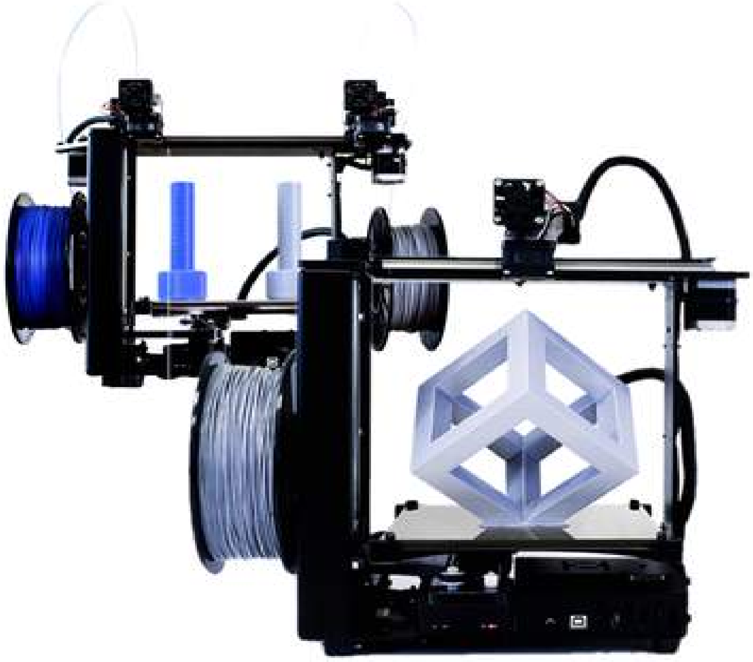

Figure 13. MakerGear M3-SE 3D printer. Source: MakerGear (2019).

The MakerGear M3-SE is the last of the 3D printers that makes up the AML afloat. Its fabrication size range is approximately 8” × 9.1” × 8” (MakerGear, 2019). This printer has been deemed very reliable and is favored by machinery repairmen (MR) technicians, primarily due to the different configurations and the ease of adjustments available to them. Like TAZ 6 printers, this printer has an open design, and it is susceptible to cold air being blown directly at it. Just like the TAZ 6, once the M3-SE was relocated to a different part of the shop, the printer performed as expected. Its price is between $2,500 and $3,100, depending on manufacturers’ add-ons (MakerGear, 2019).

This machine is used as the backup to the uPrint. Again, the MRs recommend either building an enclosure for the printer or buying one to protect its components and prevent any disruptive airflow.

4. Boss Laser Engraver LS-1630

Figure 14. Boss Laser Engraver LS-1630. Source: Boss Laser (2019).

The AML at sea is composed not only of 3D printers but also of other machines to supplement and complement the shop and its manufacturing capabilities. One of those aspects is the cutting and engraving of material such as acrylic, plastic, and even metal. The LS-1630 was the machine selected to meet this task for the AML. The Boss laser is a mid-grade laser cutter and engraver and is not designed for complex fabrication jobs. Its cost ranges from $8,000 to $16,500 depending on the different upgrades offered by the manufactured (Boss Laser, 2019).

Aside from laser cutting, the LS-1630 also serves as an engraver. Engraving aboard any ship is constantly requested: personalized plaques for distinguished visitors as keepsakes, sailors' uniform name tags, recognition awards such as Sailor of the Year or Sailor of the Quarter, and other mementos of recognition are some of the items that are always in demand. The Stennis's SMEs do not see the LS-1630 as an upgrade compared to their old machine, the GRAVO Graph LS-900; instead, they view it as slower and much more complicated to program and operate.

As the research team observed, the LS-1630 is a large machine compared to others of similar functionality (65.5” × 37.5” × 44.5”). Onboard a large vessel like the Stennis, its size may not be a problem. Its size could be a drawback for the installation on smaller ships, especially when combined with the added external components needed for its proper operation, such as an industrial chiller (CW5000).

Compounding these issues, the LS-1630 uses a standalone computer to run its operating system (software) in order to make the designs and transmit them to the machine. It is also important to note that although the LS-1630 final assembly location is the United States, as stated by the manufacturer, the majority of the markings of the machinery parts and components that have been seen by the technicians up close indicate that they are made in China (as stated by the Stennis’s SMEs). The Stennis’s SMEs had mixed opinions regarding the LS-1630, its versatility, and its value overall to the AML versus other machines of similar characteristics and price in the market.

5. Artec Eva handheld 3D scanner

Figure 15. Artec Eva handheld 3D scanner. Source: Artec 3D (2019).

Currently, the handheld 3D scanner is another component to the AML at sea, which is ideal for scanning large objects. This structured light 3D scanner allows technicians to make a quick, textured, and accurate 3D model of medium and large-sized objects such as a human bust, an alloy wheel, or even exhaust systems such as from a motorcycle, according to the manufacturer's description. It scans and captures precise measurements in high resolution (Artec 3D, 2019).

Although this is a highly useful and sophisticated piece of engineering, its primary purpose is to scan medium to large objects. As previously mentioned, the AML is constrained to the manufacturing of small pieces, or at least not to exceed the capabilities of its largest printer, the LulzBot (11.02" × 11.02" × 9.80"). Due to this reason, the 3D scanner is barely used or at least not enough to justify a price tag of almost $20,000 per scanner (Artec 3D, 2019).

The MRs believe that adding a more functional 3D scanner or laser scanner (handheld or stationary/enclosed) could make a significant impact because it could help them speed up the design and measurement process of small parts, which make up approximately 90% of their part manufacturing requests. Because the most time-consuming aspect of manufacturing a part is the design phase, having a 3D scanner capable of scanning small objects could drastically reduce the amount of time required for measuring and designing.

6. Tormach PCNC 440 Benchtop Mill

Figure 16. Tormach PCNC 440 Benchtop Mill. Source: Tormach (2019).

The Tormach PCNC 440 is a computer-controlled milling machine installed to compensate for the lack of a metal printer in the AML at sea. This subtractive manufacturing piece of equipment is the last item that comprises the Stennis AML. It is a versatile machine that allows the MRs to cut metals such as aluminum, steel, and titanium. Additionally, it works well with plastics, wood and other synthetic materials. Because the current configuration of the AML does not include metal AM printers, this is the current alternative the shop uses to manufacture metal pieces using the CAD software design tools.

The PCNC 440 as described by its manufacturer is "a benchtop mill that fits all-around capability in a small and affordable package; the PCNC 440 is perfect for anybody that wants to perform machining operations but does not have much space" (Tormach, 2019). According to the manufacturer, its work envelope is 10" × 6.25" × 10" and its price ranges from $6,800 to $13,200, depending on the attachments and accessories ordered (Tormach, 2019).

The PCNC 440 has received mixed reactions from the AML technicians. Their suggestion is to incorporate a commercial-grade milling machine or a metal AM printer into the AML to increase the capability of the shop.

B. MISCELLANEOUS EQUIPMENT

The initial loadout of the AML installation onboard the Stennis was made up of the equipment listed above, as well as miscellaneous items that complement the major equipment. Among these items are two computers with pre-installed design software: one for the AM printers and the other one for the LS-1630. The lab also comes with enough raw material and manufacturing supplies for over a month's operation. Table 27 lists the materials issued.

Table 27. AML Initial List of Material and Supplies. Adapted from NAVSEA AML Installation Team, email to author (June 27, 2019).

ALT NO.	NOMENCLATURE	QTY	NOTE
SCD 24036	STRATASYS UPRINT SE/UPRINT SE PLUS TIP	3	TIP REPAIR KITS FOR UPRINT
SCD 24036	MAKERGEAR M3 REPLACEMENT BEDS	16	REPLACEMENT BEDS WITH YELLOW POLYIMIDE PRINTING FILM FOR MAKERGEAR M3
SCD 24036	MAKERGEAR REPLACEMENT PRINT HEAD KIT	4	NOZZLE, FAN AND PRINT HEAD FOR MAKERGEAR M3
SCD 24036	MAKERGEAR BELT AND FILAMENT TUBE REPLACEMENT KIT	2	REPLACEMENT KIT FOR BELT DRIVE AND THE FILAMENT TUBE ON MAKERGEAR M3
SCD 24036	REPLACEMENT SUPPORT MATERIAL FILAMENT TUBE FOR UPRINT SE PLUS	1	TUBE THAT SUPPORT FILAMENT RUNS THROUGH ON THE BACK OF THE MACHINE
SCD 24036	REPLACEMENT MODEL MATERIAL FILAMENT TUBE FOR UPRINT SE PLUS	1	TUBE THAT MODEL MATERIAL FILMANENT RUNS THROUGH ON THE BACK OF THE MACHINE
SCD 24036	REPLACEMENT DATA CABLE FOR UPRINT SE PLUS	1	DATA CABLE THAT CONNECTS MATERIAL BAY TO UPRINT SE PLUS ON BACK OF MACHINE
SCD 24036	BOSS LASER REPAIR KIT	1	INCLUDES 20MM 3.0" FOCUSING LENS; 20MM 2.0" FOCUSING LENS AND 20MM 2.5" FOCUSIN GLENS WITH 3 SETS OF MAINTENANCE ACCESS PANEL KEYS AND 1 SET OF IGNITION KEYS
SCD 24036	TAZ 5/6 HEATBED KIT	3	REPLACEMENT PRINT BED KIT FOR TAZ 6
SCD 24036	UPRINT PRINT HEAD LOCKS	1	1 SET OF UPRINT PRINT HEAD LOCKS FOR TRAVEL
SCD 24036	UPRINT SE PLUS PRINT BED PLATES	53	DISPOSABLE PRINT BED PLATES FOR UPRINT SE PLUS
SCD 24036	ETHERNET CABLE	1	ETHERNET CABLE TO SUPPORT CONNECTION BETWEEN PRINTERS AND PROVIDED COMPUTERS
SCD 24036	PUSH PLASTIC PETG	5	Push Plastic 1.75 mm silver
SCD 24036	PUSH PLASTIC PETG	5	Push Plastic 1.75 mm Desert Tan
SCD 24036	PUSH PLASTIC PETG	10	Push Plastic 1.75 mm Blue
SCD 24036	PUSH PLASTIC PETG	10	Push Plastic 2.85 mm Blue
SCD 24036	PUSH PLASTIC PETG	5	Push Plastic 2.85 mm Silver
SCD 24036	PUSH PLASTIC PETG	5	Push Plastic 2.85 mm Desert Tan
SCD 24036	UPRINT SE PLUS MODEL MATERIAL	5	Yellow Uprint material
SCD 24036	UPRINT SE PLUS MODEL MATERIAL	1	Black
SCD 24036	UPRINT SE PLUS MODEL MATERIAL	1	Blue
SCD 24036	UPRINT SE PLUS MODEL MATERIAL	1	Green
SCD 24036	UPRINT SE PLUS MODEL MATERIAL	2	Ivory
SCD 24036	UPRINT SE PLUS SUPPORT MATERIAL	5	Support Material

One miscellaneous piece to the AML is a hazardous materials (hazmat) locker for storing the material utilized for AM (raw material). However, these products and materials are not flammable or toxic or considered to be hazmat, as per the ABS plastics material safety data sheet (Netco, 2019). Hence, the installation of this type of storage locker creates a "self-inflicted wound" for the shop since the locker has requirements that need to be met in order to comply with the hazmat program, such as regular inventories and inspections. A storage locker or bin is required; however, a hazmat locker is most likely not the most appropriate solution.

Other components include two stand-alone computers, one to design and transmit to the 3D printers and one for the Boss laser cutter and engraver. The requirement for efficiency, however, should be three computers, as suggested by the SMEs. Two computers should be able to design, execute, and transmit the parts designed to the printers, and a third computer should be dedicated to the laser cutter and engraver.

In terms of printing, all four AM printers receive the manufacturing designs from the one stand-alone computer; however, the MRs are required to plug and unplug the required printer to the computer for each manufacturing process, causing the cables, plug-ins, and even the computer to become damaged sooner rather than later. The sailors running the shop came up with a simple solution by purchasing a switch that allows the MRs to select and switch quickly between printers as required. A switch of this type should be included in future iterations of AMLs to allow users to shift between different printers without having to manually disconnect and reconnect the cables, allowing for better productivity and practicality.

Another area for further study is the need to equip the AMLs with file-sharing capabilities among its computers, so a user does not have to download the file into an external drive to upload the design to the other computer for manufacturing or laser cutting, potentially causing delays or file corruption. Ideally, a shared hard drive acting as a server between the computers for data-design sharing would solve this issue. Lastly, a hard drive or server would be very beneficial because after the parts are manufactured (final print), they must be downloaded and sent to NAVSEA. NAVSEA is developing a storage database that will be shared with other AMLs in the fleet, reducing or even eliminating the design times in the long run. Therefore, installing this hard drive in the AML will streamline the process of uploading and storing these file designs.

C. TRAINING

The AML at sea onboard the Stennis has added extra capabilities to the warfighter and to the mission that the ship did not have before NAVSEA's installation. Because it is the first of its kind, however, there is room for improvement, specifically in the area of training. The recommendations listed here were offered by the MRs onboard, technicians, and leadership positively and constructively. It is important to note that as of today, the Navy does not have mandatory or formal training for sailors such as a Personal Qualification Standards (PQS) for technicians to operate the AML.

The Navy's Machinery Repairman (MR) rating has been informally identified as the appropriate Navy technicians to run and operate the AML. This is consistent with their skills, and job assignment in the fleet; however, our study recommends that these personnel operating the AMLs should receive formal education and training with specific Navy Enlisted Classification (NEC) for operation of AML either in "A" School or a more advanced training set-up such as a "C" School (Edenfield, Garcia, & Yoshida, 2019).[3]

NAVSEA SMEs conducted the initial training for this first AML at sea to experienced MRs. It consisted of a two-day classroom training session aboard USS John C. Stennis (CVN 74), followed by approximately 20 hours of supervised on-the-job training (OJT). The recommendation is to implement formal education and training for the MR rating during their "A" school or to become a "C" in itself as soon as possible, to eliminate or reduce self-learning time, deficiencies, and mistakes that could prove to be costly during the adoption and universal implementation of AMLs in other ships.

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[3] The Navy calls its initial job training "A" school. All Navy enlisted ratings (jobs) have an "A" school, which teaches sailors the fundamentals of their new Navy job. "C" school is advanced training within your rating (job). For example, if you attended "A" school for general computer maintenance, it may be followed with "C" school to teach you how to work on a specific complicated computer system. Being chosen for "C" school means that you have proven that you're qualified to be trained in an advanced area of the job. http://www.military.com, (accessed 02 October 2019).

D. AML OPERATIONS

NAVSEA has established informal procedures and processes for AML equipment operation, maintenance, and service support. All AML equipment has been deemed safe to operate in any given sea condition or sea state. There are currently no restrictions on operational timeframes for the AML, and 24-hour continuous operations are authorized if required. Additionally, the USS John C. Stennis (CVN 74), in collaboration with NAVSEA, has produced an implemented standard operating procedures (SOP) to guide the operation of the AML. All AML equipment and its associated warranty control and management remain with NAVSEA.

The planned maintenance system, also known as PMS, is the lifeblood of the Surface Navy. Currently, all preventive and unscheduled corrective maintenance on AML equipment is performed by MR personnel onboard the Stennis. However, there are neither established procedures nor scheduled Maintenance and Material Management (3M) for the AML to schedule or perform preventive maintenance. All recommended and preventive maintenance conducted follows the recommendations from the AM equipment manufacturers' operating manuals. The standard and most frequently performed preventive maintenance required for the printers includes greasing and lubrication and the replacement of extruder tips and brushes approximately every 400 operational hours. Although the MRs onboard are performing the suggested manufacturer-recommended preventive maintenance as required, it is not being scheduled or tracked.

Lastly, the most important lesson learned from this research project is the realization of a complete lack of communication between the Supply department and the Engineering department regarding 3D printing and the manufacturing of parts in the AML. Although Navy Supply Systems Command (NAVSUP) and the Office of the Chief of Naval Operations (OPNAV), specifically the N4 shop, have made their interests in the program known and continue to show overwhelming support outside the lifelines in the growth and implementation of the AM technology, this is not reflected inside the Stennis's lifelines.

The Stennis AML has manufactured approximately 60 parts that have either replaced or supplanted parts that could have been obtained through the Supply system, but because of lack of availability or delays in shipping, they were 3D printed in the AML by MRs. The Supply Department is not tracking these parts and lacks any visibility on them. There is no procedure yet to ensure that the Repair Parts Petty Officers (RPPOs) of the customer division are identifying the parts being ordered for manufacturing via utilizing part numbers, NIINs or NSNs. Likewise, the AML technicians do not maintain a list of NIINs of parts manufactured for identification, much less whether these parts produced belong to a bigger assembly.

What is of concern is that without relevant information being tracked such as NIINs, NSNs or bigger assembly identification information, any analysis associated with part costs or savings will not be possible. A clear example of these facts is that the research team had to utilize a U.S. Marine detachment AM-printed part information in order to make the CBA used in this research. Without it, the research team would not have been able to analyze whether there is any benefit for having the AML onboard.

V. CONCLUSION

A. RESEARCH LIMITATIONS

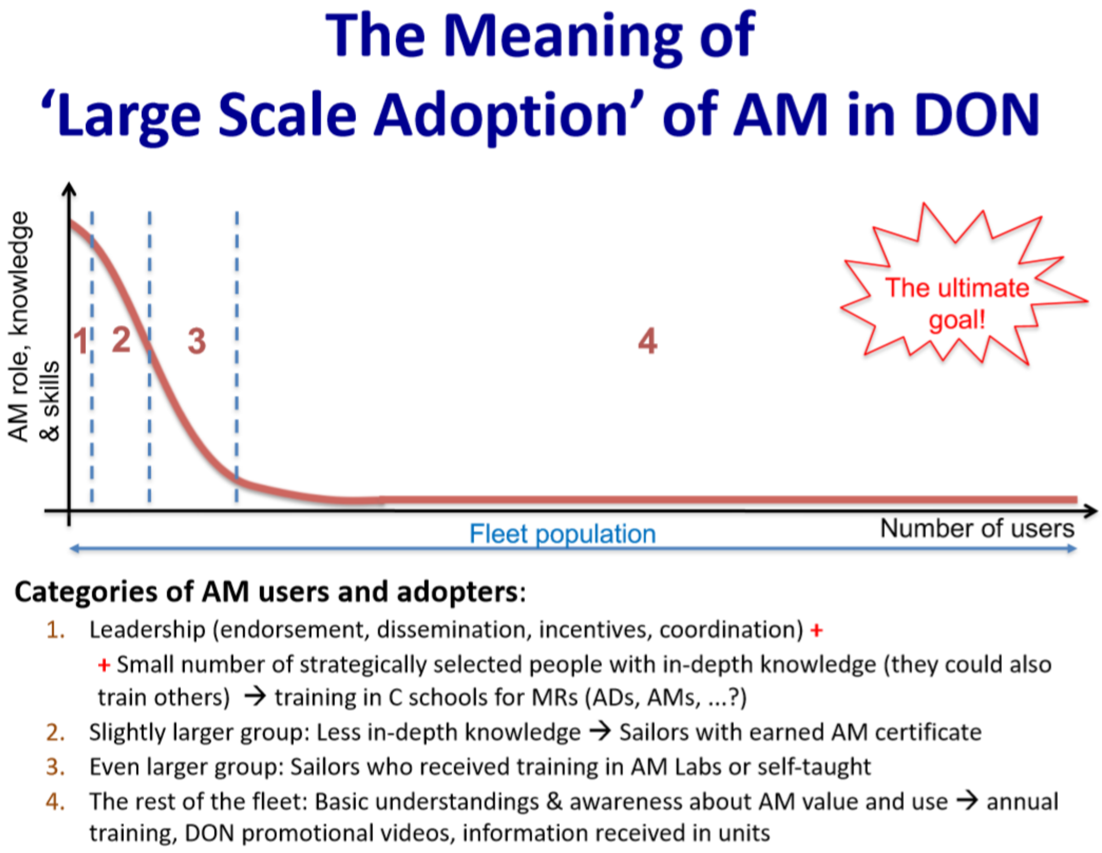
The limitations encountered during this research restricted our ability to produce a more comprehensive analysis, due to the state of infancy of AM at sea. As stated earlier in Chapter IV, the lack of recorded data on parts manufactured in the Stennis's AML denied the team the ability to conduct a CBA on a part produced at sea versus in a shore facility.

Also, it is important to note that the research and lessons learned gathered were from only one ship, the USS John C. Stennis (CVN 74). During the process of investigation, OPNAV N41 informed the research team, that seven more ships in the U.S. Navy were in the process of being outfitted with AMLs. Due to time constraints while completing this thesis, data collection, interviews, and the corresponding analysis, it was not feasible for the team to include these ships in the research. Therefore, future studies with larger scopes, more ships, and platforms are required in order to calculate the cumulative value and benefits added to the seagoing warfighter. Future research suggestions are delineated later in this chapter.

B. FINDINGS

The findings from the CBA and KVA provide clear evidence that the overall benefits of AM implementation outweigh the cost of investment with a ROK and ROI of 334% and 234% respectively, and a correlation between them of one. Because AM could potentially play a major role in manufacturing time-sensitive parts on demand for sustainment and readiness for entire Battle Groups at sea, AML installation on naval vessels clearly provides a value-added capability to the Navy.

Lessons learned from the USS John C. Stennis (CVN 74) provide the process improvement requirements and insights into what will provide guidance for future investments in alternative maintenance options to increase efficiency and effectiveness. The Navy's primary goal is to do a large-scale adoption of AM to prevent vulnerability of the supply chain in contested environments. According to Sadagic (2019), as more entities within the DoN adopt the AM technology, with proper training, knowledge growth, and improved skills, the learning curve that indicates how resulting widespread AM knowledge will extend to a very large population within the Fleet. In Figure 17: The meaning of large scale adoption of AM in DON, as with anything else, population of experts, knowledgeable people, users, and finally the everyday sailor, will become aware of the possibilities and capabilities that AM has to offer and begin to use AM. (see Figure 17).



The Meaning of 'Large Scale Adoption' of AM in DON

Categories of AM users and adopters:

1. Leadership (endorsement, dissemination, incentives, coordination) +
   + Small number of strategically selected people with in-depth knowledge (they could also train others) → training in C schools for MRs (ADs, AMs, ...?)
2. Slightly larger group: Less in-depth knowledge → Sailors with earned AM certificate
3. Even larger group: Sailors who received training in AM Labs or self-taught
4. The rest of the fleet: Basic understandings & awareness about AM value and use → annual training, DON promotional videos, information received in units

Figure 17. Large-Scale Adoption of AM in the DoN. Source: A. Sadagic, email to author, (October 8, 2019).

As AM knowledge grows within the DoN, more personnel will become aware of the AM benefits. The result will be an overall increase in ROI resulting from the adoption of AM on a wide scale—all DoN personnel. Ultimately, as knowledge spreads, the cumulative ROI of AM will increase. This ROI will be a byproduct of AMLs being installed in as many ships as possible, so every sailor stationed at sea will come into contact with or at least have knowledge of AM existence.

Figure 18 explains the four categories as AM is widely incorporated. The first group, which is the smallest, includes NPS faculty members and other research facilities and researchers that teach, experiment and advise theses on AM topics. The second group pertains to a less knowledgeable crowd but still fully immersed in the topic, for instance, NPS students who learned and studied AM topics in their classes or technicians onboard AMLs at sea and ashore. The third group, slightly larger, encompasses personnel who are self-taught and understand how to operate AM equipment. Lastly, the largest group includes all other personnel who will be aware of AM in the fleet and understand it as a capability that is available to the warfighter.

Overall, the added value that AM offers to the fleet and the cumulation of knowledge that subsequently is produced, are what is most important. As technology matures and AM becomes more accessible to the fleet population, its utilization will spread in Naval operations. It will also affect how it will be used in daily maintenance and the Navy's Supply chain. The ROI and ROK will continue to exponentially increase with each Sailor and Marine utilizing AM whether it is direct or indirect (see Figure 18).

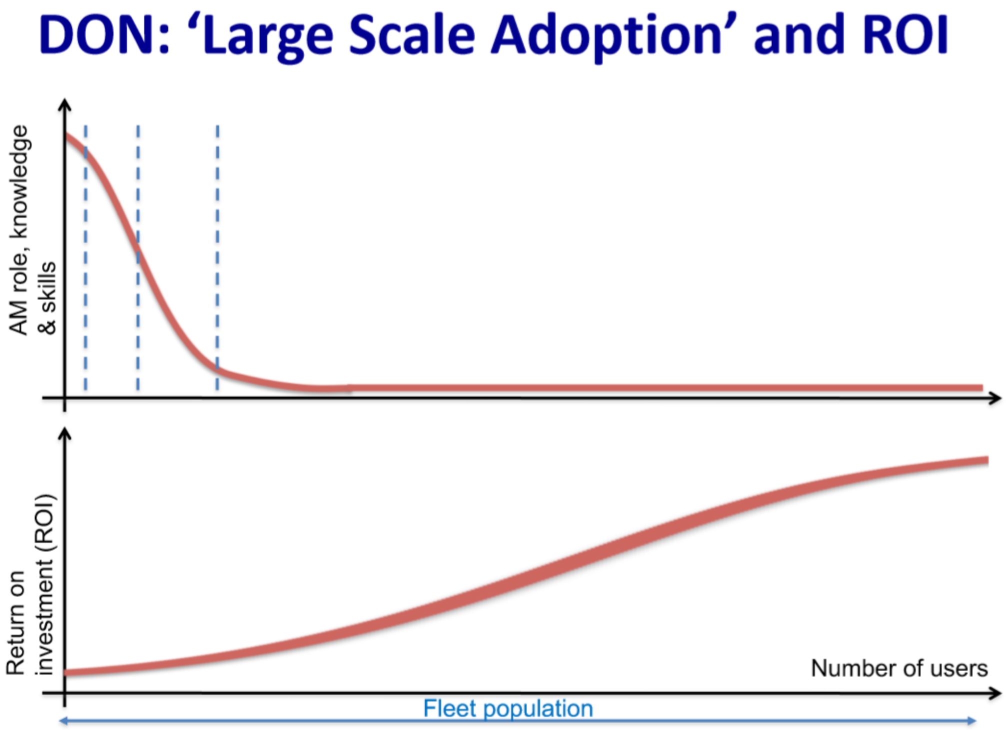


Figure 18. Navy's Large-Scale Adoption of AM and Its ROI. Source: Sadagic (2019).

C. RECOMMENDATIONS

While the AM technology in the military continues to gain ground at shore research facilities and the installation of AMLs at sea expands to other platforms, formal procedures for performance data collection, requirements and data sharing processes should be established to harvest the benefits of AMLs. Additionally, establishing standard procedures will serve as the means to better evaluate and analyze the efficiency and effectiveness, identify shortfalls, implement new storeroom stocking requirements, and identify the key players and their roles within this new AM structure.

In order to improve current procedures, the research team recommends the development of standard operating procedures (SOPs) that would include the role the ship's Supply department plays within the AML operations; the necessary interactions between the customer, Supply, and the AML personnel; and last, the storing, integrity, and sharing of the AML data whether internal or external to the ship.

The role of the Supply department in relation to the AML includes the proper recording of demand history for parts being printed via AM, location, availability at shore facilities, and even establishing that whether the part exists or whether to contract it out for manufacturing. Additionally, the Supply department is to maintain a close interaction and open communications with all ship's divisional Repairs Parts Petty Officer (RPPO) in all aspects of AM procurement.

RPPOs are responsible for identifying a part, verifying part availability, and identifying next-bigger-assembly, or in many cases, whether it is a smaller piece of a component or part. RPPOs do not belong to the Supply department, and their role is the role of the customer. They identify the part needed and submit it to the Supply department for issuing, but when the part is not readily available or onboard the ship, the RPPO should look to the AML for their ability to support the manufacturing of the part. Throughout this process, proper procedures for identification of the part, its name/nomenclature, NIIN/NSN, part numbers, or other methods of identification are crucial in synchronizing the entire supply chain and AML operations.

The proper identification of the parts as well as the proper logging and cataloguing of the collected data and parts manufactured is the research group's final recommendation.

1. Internal to the Ship

Currently, the process of gathering the correct information and properly storing it has several weaknesses and shortcomings. This can be a major issue since failure to properly identify what is being manufactured makes it almost impossible to conduct a proper review of the benefits, costs, and requirements needed to run the AML at sea. The logging of key information is being overlooked; for instance, information such as part numbers, NIIN/NSN, and even the name of the part, component, or piece being fabricated is either missing or incorrect.

The research team was forced to utilize the information of a part manufactured by the United States Marine Corps Systems Command's (MCSC) AML to conduct the CBA for this research study. This was due to the lack of complete information on any one part that has been fabricated on the Stennis's AML. Although the AML personnel attempts to keep and obtain as much information as possible, the collected data is kept on a single spreadsheet, and many key fields on it are blank. This is not the AML's shortcoming, but instead it is a flaw that it is justified due to the infancy of the program.

With proper and accurate data collection, future research and studies will be able to accurately analyze the affordability, reliability, maintainability, manpower requirements, inventory requirements, and readiness of the supply chain. It is imperative that strict data collection requirements are established to measure the effectiveness and forecast the future of the AM technology and its effects on the Navy's supply chain.

2. External to the Ship

NAVSEA's central database of parts, from the files of parts being fabricated by the AMLs at sea, will be used to share these files with other AMLs in the future. Again, it is imperative to have established strict data collection requirements. Our research team recommendation is to utilize a stand-alone server within the AML on the ship to store its own part data. By maintaining the individual server on the ship, SMEs on that ship can utilize and share the database and files during times of unavailability of NAVSEA's central database. Once the ship's communication system is up or online, the individual server can download the updates from the cloud or central database. Therefore, users can utilize the database without disruptions due to operational unavailability during operations in a contested environment.

According to the SMEs onboard USS John C. Stennis (CVN 74), the design process is the lengthiest of all the steps of AM. In the KVA conducted in Chapter 3, the ROK for design, test print, and final print are 150%, 54%, and 54% respectively, which are the lowest three aspects of the manufacturing process. Table 24 shows that it takes an average of 24 hours for a part design to be completed with a ROI of 50%. However, if there is no longer a need for designing the part, but instead, the new step consists of loading a file in a computer in under an hour, (as a conservative estimation) and assuming that every hour produces the same amount of output, then we have:

$$If\ 24\ hours = 50\%\ ROI, then\ 1\ hour = 1{,}200\%\ ROI$$

Hence, if a needed part has already been designed and test printed, and a file is available, the ROI of the overall 3D printing process, or in this case the "acquisition process," will improve by 1,200% since the design element would be eliminated. However, this will only become reality once NAVSEA or any other entity begins managing a fully functional database for AMLs at sea, giving way to a revolution in the Navy Supply chain, or the first virtual storeroom at sea.

D. FUTURE RESEARCH

AM has already had a great positive impact on operational readiness and maintenance within the fleet, so in the near future, the research team believes that the growth in demand for AM part fabrications will greatly increase the number of AMLs requested onboard naval vessels and other operational-level commands. In order for the U.S. Navy to be ready and properly postured for further implementation of AM throughout the entire fleet, further research is required, and this research team recommends future research in the following areas:

1. Economical and Financial Analysis

AM implementation has significant potential to enhance material and operational readiness for the fleet. Analysis of AMLs installations and operations onboard different naval platforms will help identify similar findings that align or veer away from those that our research found for the CVN platforms. In addition to results, it would be important to gather lessons learned for each unique platform, such as submarines, LHDs, DDGs, CGs, LPDs, and even LCSs. Further financial studies such as CBAs will vastly contribute to the effective use of AM within the DoN and increased sustainment of material readiness and warfighting capabilities, with great emphasis and positive impacts on deployment and expeditionary readiness goals. Although our in-depth research identified the overall benefits of AM implementation onboard naval vessels, a more robust CBA or financial study that takes into consideration the overall investment versus benefit, as well as ROI and/or ROK, of all naval vessels having an AML is necessary.

2. AML and Supply Chain

Further detailed analysis is required to review the overall effects of AM on the DoN supply chain. To yield the best and most effective research objectives and learning outcomes, a synchronization among NAVSUP and NAVSEA on AM implementation and supply chain management is highly recommended. Definitive and ongoing research that examines and provides recommendations on how to best leverage AM technology with the current supply chain will be warranted in the very near future. This is primarily due to the finding that AM will ultimately result in reduction of inventory in storerooms, which will directly address the ongoing limited space issue that all naval vessels have to confront. The research will also help determine whether AM implementation is truly the ideal solution for custom component and obsolete part production, which allows for the capability of producing maintenance spare parts for replacement at a lower cost than the original equipment manufacturer (OEM) could offer. As data is continually collected and accumulated in the fleet regarding AML operations, it will likely demonstrate and reinforce the benefits and effectiveness of AM for the DoN, specifically through the enhancement of alternative methods for part procurement and replenishment and the decrease in supply chain management costs and cycle times. Studies in this area will enable better measurement of the potential effectiveness and improvements of the entire supply chain.

3. AM File Database

AM technology today is producing cost savings and adding value even at these early stages of implementation within the DoN. Overall cost savings are also clearly reduced in terms of transportation costs, holding costs, and other aspects and expenses associated with supply chain management. Due to the known benefits of AM, a requirement currently exists for an extended supply database of approved printable AM parts and components for fleetwide implementation and application. Given the current advancement in today's technology and the global operational posture and areas for the DoN, the creation and utilization of an unclassified version of a virtual or cloud database for AML file sharing should be analyzed for feasibility. Provided that the appropriate cybersecurity measures and protocols are in place and properly executed, strong consideration should be given to an AML virtual database, which will also greatly contribute to a reduction in design and/or production time.

4. AML Operating Procedures

Currently the DoN does not have SOPs for AMLs, so further analysis and recommendations for the establishment of formal AML SOPs and maintenance procedures are required to ensure the safe application of AM throughout the fleet. Training, including formal and on-the-job (OTJ) training, will also need to be addressed and formalized for AML operations. The extensiveness or scale of the training required to meet AML operations may be dependent on the demand for certified AML personnel by afloat commands and funding associated with the implementation of AM technology throughout the DoN, specifically at the Navy "A" and "C" school levels. To ensure and verify the specifications and integrity of manufactured repair, remanufactured, and refurbished components, the AML SOP will also require the inclusion of an effective quality assurance (QA) program.

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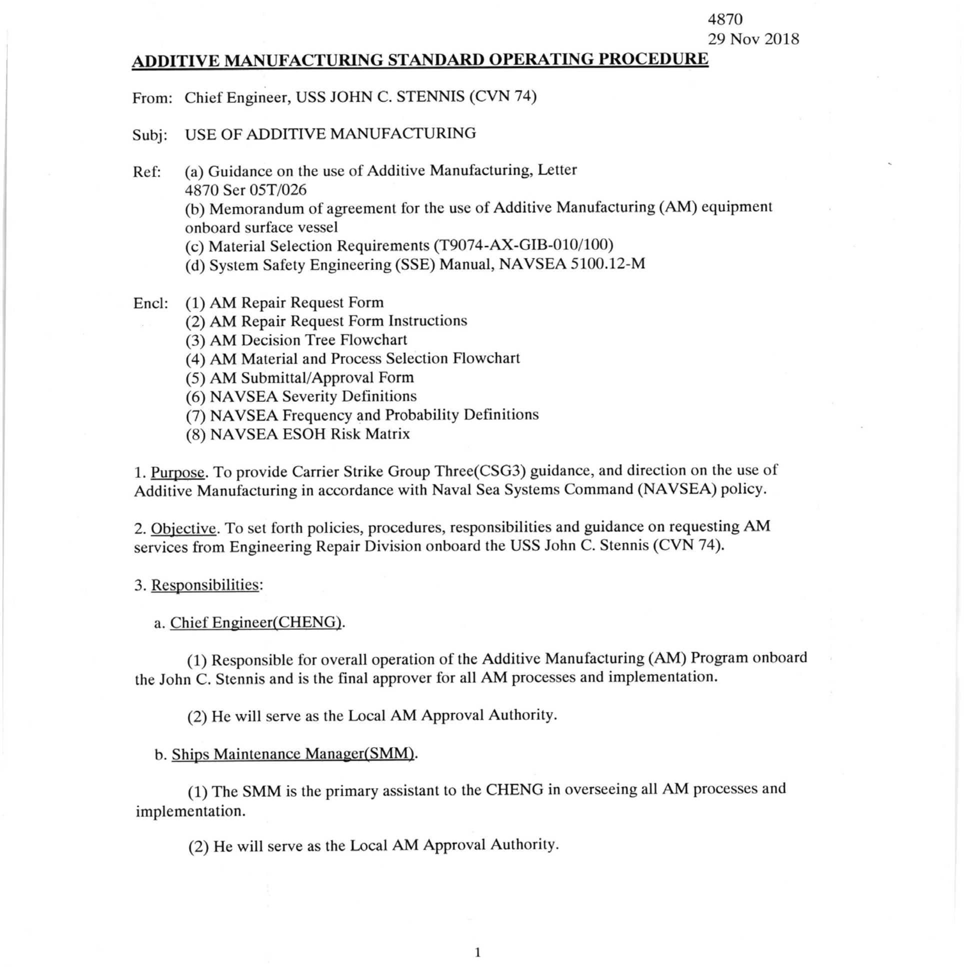
APPENDIX A. DATA COLLECTION QUESTIONS

- What was the initial material supply stock required to establish the Additive Manufacturing Labs (AML) as operational onboard?
- How does the initial stock inventory used to manufacture on-demand parts differ from what is currently being utilized? Are there any significant changes to note? Were there any items added or removed from supply inventory listings? Were there any quantity changes?
- How does the manufacturing requirements of parts reshape the contents of the material in stock?
- Are the supplies for manufacturing on-demand parts available through the Supply system or only available as commercial-of-the-shelf products (COTS)?
- If supplies are only available as COTS, how are they procured? Are COTS purchased through the government credit card program?
- Which Navy Enlisted Rates have been identified to receive AM training?
- What is the required training and/or training pipeline for AML technicians?
- What additional training should be incorporated for future applications? Are there any training restrictions?
- Are there any warranties associated with AML equipment?
- Who controls and manages the warranties on the AML equipment?
- What level of service support is provided for AML equipment?
- What are the established operating procedures for AML's equipment?
- Are there established procedures for preventive maintenance (PM) and corrective maintenance (CM) for AML equipment?
- Who performs PM and CM on AML equipment? Is PM and CM being tracked on the ship's Preventive Maintenance Scheduling Program (SKED)?
- What are the guidelines for the manufacturing of parts?
- What are the guidelines to establish and determine what to print, or what not to print?
- Who authorizes a valid requirement for manufacturing?
- Who authorizes installation and utilization of finished 3D printed parts for onboard applications?
- Is there a database being utilized and maintained with instructions on how to manufacture parts from historical data?
- Who manages the information of parts produced? Where is the information being maintained and stored?

- Who manages quality assurance (QA) for the AM program?
- How is QA being managed for the AM program?
- Does the sea state or sea conditions affect AML operations while underway?
- Are there any restrictions for operating the AML, such as for flight operations, quiet hours, etc.?
- What are some clear lessons learned from operating the AML, such as suggested locations of installed AM machines in the lab, desired types of AM equipment to be installed, types of AM machines not recommended for installation, etc.?

APPENDIX B. USS JOHN C. STENNIS (CVN 74*)* AM STANDARD OPERATING PROCEDURE



4870
29 Nov 2018

ADDITIVE MANUFACTURING STANDARD OPERATING PROCEDURE

From: Chief Engineer, USS JOHN C. STENNIS (CVN 74)

Subj: USE OF ADDITIVE MANUFACTURING

Ref: (a) Guidance on the use of Additive Manufacturing, Letter 4870 Ser 05T/026
(b) Memorandum of agreement for the use of Additive Manufacturing (AM) equipment onboard surface vessel
(c) Material Selection Requirements (T9074-AX-GIB-010/100)
(d) System Safety Engineering (SSE) Manual, NAVSEA 5100.12-M

Encl: (1) AM Repair Request Form
(2) AM Repair Request Form Instructions
(3) AM Decision Tree Flowchart
(4) AM Material and Process Selection Flowchart
(5) AM Submittal/Approval Form
(6) NAVSEA Severity Definitions
(7) NAVSEA Frequency and Probability Definitions
(8) NAVSEA ESOH Risk Matrix

1. Purpose. To provide Carrier Strike Group Three(CSG3) guidance, and direction on the use of Additive Manufacturing in accordance with Naval Sea Systems Command (NAVSEA) policy.

2. Objective. To set forth policies, procedures, responsibilities and guidance on requesting AM services from Engineering Repair Division onboard the USS John C. Stennis (CVN 74).

3. Responsibilities:

a. Chief Engineer(CHENG).

(1) Responsible for overall operation of the Additive Manufacturing (AM) Program onboard the John C. Stennis and is the final approver for all AM processes and implementation.

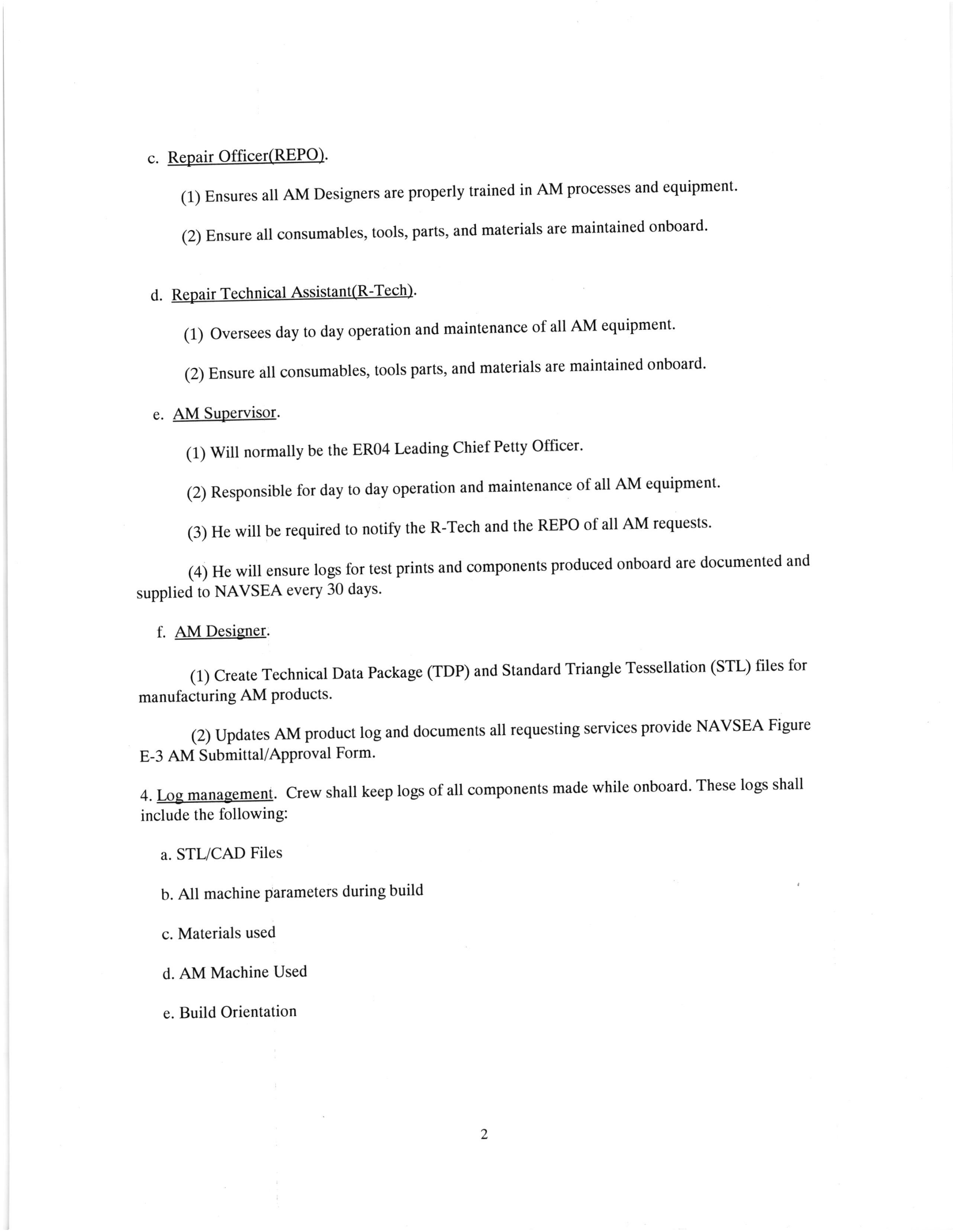
(2) He will serve as the Local AM Approval Authority.

b. Ships Maintenance Manager(SMM).

(1) The SMM is the primary assistant to the CHENG in overseeing all AM processes and implementation.

(2) He will serve as the Local AM Approval Authority.

Figure 19. USS John C. Stennis (CVN 74) Additive Manufacturing Standard Operating Procedures, First Page. Source: USS John C. Stennis (2019).



c. Repair Officer(REPO).

(1) Ensures all AM Designers are properly trained in AM processes and equipment.

(2) Ensure all consumables, tools, parts, and materials are maintained onboard.

d. Repair Technical Assistant(R-Tech).

(1) Oversees day to day operation and maintenance of all AM equipment.

(2) Ensure all consumables, tools parts, and materials are maintained onboard.

e. AM Supervisor.

(1) Will normally be the ER04 Leading Chief Petty Officer.

(2) Responsible for day to day operation and maintenance of all AM equipment.

(3) He will be required to notify the R-Tech and the REPO of all AM requests.

(4) He will ensure logs for test prints and components produced onboard are documented and supplied to NAVSEA every 30 days.

f. AM Designer.

(1) Create Technical Data Package (TDP) and Standard Triangle Tessellation (STL) files for manufacturing AM products.

(2) Updates AM product log and documents all requesting services provide NAVSEA Figure E-3 AM Submittal/Approval Form.

4. Log management. Crew shall keep logs of all components made while onboard. These logs shall include the following:

a. STL/CAD Files

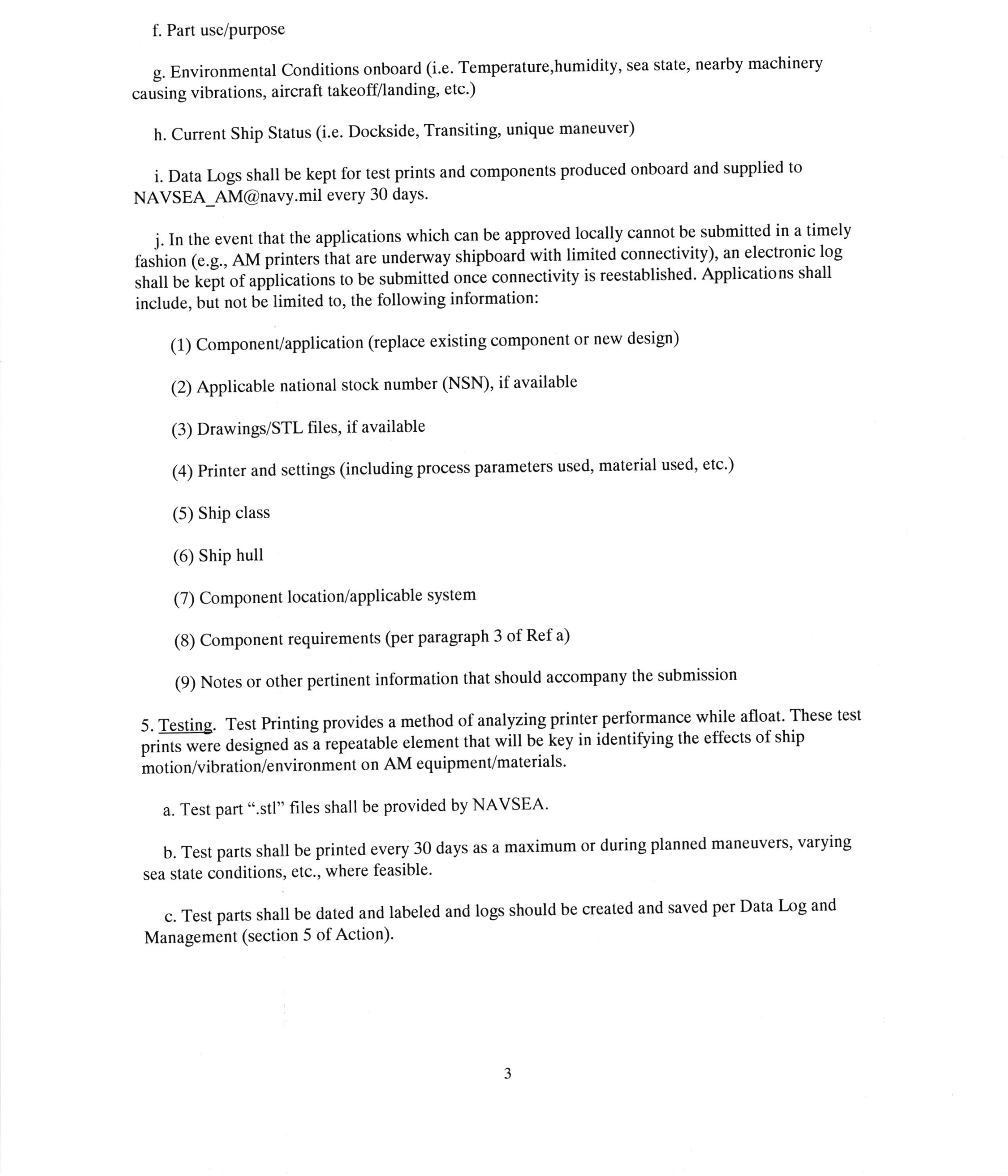
b. All machine parameters during build

c. Materials used

d. AM Machine Used

e. Build Orientation

Figure 20. USS John C. Stennis (CVN 74) Additive Manufacturing Standard Operating Procedures, Second Page. Source: USS John C. Stennis (2019).



f. Part use/purpose

g. Environmental Conditions onboard (i.e. Temperature,humidity, sea state, nearby machinery causing vibrations, aircraft takeoff/landing, etc.)

h. Current Ship Status (i.e. Dockside, Transiting, unique maneuver)

i. Data Logs shall be kept for test prints and components produced onboard and supplied to NAVSEA_AM@navy.mil every 30 days.

j. In the event that the applications which can be approved locally cannot be submitted in a timely fashion (e.g., AM printers that are underway shipboard with limited connectivity), an electronic log shall be kept of applications to be submitted once connectivity is reestablished. Applications shall include, but not be limited to, the following information:

(1) Component/application (replace existing component or new design)

(2) Applicable national stock number (NSN), if available

(3) Drawings/STL files, if available

(4) Printer and settings (including process parameters used, material used, etc.)

(5) Ship class

(6) Ship hull

(7) Component location/applicable system

(8) Component requirements (per paragraph 3 of Ref a)

(9) Notes or other pertinent information that should accompany the submission

5. Testing. Test Printing provides a method of analyzing printer performance while afloat. These test prints were designed as a repeatable element that will be key in identifying the effects of ship motion/vibration/environment on AM equipment/materials.

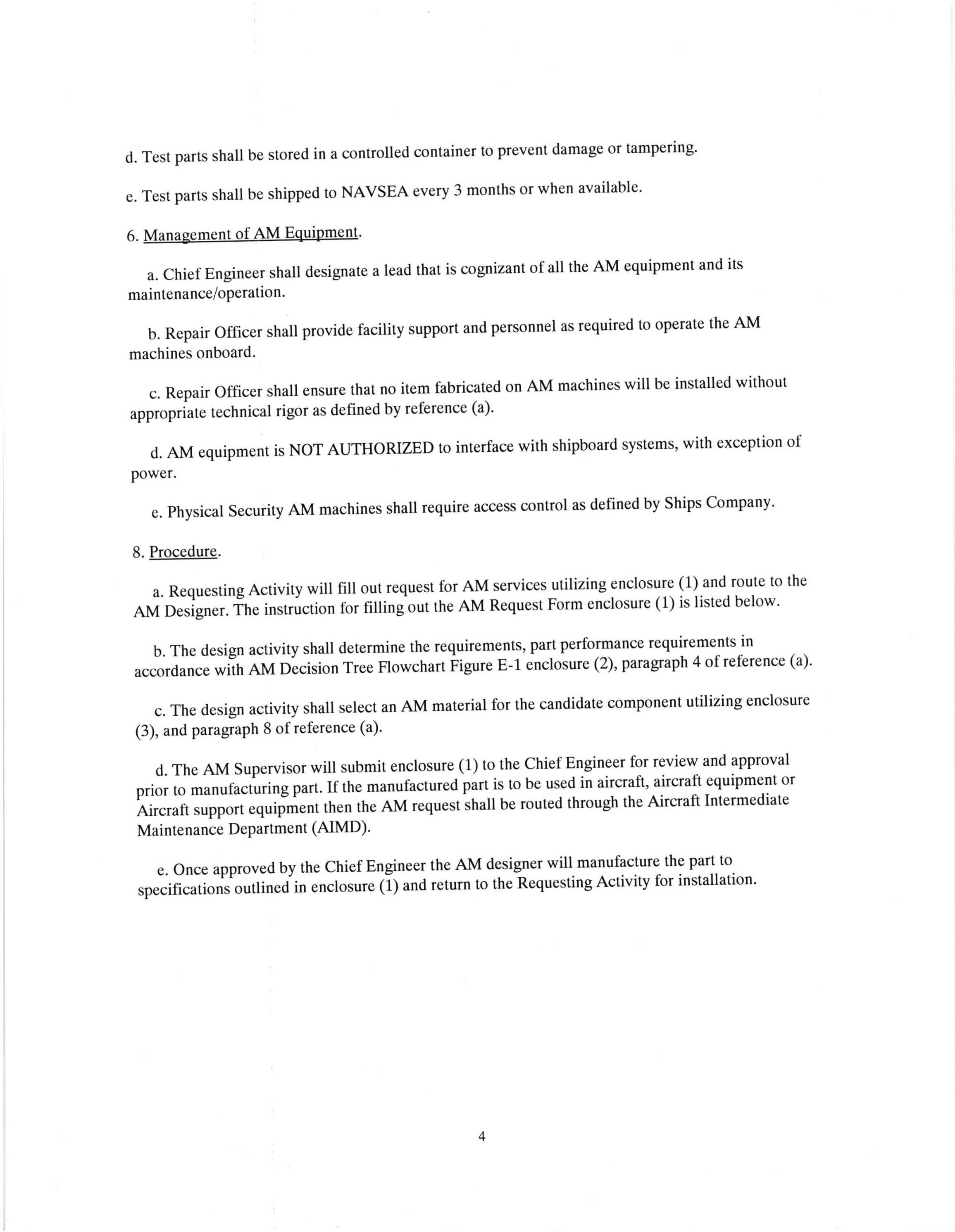
a. Test part ".stl" files shall be provided by NAVSEA.

b. Test parts shall be printed every 30 days as a maximum or during planned maneuvers, varying sea state conditions, etc., where feasible.

c. Test parts shall be dated and labeled and logs should be created and saved per Data Log and Management (section 5 of Action).

3

Figure 21. USS John C. Stennis (CVN 74) Additive Manufacturing Standard Operating Procedures, Third Page. Source: USS John C. Stennis (2019).



d. Test parts shall be stored in a controlled container to prevent damage or tampering.

e. Test parts shall be shipped to NAVSEA every 3 months or when available.

6. Management of AM Equipment.

a. Chief Engineer shall designate a lead that is cognizant of all the AM equipment and its maintenance/operation.

b. Repair Officer shall provide facility support and personnel as required to operate the AM machines onboard.

c. Repair Officer shall ensure that no item fabricated on AM machines will be installed without appropriate technical rigor as defined by reference (a).

d. AM equipment is NOT AUTHORIZED to interface with shipboard systems, with exception of power.

e. Physical Security AM machines shall require access control as defined by Ships Company.

8. Procedure.

a. Requesting Activity will fill out request for AM services utilizing enclosure (1) and route to the AM Designer. The instruction for filling out the AM Request Form enclosure (1) is listed below.

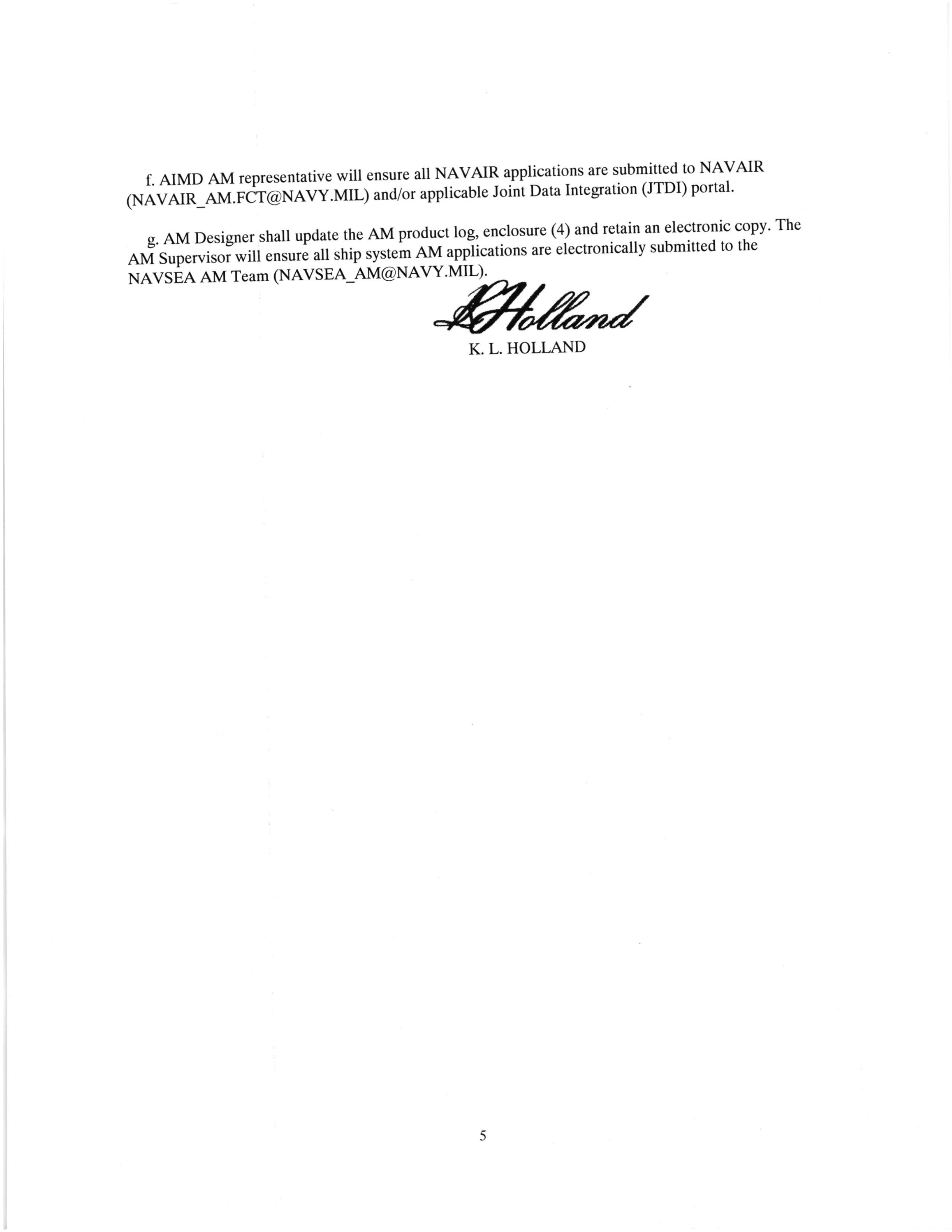
b. The design activity shall determine the requirements, part performance requirements in accordance with AM Decision Tree Flowchart Figure E-1 enclosure (2), paragraph 4 of reference (a).

c. The design activity shall select an AM material for the candidate component utilizing enclosure (3), and paragraph 8 of reference (a).

d. The AM Supervisor will submit enclosure (1) to the Chief Engineer for review and approval prior to manufacturing part. If the manufactured part is to be used in aircraft, aircraft equipment or Aircraft support equipment then the AM request shall be routed through the Aircraft Intermediate Maintenance Department (AIMD).

e. Once approved by the Chief Engineer the AM designer will manufacture the part to specifications outlined in enclosure (1) and return to the Requesting Activity for installation.

Figure 22. USS John C. Stennis (CVN 74) Additive Manufacturing Standard Operating Procedures, Fourth Page. Source: USS John C. Stennis (2019).



f. AIMD AM representative will ensure all NAVAIR applications are submitted to NAVAIR (NAVAIR_AM.FCT@NAVY.MIL) and/or applicable Joint Data Integration (JTDI) portal.

g. AM Designer shall update the AM product log, enclosure (4) and retain an electronic copy. The AM Supervisor will ensure all ship system AM applications are electronically submitted to the NAVSEA AM Team (NAVSEA_AM@NAVY.MIL).

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Figure 23. USS John C. Stennis (CVN 74) Additive Manufacturing Standard Operating Procedures, Fifth Page. Source: USS John C. Stennis (2019).

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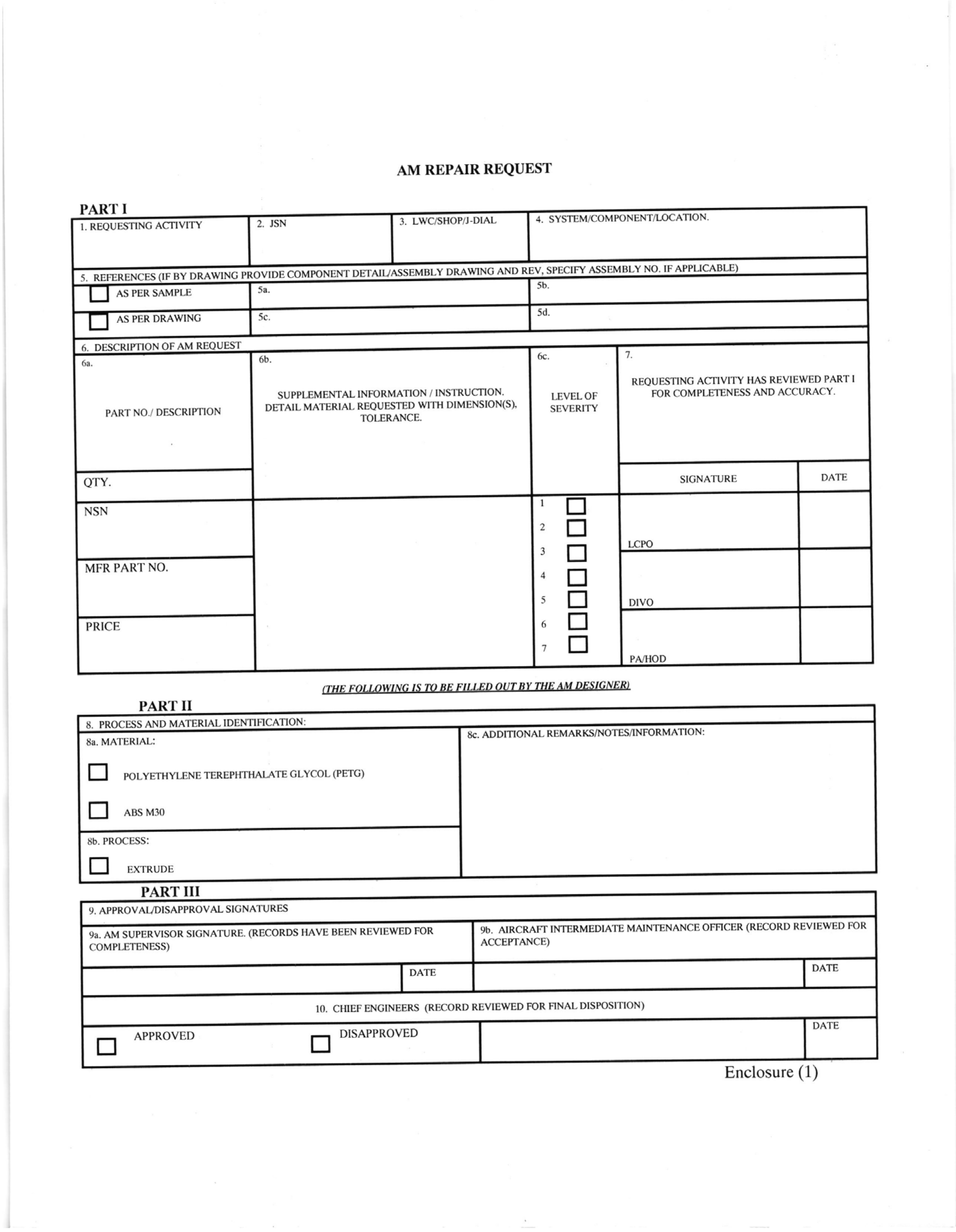
APPENDIX C. AM REPAIR REQUEST FORM



AM REPAIR REQUEST

PART I

1. REQUESTING ACTIVITY	2. JSN	3. LWC/SHOP/J-DIAL	4. SYSTEM/COMPONENT/LOCATION.

5. REFERENCES (IF BY DRAWING PROVIDE COMPONENT DETAIL/ASSEMBLY DRAWING AND REV, SPECIFY ASSEMBLY NO. IF APPLICABLE)

☐ AS PER SAMPLE	5a.	5b.
☐ AS PER DRAWING	5c.	5d.

6. DESCRIPTION OF AM REQUEST

6a. PART NO./ DESCRIPTION	6b. SUPPLEMENTAL INFORMATION / INSTRUCTION. DETAIL MATERIAL REQUESTED WITH DIMENSION(S), TOLERANCE.	6c. LEVEL OF SEVERITY	7. REQUESTING ACTIVITY HAS REVIEWED PART I FOR COMPLETENESS AND ACCURACY.	
QTY.			SIGNATURE	DATE
NSN		1 ☐ 2 ☐ 3 ☐	LCPO	
MFR PART NO.		4 ☐ 5 ☐	DIVO	
PRICE		6 ☐ 7 ☐	PA/HOD	

(THE FOLLOWING IS TO BE FILLED OUT BY THE AM DESIGNER)

PART II

8. PROCESS AND MATERIAL IDENTIFICATION:

8a. MATERIAL: ☐ POLYETHYLENE TEREPHTHALATE GLYCOL (PETG) ☐ ABS M30	8c. ADDITIONAL REMARKS/NOTES/INFORMATION:
8b. PROCESS: ☐ EXTRUDE	

PART III

9. APPROVAL/DISAPPROVAL SIGNATURES

9a. AM SUPERVISOR SIGNATURE. (RECORDS HAVE BEEN REVIEWED FOR COMPLETENESS)		9b. AIRCRAFT INTERMEDIATE MAINTENANCE OFFICER (RECORD REVIEWED FOR ACCEPTANCE)	
	DATE		DATE

10. CHIEF ENGINEERS (RECORD REVIEWED FOR FINAL DISPOSITION)

☐ APPROVED	☐ DISAPPROVED		DATE

Enclosure (1)

Figure 24. USS John C. Stennis (CVN 74) Additive Manufacturing Repair Request Form. Source: USS John C. Stennis (2019).

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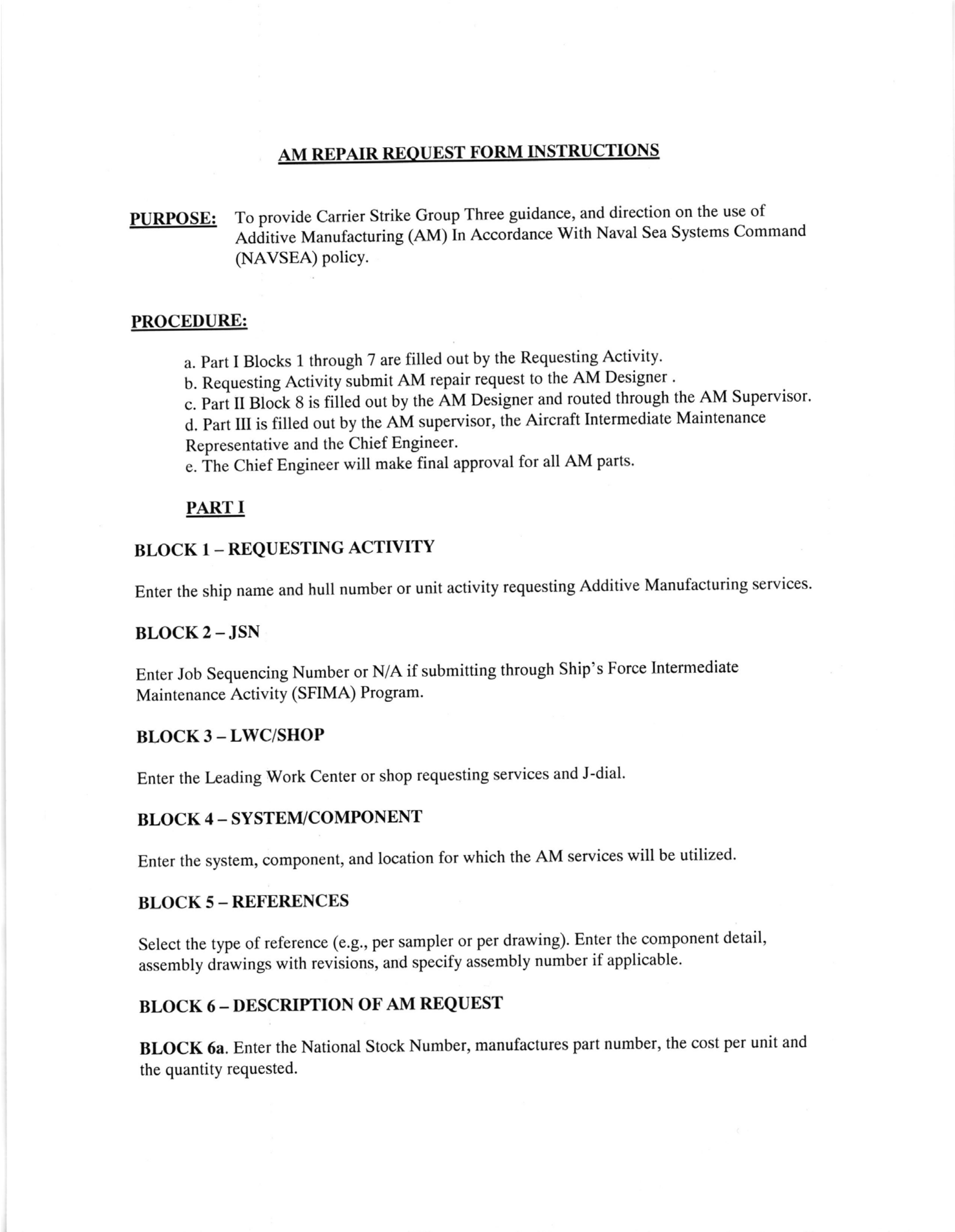
APPENDIX D. AM REPAIR REQUEST FORM INSTRUCTIONS



AM REPAIR REQUEST FORM INSTRUCTIONS

PURPOSE: To provide Carrier Strike Group Three guidance, and direction on the use of Additive Manufacturing (AM) In Accordance With Naval Sea Systems Command (NAVSEA) policy.

PROCEDURE:

a. Part I Blocks 1 through 7 are filled out by the Requesting Activity.
b. Requesting Activity submit AM repair request to the AM Designer .
c. Part II Block 8 is filled out by the AM Designer and routed through the AM Supervisor.
d. Part III is filled out by the AM supervisor, the Aircraft Intermediate Maintenance Representative and the Chief Engineer.
e. The Chief Engineer will make final approval for all AM parts.

PART I

BLOCK 1 – REQUESTING ACTIVITY

Enter the ship name and hull number or unit activity requesting Additive Manufacturing services.

BLOCK 2 – JSN

Enter Job Sequencing Number or N/A if submitting through Ship's Force Intermediate Maintenance Activity (SFIMA) Program.

BLOCK 3 – LWC/SHOP

Enter the Leading Work Center or shop requesting services and J-dial.

BLOCK 4 – SYSTEM/COMPONENT

Enter the system, component, and location for which the AM services will be utilized.

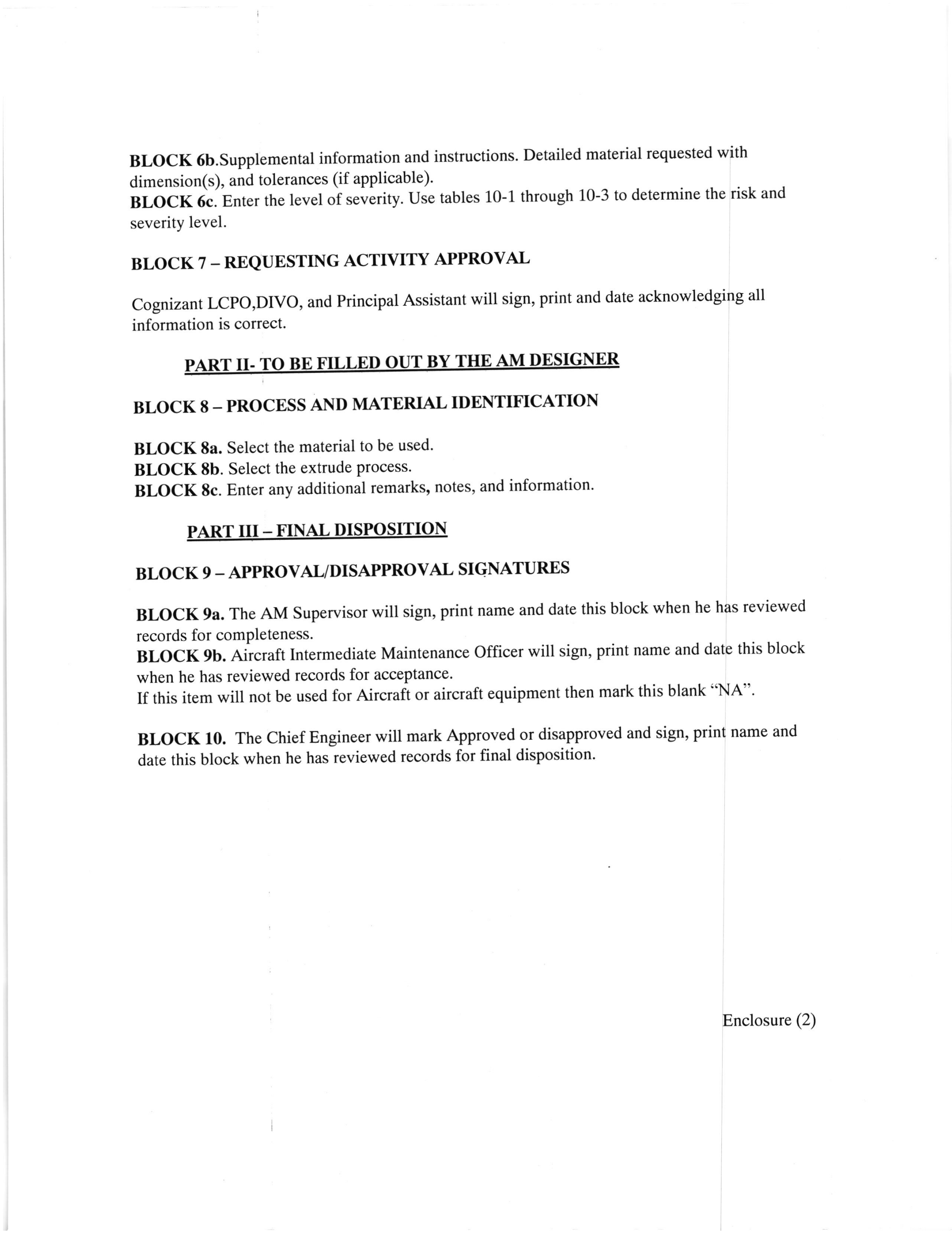
BLOCK 5 – REFERENCES

Select the type of reference (e.g., per sampler or per drawing). Enter the component detail, assembly drawings with revisions, and specify assembly number if applicable.

BLOCK 6 – DESCRIPTION OF AM REQUEST

BLOCK 6a. Enter the National Stock Number, manufactures part number, the cost per unit and the quantity requested.

Figure 25. USS John C. Stennis (CVN 74) Additive Manufacturing Repair Request Form, First Page. Source: USS John C. Stennis (2019).



BLOCK 6b.Supplemental information and instructions. Detailed material requested with dimension(s), and tolerances (if applicable).
BLOCK 6c. Enter the level of severity. Use tables 10-1 through 10-3 to determine the risk and severity level.

BLOCK 7 – REQUESTING ACTIVITY APPROVAL

Cognizant LCPO,DIVO, and Principal Assistant will sign, print and date acknowledging all information is correct.

PART II- TO BE FILLED OUT BY THE AM DESIGNER

BLOCK 8 – PROCESS AND MATERIAL IDENTIFICATION

BLOCK 8a. Select the material to be used.
BLOCK 8b. Select the extrude process.
BLOCK 8c. Enter any additional remarks, notes, and information.

PART III – FINAL DISPOSITION

BLOCK 9 – APPROVAL/DISAPPROVAL SIGNATURES

BLOCK 9a. The AM Supervisor will sign, print name and date this block when he has reviewed records for completeness.
BLOCK 9b. Aircraft Intermediate Maintenance Officer will sign, print name and date this block when he has reviewed records for acceptance.
If this item will not be used for Aircraft or aircraft equipment then mark this blank "NA".

BLOCK 10. The Chief Engineer will mark Approved or disapproved and sign, print name and date this block when he has reviewed records for final disposition.

Enclosure (2)

Figure 26. USS John C. Stennis (CVN 74) Additive Manufacturing Repair Request Form, Second Page. Source: USS John C. Stennis (2019).

APPENDIX E. AM DECISION TREE FLOWCHART

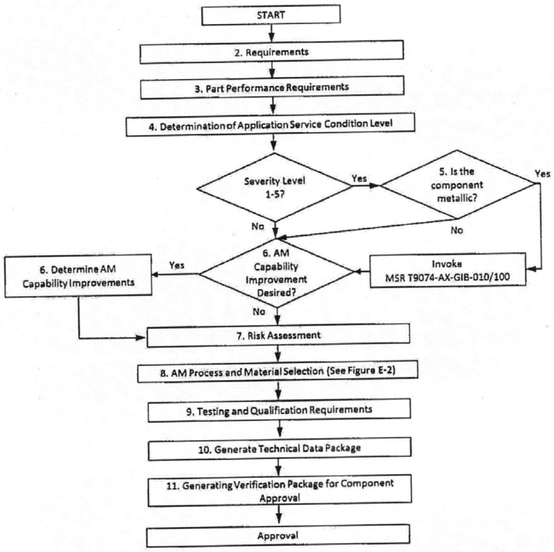


Figure E-1. AM Decision Tree Flowchart

Enclosure (3)

Figure 27. USS John C. Stennis (CVN 74) Additive Manufacturing Repair Decision Tree Flowchart. Source: USS John C. Stennis (2019).

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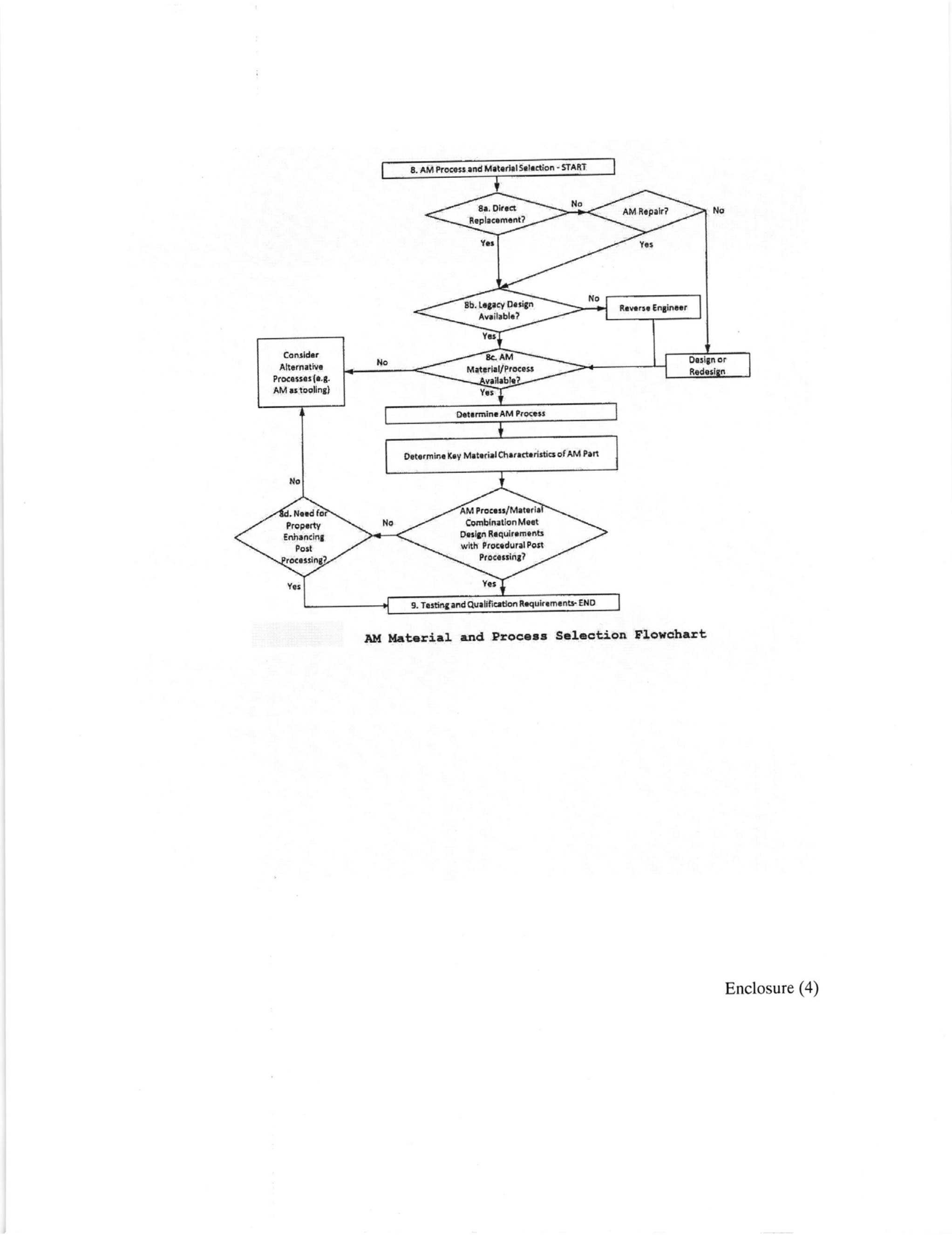
APPENDIX F. AM MATERIAL AND PROCESS SELECTION FLOWCHART



AM Material and Process Selection Flowchart

Enclosure (4)

Figure 28. USS John C. Stennis (CVN 74) Additive Manufacturing Material and Process Selection Flowchart. Source: USS John C. Stennis (2019).

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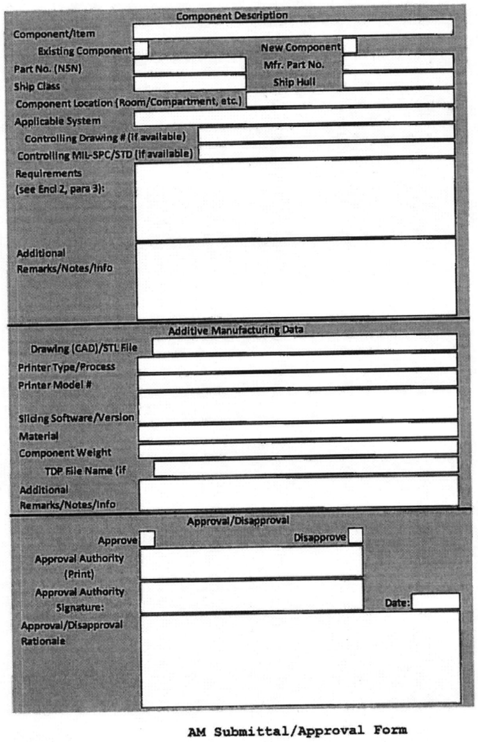
APPENDIX G. AM SUBMITTAL AND APPROVAL FORM



Component Description

Component/Item

Existing Component ☐ New Component ☐

Part No. (NSN)

Mfr. Part No.

Ship Class

Ship Hull

Component Location (Room/Compartment, etc.)

Applicable System

Controlling Drawing # (if available)

Controlling MIL-SPC/STD (if available)

Requirements (see Encl 2, para 3):

Additional Remarks/Notes/Info

Additive Manufacturing Data

Drawing (CAD)/STL File

Printer Type/Process

Printer Model #

Slicing Software/Version

Material

Component Weight

TDP File Name (if

Additional Remarks/Notes/Info

Approval/Disapproval

Approve ☐ Disapprove ☐

Approval Authority (Print)

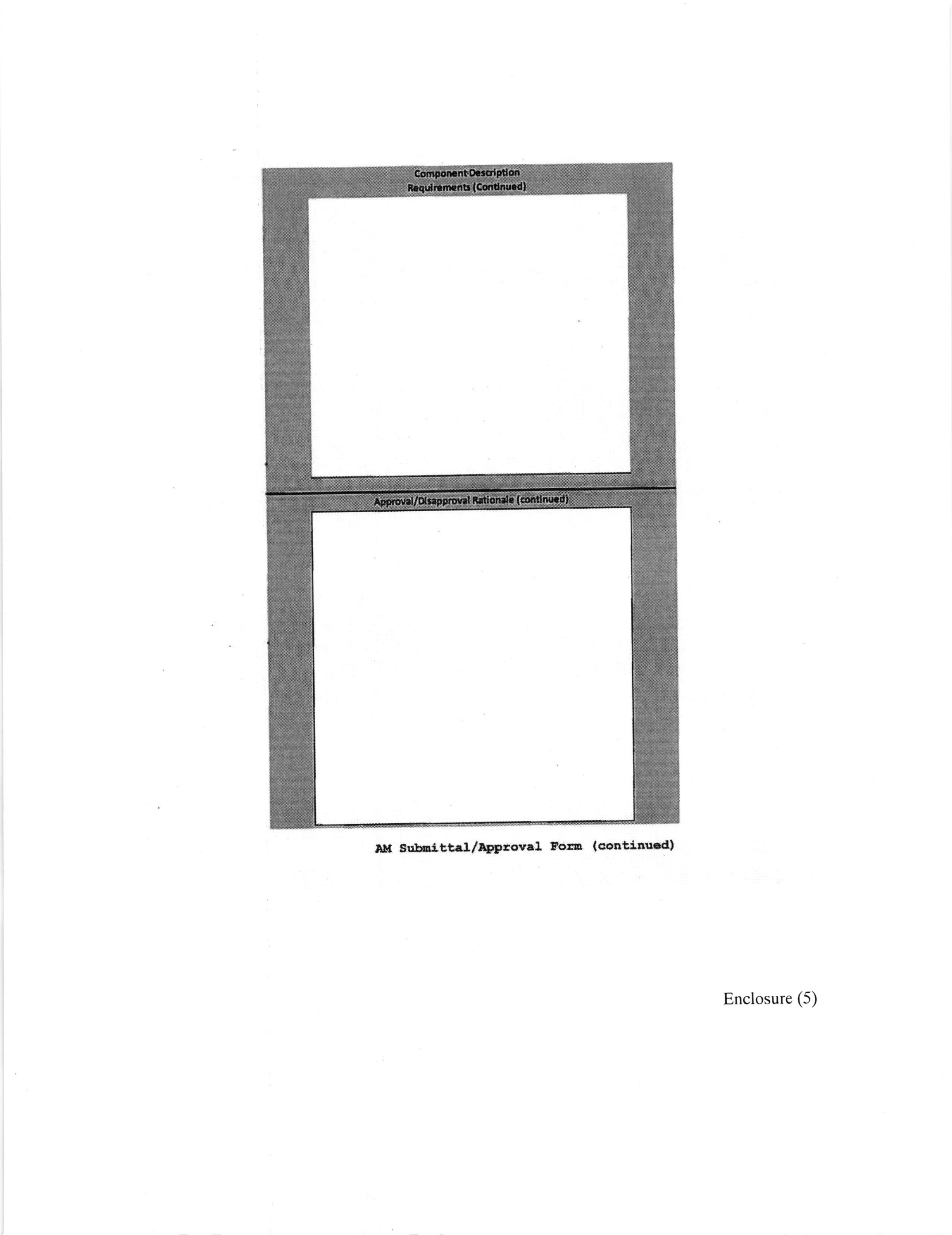
Approval Authority Signature:

Date:

Approval/Disapproval Rationale

AM Submittal/Approval Form

Figure 29. USS John C. Stennis (CVN 74) Additive Manufacturing Submittal and Approval Form, First Page. Source: USS John C. Stennis (2019).



Component Description Requirements (Continued)

Approval/Disapproval Rationale (continued)

AM Submittal/Approval Form (continued)

Enclosure (5)

Figure 30. USS John C. Stennis (CVN 74) Additive Manufacturing Submittal and Approval Form, Second Page. Source: USS John C. Stennis (2019).

APPENDIX H. NAVSEA SEVERITY DEFINITIONS

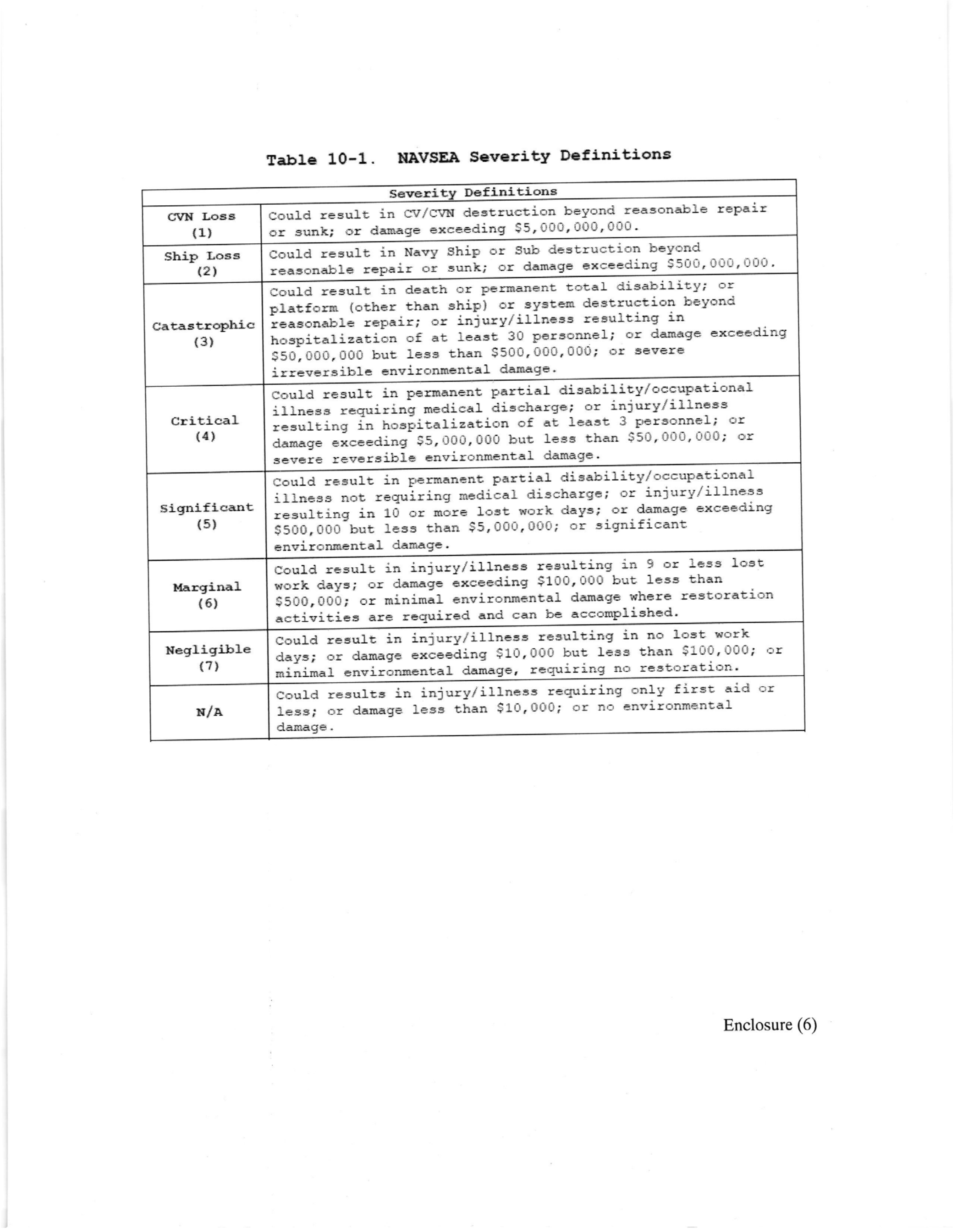


Table 10-1. NAVSEA Severity Definitions

Severity Definitions	
CVN Loss (1)	Could result in CV/CVN destruction beyond reasonable repair or sunk; or damage exceeding $5,000,000,000.
Ship Loss (2)	Could result in Navy Ship or Sub destruction beyond reasonable repair or sunk; or damage exceeding $500,000,000.
Catastrophic (3)	Could result in death or permanent total disability; or platform (other than ship) or system destruction beyond reasonable repair; or injury/illness resulting in hospitalization of at least 30 personnel; or damage exceeding $50,000,000 but less than $500,000,000; or severe irreversible environmental damage.
Critical (4)	Could result in permanent partial disability/occupational illness requiring medical discharge; or injury/illness resulting in hospitalization of at least 3 personnel; or damage exceeding $5,000,000 but less than $50,000,000; or severe reversible environmental damage.
Significant (5)	Could result in permanent partial disability/occupational illness not requiring medical discharge; or injury/illness resulting in 10 or more lost work days; or damage exceeding $500,000 but less than $5,000,000; or significant environmental damage.
Marginal (6)	Could result in injury/illness resulting in 9 or less lost work days; or damage exceeding $100,000 but less than $500,000; or minimal environmental damage where restoration activities are required and can be accomplished.
Negligible (7)	Could result in injury/illness resulting in no lost work days; or damage exceeding $10,000 but less than $100,000; or minimal environmental damage, requiring no restoration.
N/A	Could results in injury/illness requiring only first aid or less; or damage less than $10,000; or no environmental damage.

Enclosure (6)

Figure 31. NAVSEA Mishap Severity Definitions. Source: USS John C. Stennis (2019).

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APPENDIX I. NAVSEA FREQUENCY AND PROBABILITY DEFINITIONS

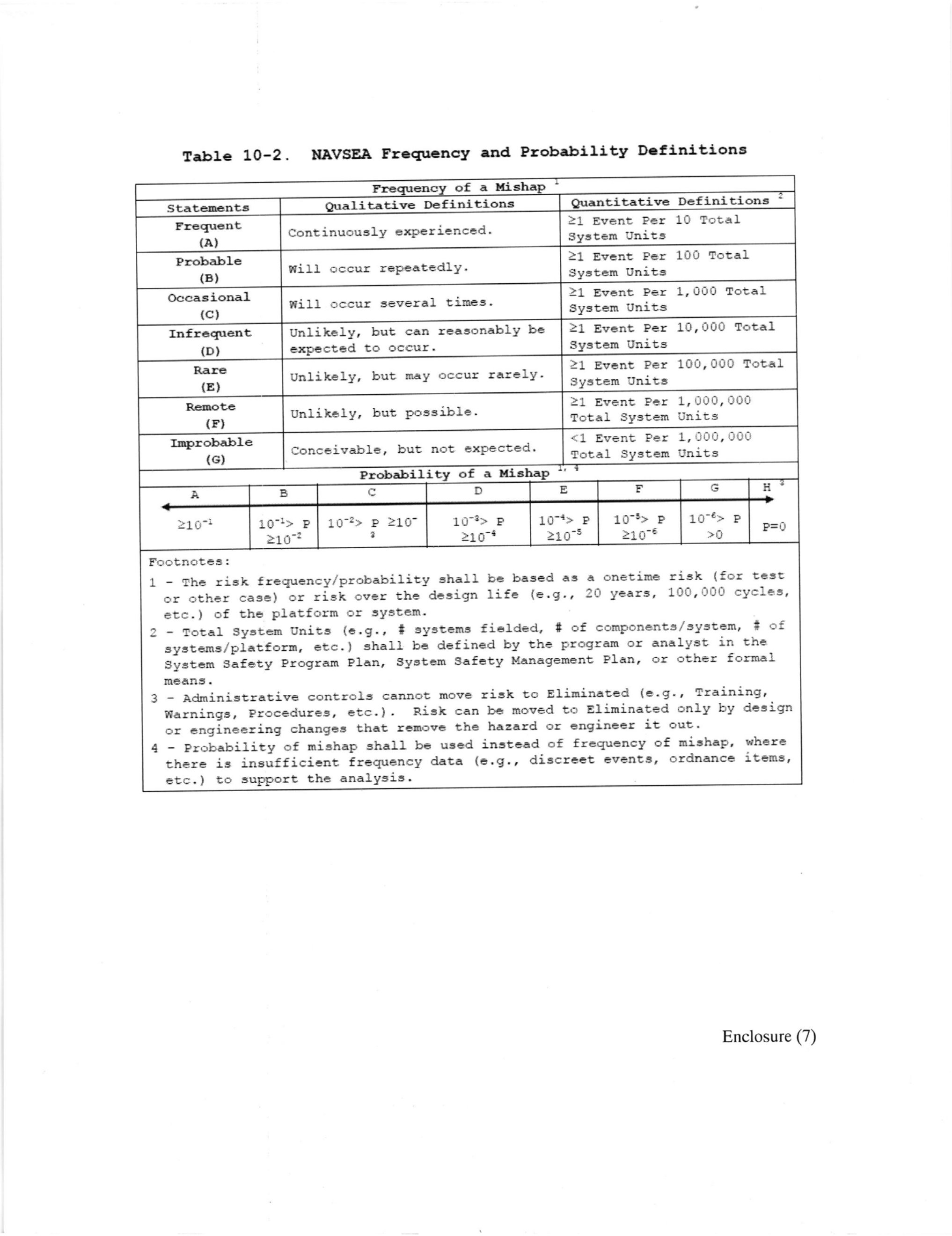

Table 10-2. NAVSEA Frequency and Probability Definitions

Frequency of a Mishap [1]		
Statements	Qualitative Definitions	Quantitative Definitions [2]
Frequent (A)	Continuously experienced.	≥1 Event Per 10 Total System Units
Probable (B)	Will occur repeatedly.	≥1 Event Per 100 Total System Units
Occasional (C)	Will occur several times.	≥1 Event Per 1,000 Total System Units
Infrequent (D)	Unlikely, but can reasonably be expected to occur.	≥1 Event Per 10,000 Total System Units
Rare (E)	Unlikely, but may occur rarely.	≥1 Event Per 100,000 Total System Units
Remote (F)	Unlikely, but possible.	≥1 Event Per 1,000,000 Total System Units
Improbable (G)	Conceivable, but not expected.	<1 Event Per 1,000,000 Total System Units

Probability of a Mishap [1, 4]

A	B	C	D	E	F	G	H [3]
$\geq 10^{-1}$	$10^{-1} > P \geq 10^{-2}$	$10^{-2} > P \geq 10^{-3}$	$10^{-3} > P \geq 10^{-4}$	$10^{-4} > P \geq 10^{-5}$	$10^{-5} > P \geq 10^{-6}$	$10^{-6} > P > 0$	P=0

Footnotes:

1 - The risk frequency/probability shall be based as a onetime risk (for test or other case) or risk over the design life (e.g., 20 years, 100,000 cycles, etc.) of the platform or system.

2 - Total System Units (e.g., # systems fielded, # of components/system, # of systems/platform, etc.) shall be defined by the program or analyst in the System Safety Program Plan, System Safety Management Plan, or other formal means.

3 - Administrative controls cannot move risk to Eliminated (e.g., Training, Warnings, Procedures, etc.). Risk can be moved to Eliminated only by design or engineering changes that remove the hazard or engineer it out.

4 - Probability of mishap shall be used instead of frequency of mishap, where there is insufficient frequency data (e.g., discreet events, ordnance items, etc.) to support the analysis.

Enclosure (7)

Figure 32. NAVSEA Frequency and Probability Definitions. Source: USS John C. Stennis (2019).

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APPENDIX J. NAVSEA ESOH RISK MATRIX

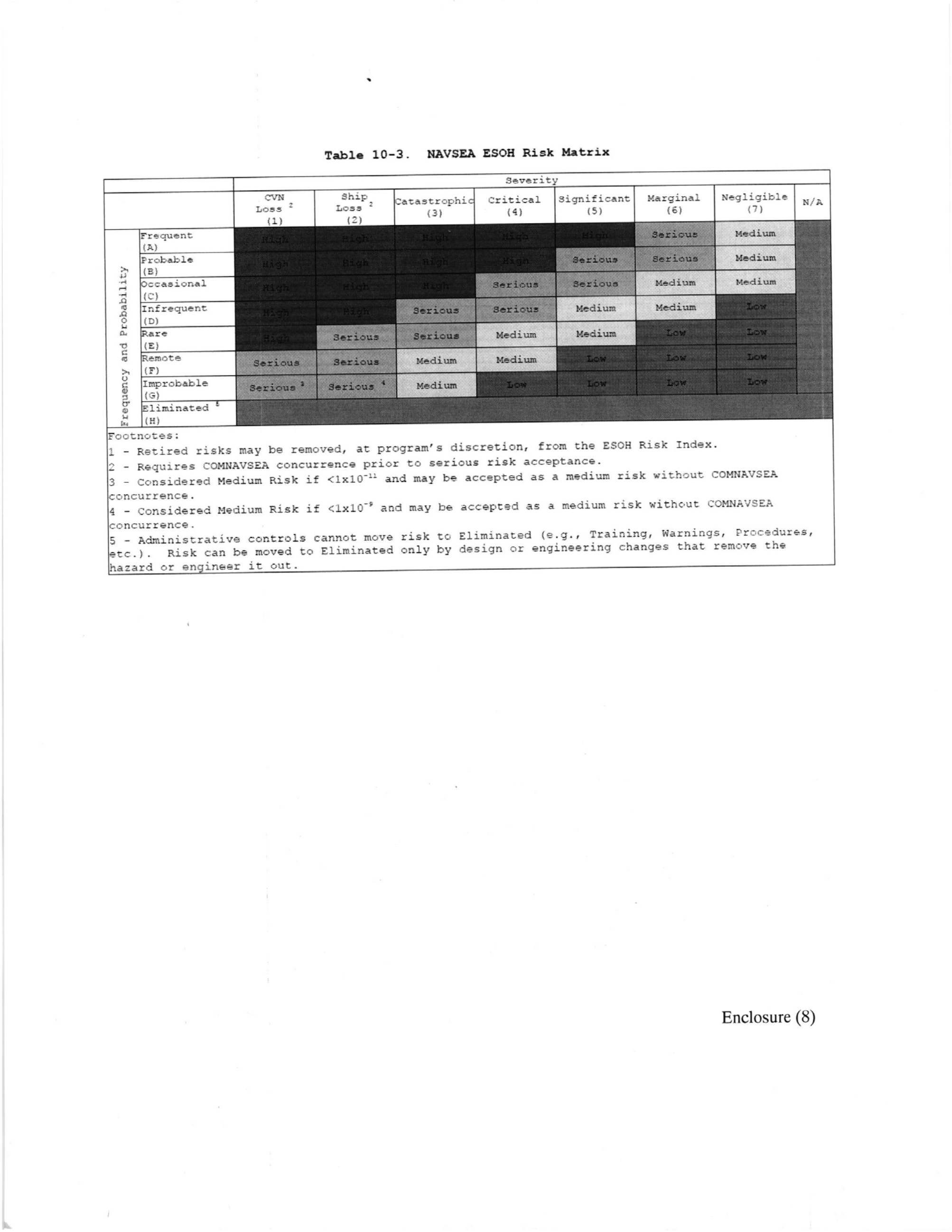

Table 10-3. NAVSEA ESOH Risk Matrix

		Severity							
		CVN Loss [2] (1)	Ship Loss [2] (2)	Catastrophic (3)	Critical (4)	Significant (5)	Marginal (6)	Negligible (7)	N/A
Frequency and Probability	Frequent (A)	High	High	High	High	High	Serious	Medium	
	Probable (B)	High	High	High	High	Serious	Serious	Medium	
	Occasional (C)	High	High	High	Serious	Serious	Medium	Medium	
	Infrequent (D)	High	High	Serious	Serious	Medium	Medium	Low	
	Rare (E)	High	Serious	Serious	Medium	Medium	Low	Low	
	Remote (F)	Serious	Serious	Medium	Medium	Low	Low	Low	
	Improbable (G)	Serious [3]	Serious [4]	Medium	Low	Low	Low	Low	
	Eliminated [5] (H)								

Footnotes:

1 - Retired risks may be removed, at program's discretion, from the ESOH Risk Index.

2 - Requires COMNAVSEA concurrence prior to serious risk acceptance.

3 - Considered Medium Risk if $<1x10^{-11}$ and may be accepted as a medium risk without COMNAVSEA concurrence.

4 - Considered Medium Risk if $<1x10^{-9}$ and may be accepted as a medium risk without COMNAVSEA concurrence.

5 - Administrative controls cannot move risk to Eliminated (e.g., Training, Warnings, Procedures, etc.). Risk can be moved to Eliminated only by design or engineering changes that remove the hazard or engineer it out.

Enclosure (8)

Figure 33. NAVSEA Environment, Safety and Occupational Health (ESOH) Risk Matrix. Source: USS John C. Stennis (2019).

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