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ANALYSIS OF ADDITIVE MANUFACTURING FOR SUSTAINMENT OF NAVAL AVIATION SYSTEMS

by

David M. Coyle

September 2017

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To preserve national security, the United States Navy must continuously explore new technologies that can enhance warfighting capabilities, increase weapon system readiness and operate in a narrowing fiscal environment. The high cost of sustainment of military systems, coupled with extended life cycles, has compelled the Department of the Navy to find innovative ways to sustain in-service equipment. Additive manufacturing, also known as 3D printing, is one technology that demonstrates potential to provide novel warfighting capabilities and reduce sustainment costs of military weapon systems. But how can the Navy leverage the cost savings and lead-time reductions promised by additive manufacturing and simultaneously minimize the risks associated with a rapidly evolving technology? This thesis explores the technical and logistical factors necessary to identify applications of additive manufacturing for sustainment of in-service naval aviation equipment. The thesis introduces a component selection methodology to query the aviation spare-parts inventory for identification of additive manufacturing candidates. The methodology organizes the resultant data using a top-down approach that aligns technical feasibility with programmatic objectives. Finally, a discrete event simulation (DES) in Innoslate analyzes the data to provide engineers and logisticians with a decision-management framework to support the development of a business case for additive manufacturing.

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ANALYSIS OF ADDITIVE MANUFACTURING FOR SUSTAINMENT OF NAVAL AVIATION SYSTEMS

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ABSTRACT

To preserve national security, the United States Navy must continuously explore new technologies that can enhance warfighting capabilities, increase weapon system readiness and operate in a narrowing fiscal environment. The high cost of sustainment of military systems, coupled with extended life cycles, has compelled the Department of the Navy to find innovative ways to sustain in-service equipment. Additive manufacturing, also known as 3D printing, is one technology that demonstrates potential to provide novel warfighting capabilities and reduce sustainment costs of military weapon systems. But how can the Navy leverage the cost savings and lead-time reductions promised by additive manufacturing and simultaneously minimize the risks associated with a rapidly evolving technology? This thesis explores the technical and logistical factors necessary to identify applications of additive manufacturing for sustainment of in-service naval aviation equipment. The thesis introduces a component selection methodology to query the aviation spare-parts inventory for identification of additive manufacturing candidates. The methodology organizes the resultant data using a top-down approach that aligns technical feasibility with programmatic objectives. Finally, a discrete event simulation (DES) in Innoslate analyzes the data to provide engineers and logisticians with a decision-management framework to support the development of a business case for additive manufacturing.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
AAC	acquisition advice code
AFIT	Air Force Institute of Technology
AHP	analytical hierarchy process
ALT	administrative lead-time
AM	additive manufacturing
AMC	acquisition method code
AMSC	acquisition method suffix code
ASN (RDA)	Assistant Secretary of the Navy for Research, Development and Acquisition
ASSIST	acquisition streamlining and standardization information system
ASTM	American Society for Testing and Materials
AVDLR	aviation depot-level repairable
AWP	awaiting parts
BB	backorder
BCA	business case analysis
BCM	beyond capable maintenance
CAD	computer-aided design
CAGE	commercial and government entity code
CDSA	Combat Direction Systems Activity
CLIP	continuous liquid interface production
CNC	computer numerical control
CNO	Chief of Naval Operations
COG	cognizance code
CONUS	continental United States
COP	community of practice
DARPA	Defense Advanced Research Projects Agency
DASN (RDT&E)	Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation
DAU	Defense Acquisition University

DC I&L	Deputy Commandant, Installation and Logistics
DED	directed energy deposition
DES	discrete event simulation
DLA	Defense Logistics Agency
DLP	digital light processing
DMLS	direct metal laser sintering
DMSMS	diminishing manufacturing sources and material shortages
DOD	Department of Defense
DON	Department of the Navy
EBAM	electron beam additive manufacturing
EBM	electron beam melting
EBS	enterprise business system
ERMS	electronic retrograde management system
ERP	enterprise resource planning
ESA	engineering support activity
FDM	fused deposition modeling
FFF	fused filament fabrication
FLC	fleet logistics center
FLIS	Federal Logistics Information Service
FMC	fully mission capable
FRC	fleet readiness center
FSC	federal supply class
GAO	Government Accountability Office
GSA	General Services Administration
HIP	hot isostatic pressing
ICP	inventory control point
IP	intellectual property
IT	information technology
JEDMICS	Joint Engineering Data Management Information and Control System
JIT	just in time
LCC	life cycle cost

LENS	laser engineered net shaping
LMI	Logistics Management Institute
LOM	laminated object manufacturing
LRC	local routing code
MAKE	Manufacturing, Knowledge and Education Lab
MARMC	Mid-Atlantic Regional Maintenance Center
MENTOR2	Manufacturing Experimentation and Outreach Two
MIT	Massachusetts Institute of Technology
NAE	naval aviation enterprise
NAM EXCOMM	Navy Additive Manufacturing Executive Committee
NAMP	naval aviation maintenance program
NAMTI	Naval Additive Manufacturing Technical Interchange
NATEC	Naval Air Technical Data and Engineering Service Command
NAVAIR	Naval Air Systems Command
NAVICP	Naval Inventory Control Point
NAVSUP	Naval Supply Systems Command
NAVSUP WSS	Naval Supply Systems Command, Weapon Systems Support
NIIN	national item identification number
NMC	not mission capable
NMCS	not mission capable supply
NSN	national stock number
NSWC	Naval Surface Warfare Center
NSWCCD	Naval Surface Warfare Center, Carderock Division
O&S	operations and sustainment
OCONUS	outside continental United States
OEM	original equipment manufacturer
ONR	Office of Naval Research
P/N	part number
PBF	powder bed fusion
PLA	polylactic acid
PLM	product life cycle management
PLT	procurement lead-time

PMI	product manufacturing information
PSE	peculiar support equipment
PSU ARL	Penn State University, Applied Research Lab
R&D	research and development
RCQF	rate, cost, quality and flexibility
ROI	return on investment
SECNAV	Secretary of the Navy
SLA	stereolithography
SLM	selective laser melting
SLS	selective laser sintering
SMIC	special material identification code
SMR	source, maintenance and recoverability code
SOH	stock on hand
STEM	science, technology, engineering and mathematics
STL	stereolithography file
SYSCOMS	system commands
TDP	technical data package
TOC	total ownership cost
UAM	ultrasonic additive manufacturing
UV	ultraviolet
WIP	work in progress

EXECUTIVE SUMMARY

The internal challenges confronting the Department of the Navy (DON) are dynamic and often span multiple domains, including technical, political and budgetary. However, there are opportunities for the DON to address each of these challenges and remain good stewards of taxpayer dollars and national resources. The Navy, therefore, must continuously pursue novel ideas and technologies that can address emergent issues and adapt to changing environments that could impede the successful operation of the enterprise. One critical issue that plagues the Navy and compromises national security is the inefficiencies within the supply system. Unavailability of spare parts, exorbitant procurement and transportation costs, and long lead times all threaten mission success and national safety. One technology that has gained prominence in recent years is additive manufacturing (AM), which could potentially address several of the issues that degrade Navy supply system performance.

The purpose of this research effort was to investigate the use of additive manufacturing in the maintenance and sustainment of naval aviation weapon systems and determine whether AM technology can provide unique opportunities for cost reductions and improved mission readiness that are not possible with conventional sustainment processes. To answer this question, an extensive literature review was conducted to understand the current state of AM technology and its business implications, as well as any existing efforts to incorporate AM within the DON. The authors identified ongoing initiatives within the Navy and collaborations within academia and industry that incorporate AM technology to resolve supply chain issues.

This thesis drew upon previous research efforts to identify spare parts within after-sales service supply chains that could potentially benefit from the unique technical and business attributes offered by AM technologies. An overview of the Navy supply chain and maintenance infrastructure is provided to reveal possible insertion points for AM technology to support sustainment efforts for aviation weapon systems. A component selection methodology was developed to identify and categorize spare parts within the Navy supply chain that could benefit from the unique attributes of AM. The

methodology identifies relevant logistics and technical data attributes to assess a spare part's amenability to existing AM processes, as well as the data repositories needed to retrieve such data. A component prioritization methodology is presented that aligns technical feasibility with organizational objectives. The identified components are prioritized based on technical suitability for AM and the greatest potential for cost and procurement lead-time reductions. Finally, a sample component from the prioritized list of items was selected to run through a discrete event simulation modeled in Innoslate to compare additive manufacturing to conventional supply support processes.

The component selection methodology and subsequent simulation model revealed that AM has significant potential to greatly reduce spare part lead-times needed to support naval aviation weapon system repair efforts and that there are spare parts within the Navy supply chain to achieve such savings. This capability to reduce repair turnaround times at aviation repair sites corresponds to increased material availability for critical aviation systems and increased mission readiness for the fleet. Additionally, the data collection process identified the data sources available to Navy logisticians to extract logistics information specific to Navy spare parts that are relevant for an AM suitability assessment.

This research effort uncovered opportunities within the naval aviation spare parts supply chain to reduce procurement lead-times and improve material availability through AM technology. However, the data collection process exposed several gaps in data availability and information technology systems that should be addressed prior to AM implementation across the Navy. Knowledge sharing and collaborative product life cycle management tools are recommended to increase AM data transparency between Navy hardware system command engineers and Naval Supply Systems Command logisticians. A collaborative AM data infrastructure is essential to accurately and systematically identify opportunities for AM to reduce life cycle costs and improve material availability in the operations-and-sustainment phase of the system life cycle.

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I would like to thank my advisors for their insight and support during this research effort. I am grateful to Dr. Geraldo Ferrer for encouraging me to investigate a challenging problem that could provide real value to my organization and the Navy at large. I also offer my sincerest thanks to CAPT. Armen Kurdian for his wisdom and mentorship. His unwavering passion to pursue novel ideas and challenge the status quo is both inspirational and thought provoking. Likewise, I would like to acknowledge the contributions of my second reader, Dr. Karen Holness, whose guidance and support during the final iterations of this thesis were incredibly helpful in tying my thoughts together.

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I. INTRODUCTION

A. BACKGROUND

The Department of the Navy (DON) must continuously address emerging threats and vulnerabilities to remain a leader in maritime military superiority. However, the DON must confront not only threats posed by adversaries, but also must address deficiencies within the organization that could compromise national security. Such a multi-dimensional enterprise is challenged with constrained budgets, rapidly evolving needs and complex support functions. It is imperative that Navy military personnel be equipped with the right materials at the right time to sustain mission capabilities. In order to provide optimal performance, the infrastructure necessary to enable mission effectiveness must operate efficiently and reliably. One of the major challenges confronting the Navy and jeopardizing mission success is the effective operation of supply support functions. The sustainment of military weapons systems relies on effective operation of a complex supply chain that involves global industry partners, small business and government maintenance facilities. Together, government and industry execute service and supply functions to keep weapon systems in an operational condition. However, the supply chain is rife with obstacles and inefficiencies that the Navy must address to maximize warfighter readiness within cost, schedule, and performance objectives. Major obstacles include lack of system technical data and data rights, which are negotiated prior to system sustainment.

Since 1990, the Government Accountability Office (GAO) has labeled Department of Defense (DOD) inventory management as a "high-risk" process, due largely to the inefficiencies of the process and the substantial economic investment (Edwards 2010). In a 2010 report, one of the primary concerns addressed by the GAO was the poor demand forecasting of the military services, which ultimately led to stock-out and backorders for many items. Additionally, GAO discovered spare part inventories that drastically exceeded allowances, leading to material waste and increased inventory holding costs. Spare part demand forecast accuracy is, however, a difficult problem to solve for the DOD, as material requisitions for spare parts are often infrequent with a high degree of variability. In response to GAO's findings and recommendations, the Defense Logistics Agency (DLA), the largest logistics combat support agency for the DOD, partnered with the Logistics Management Institute (LMI), a not-for-profit government consulting firm, to develop and implement an inventory control solution that would improve forecast accuracy, as well as provide effective management of consumable item inventories. The collaborative effort between DLA and LMI revealed that the vast majority of DOD consumable item inventories fell within a highly variable demand pattern, as illustrated in Figures 1 and 2 (Bachman and Carroll 2013).

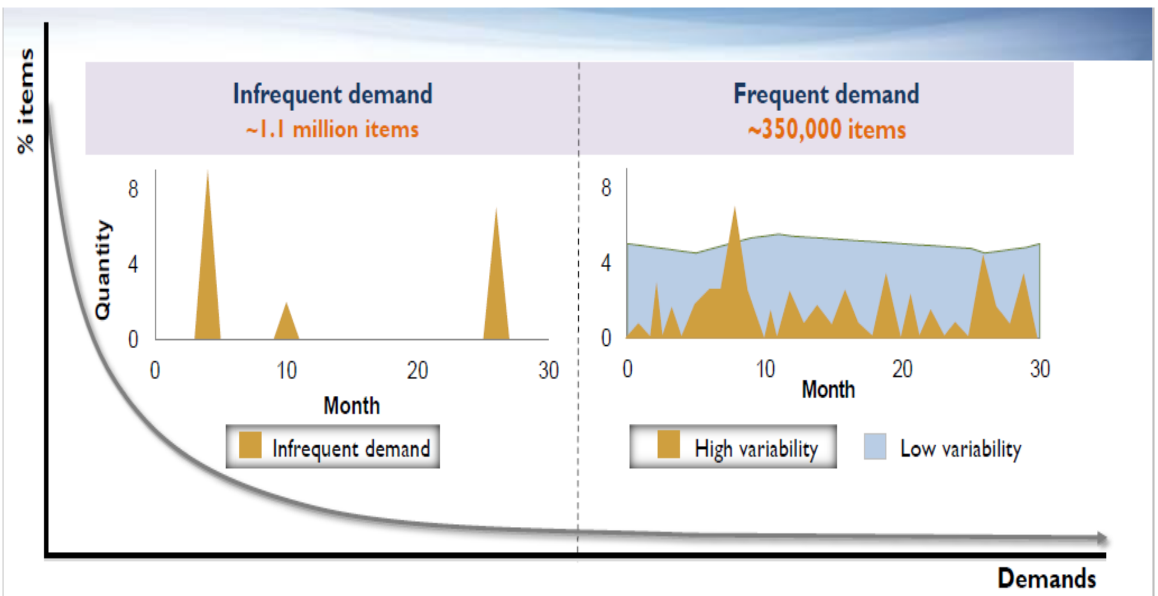

Figure 1. DOD Consumable Parts Inventory Distribution.
Source: Bachman and Carroll (2013).

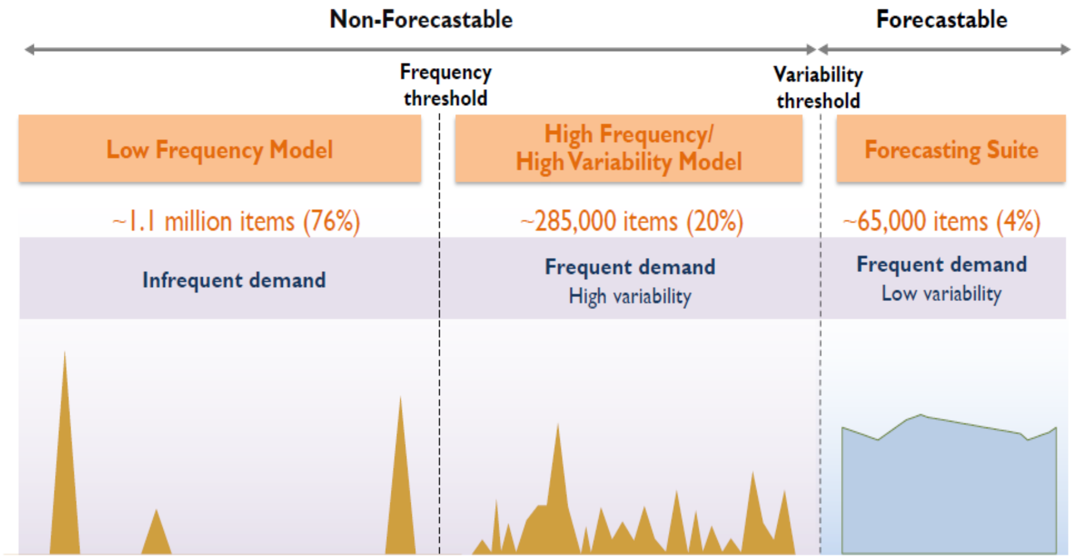

Figure 2. DOD Consumable Parts Demand Frequency. Source: Bachman and Carroll (2013).

As shown in the previous figures, a significant proportion (approximately 96%) of DOD consumable parts experience demand signals that are highly variable. Approximately 76% of consumable parts experience demand signals that are both highly variable and infrequent. Flexible order fulfillment processes, such as just-in-time (JIT) inventory, are well-suited to handle these types of demand signals; however, such processes have been unmanageable on the scale necessary to support DON weapon systems during operations and sustainment.

Compounding the issue of effective supply support are the many challenges the Navy faces with sustaining weapon systems well beyond their intended life cycles. As weapon system program life cycles are extended, the DON maintenance and sustainment communities must continuously address a myriad of issues, such as diminishing manufacturing and material shortages (DMSMS), obsolescence, higher costs, and long procurement lead times. In a 2017 article released by *Defense News*, nearly two-thirds of Navy F/A-18s are out of service; 35% of which are awaiting maintenance or parts (Cavas 2017). In many cases, spare parts are unavailable due to loss of suppliers or incomplete technical data packages (TDPs). Furthermore, the reliability of these systems severely declines after continued use in demanding operational environments and in some cases, the operational profile of weapon systems may be expanded to address emergent threats. The DON, therefore, must identify new technologies and processes that can help address these and other emergent issues.

B. THESIS PURPOSE AND RESEARCH QUESTIONS

This research effort seeks to identify cost-effective scenarios for additive manufacturing (AM) integration in the operations and sustainment phase of the system life cycle. Additive manufacturing has far reaching applications in the sustainment of military systems; however, to limit the scope, this research will explore the potential insertion points for AM strictly within the aviation supply system for aviation depot-level repairables (AVDLRs). This effort directly aligns with the objectives of the DON AM implementation plan (SECNAV 2017) to assess readiness drivers and their potential benefit from AM applications, as well as identification and amenability of parts inventories to be manufactured via additive processes. Additionally, this research effort will provide input into a business case analysis to assess economic viability of AM components, with a concentration on class IX parts, defined as consumable aviation repair parts per Joint Publication 4–0 (Joint Chiefs of Staff 2013). This thesis report seeks to answer the following questions:

- Can additive manufacturing technologies reduce costs and procurement lead times within the naval aviation supply chain that are unachievable with conventional supply support processes?
- How can the Navy systematically identify opportunities to integrate additive manufacturing within the aviation supply chain?
- What is the process flow and decision support system necessary to identify cost and lead-time savings using additive manufacturing?

II. LITERATURE REVIEW

A. ADDITIVE MANUFACTURING (3D PRINTING)

One technology that has garnered significant attention over the last several years is additive manufacturing (AM), also commonly referred to as 3D printing. Though AM technology has been around for several decades, there have been considerable advancements in recent years with AM materials and processes, as well as expansion of commercial service bureaus. Numerous studies and research efforts have suggested that AM has the potential to address many of the issues confronting the Navy maintenance and sustainment communities. Additive manufacturing is a manufacturing technology that holds many unique attributes in comparison to conventional subtractive manufacturing processes. In particular, AM is well-suited for low-volume production runs, since there are generally no fixed tooling costs for manufacturing a component through an additive process. Additionally, there is the opportunity to produce novel components that are not possible with other manufacturing methods, which could provide unique capabilities and reliability improvements for aging weapon systems. Some of the most notable unique characteristics of AM include design freedom, part consolidation, mass customization, and lightweighting. This report presents a discussion of the first two attributes.

Design freedom refers to the design of components that exploit the geometric complexity possible with AM processes. A design method known as "topology optimization" creates complex, organic shapes that make optimal use of material while maximizing component performance. Figure 3 provides an example of topology optimization, where a prismatic airframe component subject to subtractive manufacturing constraints is optimized for an additive process. As shown in Figure 3, the AM configuration uses significantly less materially than the conventionally manufactured components. Further, AM can be used to create internal lattices and cooling channels that are not possible with traditional manufacturing techniques. Internal cooling channels, for example, reduce thermal stresses for components subjected to temperature extremes and repeated heating and cooling. Figure 4 provides an example of an additively manufactured aerospace component with internal cooling channels. The following images provide examples of how conventionally manufactured parts can be reengineered to leverage the design freedom of AM and how this technology could provide leaner, cheaper, and higher performance parts.

Figure 3. Example of Topology Optimization. Source: Goehrke (2017).

Figure 4. Example of Internal Cooling Channels in AM Part. Source: Duffy (2016).

In addition to complex geometric designs, AM allows for the consolidation of multi-part assemblies into a single component. A widely acknowledged application of part consolidation is GE Aviation’s LEAP engine nozzle, in which a fuel nozzle consisting of 20 separate parts and multiple welding steps was consolidated into a single AM build process. Figure 5 shows the consolidated LEAP engine fuel nozzle. Not only has AM reduced the complex component down to a single part, it has created a part that is 25% lighter and five times stronger than its conventionally manufactured predecessor (Grunewald 2016). Such applications demonstrate the potential for AM to reduce both material and process waste through multi-part consolidation.

Figure 5. AM Part Consolidation for GE Aviation LEAP Engine Fuel Nozzle. Source: Kellner (2017).

B. ADDITIVE MANUFACTURING BUSINESS MODEL FRAMEWORK

One of the most attractive aspects of AM over conventional manufacturing processes is the tremendous degree of flexibility offered by the technology, where flexibility refers to the ease with which a process can be adapted to produce different parts or designs. Professor John Hart (2016) of the Massachusetts Institute of Technology (MIT) presents four key attributes that are used to measure manufacturing process performance: rate, cost, quality, and flexibility (RCQF). In the RCQF framework, Dr. Hart discusses how each of these attributes are interrelated and that tradeoffs must be made among them for any given manufacturing process; whether additive or subtractive. Figure 6 provides a graphic depiction of the RCQF framework.

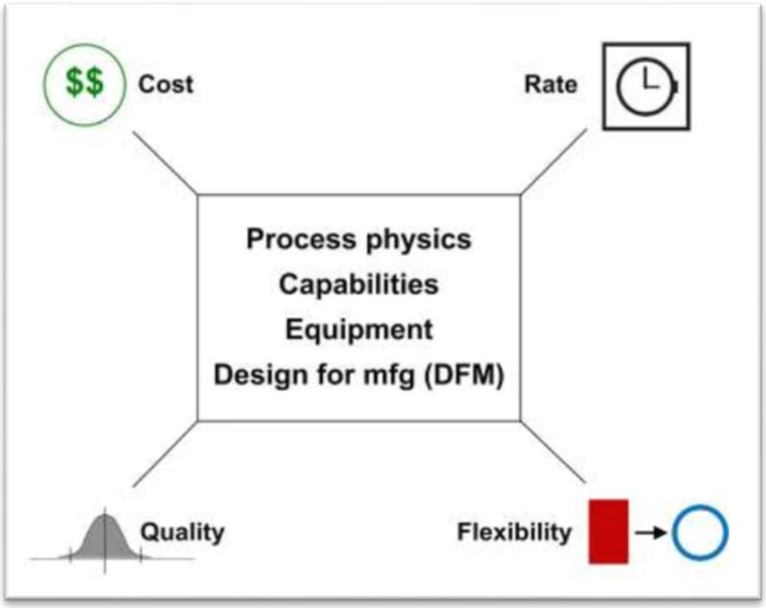

Figure 6. Rate, Cost, Quality and Flexibility Tradeoffs. Source: Hart (2016).

In a 2014 article published by Deloitte University Press, Cotteleer and Joyce describe how additive manufacturing part costs remain relatively constant over various production volumes, in comparison to variable costs for conventional manufacturing processes. Many conventional manufacturing processes require a high initial fixed cost; however, as production volumes grow, the high fixed costs can be amortized over the number of units produced, leading to lower unit costs as production volumes increase. Thus, many traditional manufacturing technologies are well-suited to produce high volumes of product consistently and cost-effectively. Additive manufacturing, on the other hand, possesses the unique capability to achieve minimum efficient scale at low production volumes—as low as one unit (Cotteleer and Joyce 2014). This unique attribute suggests that AM reduces the capital necessary for manufacturers to achieve economies of scale, which can allow many suppliers to enter into the manufacturing industry at lower risk and lower cost. This industry movement could expand small business opportunities for the Navy to increase competition and drive down spare part support costs. An illustration of the unit cost to production volume is provided in Figure 7. This trend suggests that AM is generally more cost-effective for producing low-volume production lots and for one-off tooling applications. Since the demand for Navy spare parts is analogous to the highly variable and infrequent demand signals facing the DOD at large, there is an opportunity for the Navy to exploit AM technologies to provide cost-effective sustainment solutions.

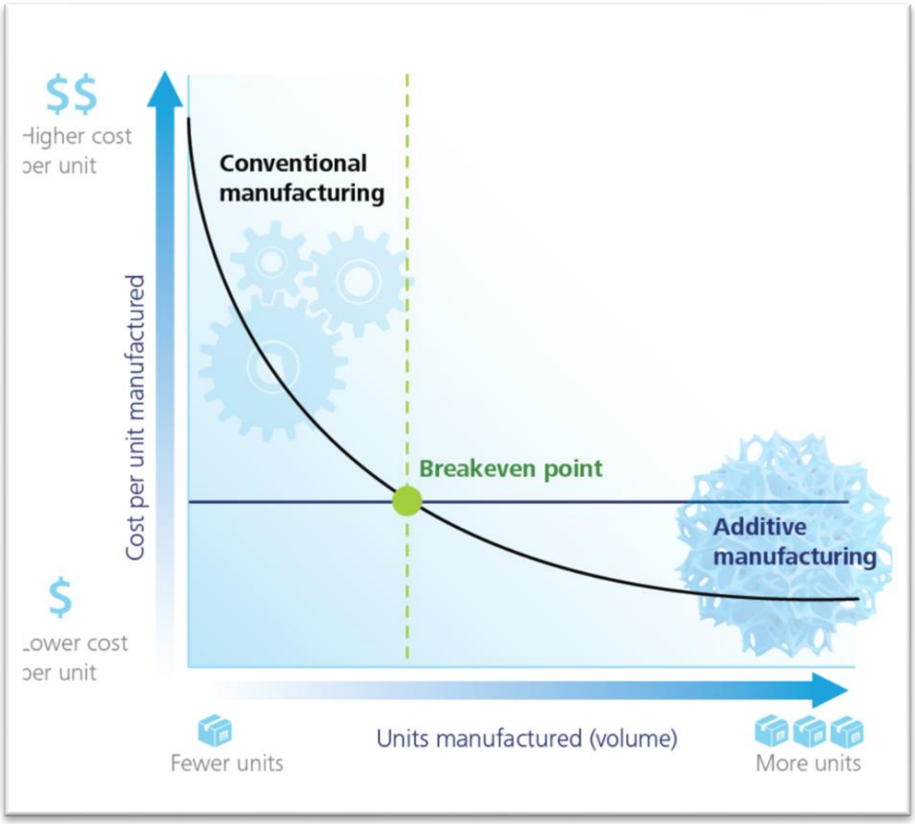

Figure 7. Break Even Analysis of AM. Source: Cotteleer and Joyce (2014).

Cotteleer and Joyce (2014) present a framework to model how organizations can leverage AM to achieve economies of scale and economies of scope. Economies of scale refer to the ability to reduce costs through high volumes of the same product, whereas economies of scope refer to the ability to reduce costs through product variety. Their AM business model framework is the result of relevant academic literature and case study reviews, as well as interviews with AM subject matter experts from government, industry and academia. Figure 8 provides an illustration of their AM business model framework. They present four tactical paths that companies can take to incorporate additive manufacturing into their supply chains. Most of the aerospace and defense industry has adopted path I, “stasis,” to leverage short-run productions and prototyping without making radical alterations to their supply chains. At present, it is generally beneficial to outsource AM applications to service bureaus rather than make large capital investments for in-house AM capability. This path takes advantage of AM’s ability to create low-cost, flexible design iterations to accelerate the product development cycle and minimize risks of rapid expansion. Therefore, if the Navy seeks to incorporate AM technology into their spare parts and repair service contracts in the near term, it is advantageous to develop an acquisition strategy that considers this business model.

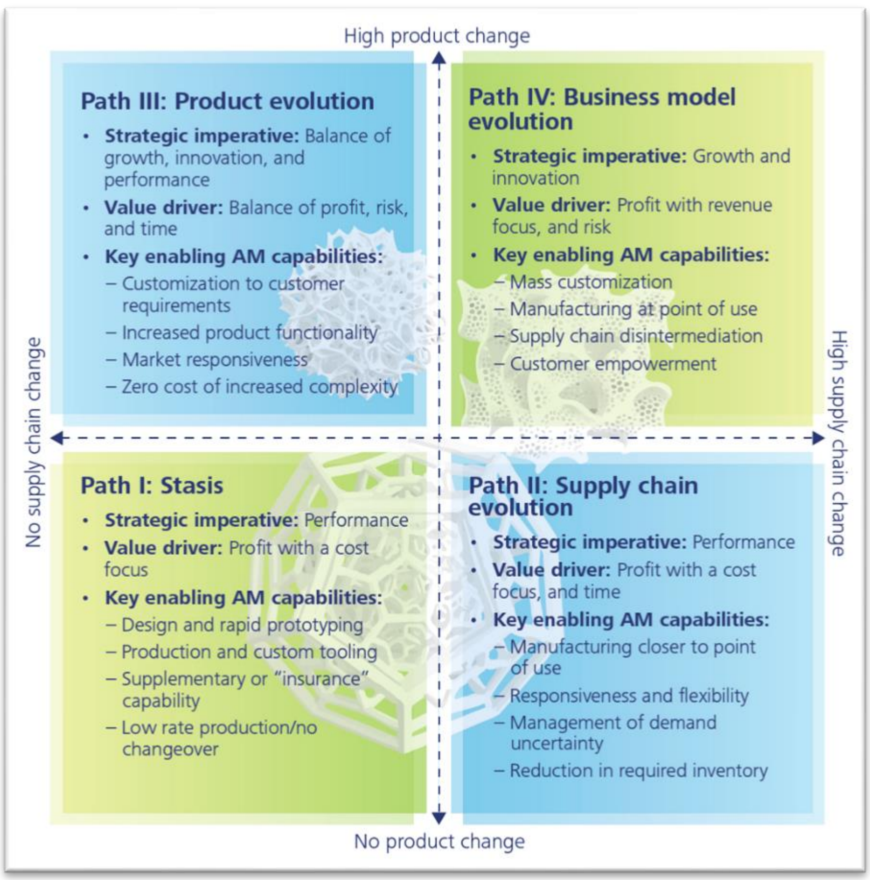

Figure 8. AM Framework for Scale and Scope. Source: Cotteleer and Joyce (2014).

According to Cotteleer and Joyce, over the next few years, aerospace and defense contractors will likely shift their strategic focus towards path III of the AM business model, “product evolution,” rather than drastically restructure their supply chain. In the product evolution path, defense contractors will exploit the benefits of economies of scope offered by AM, which will enable them to provide performance improvements not possible with conventional processes. As the variety of AM machines and materials expands, the cost to implement AM solutions will decline and allow manufacturers to explore alternative product designs and supply processes at lower risk. If the aerospace and defense industry shifts toward a path III, "product evolution" business model, the Navy may then have opportunities to source low-demand components without the need to make radical alternations to existing supply processes. This provides an opportunity to lower operations and sustainment costs for Navy weapon systems.

C. SYSTEMS ENGINEERING AND ADDITIVE MANUFACTURING

During the design and development of new products or systems, engineers must consider the tradeoffs to be made among cost, rate, quality and flexibility to identify the appropriate manufacturing process that will satisfy system and stakeholder requirements. The flexibility that AM offers over conventional manufacturing processes could enable the Navy supply chain to be more adaptive and responsive to the many challenges it faces, including sporadic demand signals, sudden loss of suppliers, performance degradation or sudden failure of equipment.

1. Spiral Model

In a 2017 handbook released by the Air Force Institute of Technology (AFIT), Shields and Valencia discuss how AM, coupled with systems engineering design methods, can provide the DOD with novel solutions to many unique and ever-changing requirements. In the AFIT AM handbook, Shields and Valencia show how a spiral systems engineering model is adopted for the design, manufacture, test and validation of an additively manufactured component. The spiral model provides a risk-driven cyclical approach to design, test, and validate alternate designs. Coupled with AM, the spiral model can accelerate system development and ensure that user requirements are met, including user supportability requirements for maintainability and spare parts support. Therefore, AM and the spiral model can be used collaboratively by systems engineers and logisticians to quickly assess alternate designs and their influence on downstream logistics support. This provides the Navy with the opportunity to incorporate AM in the system design to improve system maintainability and reduce the logistics footprint. Figure 9 provides an illustration of the spiral model.

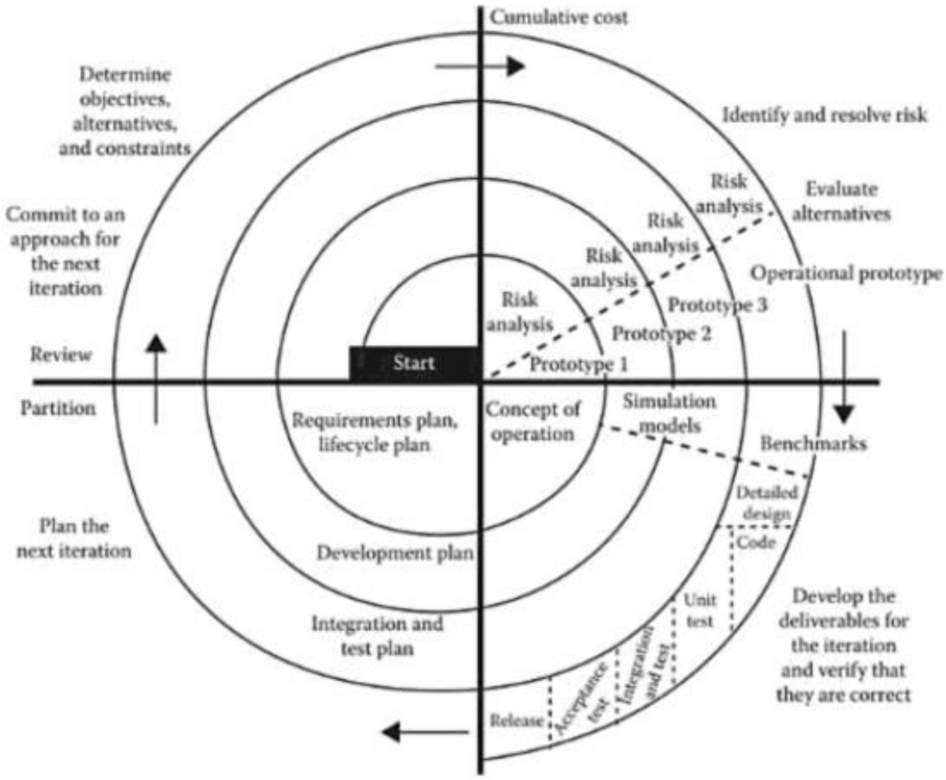

Figure 9. Systems Engineering Spiral Process Model. Source: Shields and Valencia (2017).

2. Bottom-Up Model

Use of AM and systems engineering methodologies early in the life cycle can reduce development times and costs. However, systems engineering provides a holistic perspective and considers downstream factors in the system life cycle as well, including reliability, availability, and maintainability. In the operation and sustainment (O&S) phase of the system life cycle, system reliability and availability often decline as systems gradually wear out and spare parts become obsolete. Additive manufacturing, combined with 3D scanning technology, can construct 3D models and physical prototypes for worn and obsolete components where limited technical data is available. The process flow of reverse engineering a component via 3D scanning is provided in Figure 10.

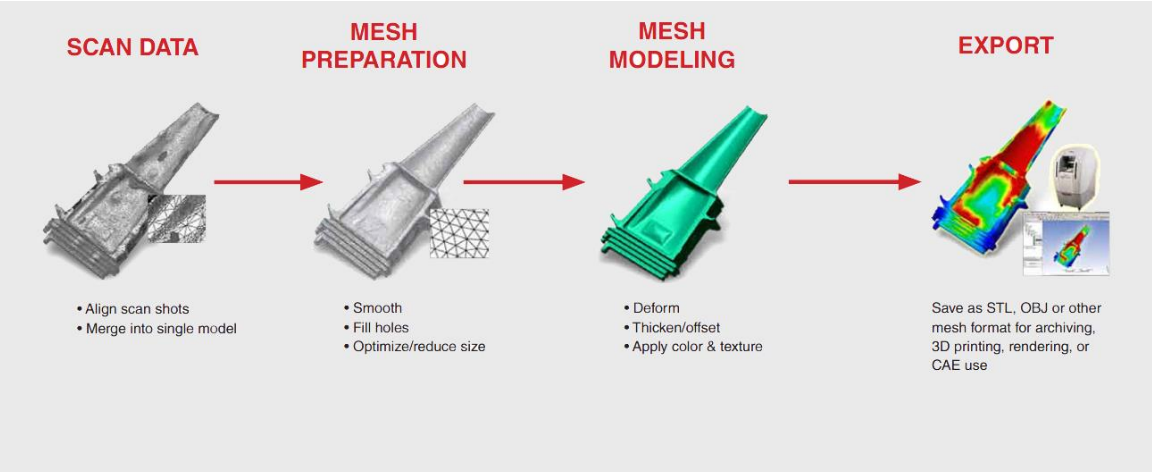

Figure 10. Reverse Engineering Process by 3D Scanning.
Source: Proto3000 (2017).

This capability to reverse engineer in-service systems and iteratively test prototypes could shorten cycle times and costs to implement engineering changes that utilize AM. In a 2015 article by Sara Sumner of Vitech Corporation, a bottom-up design approach is presented as well-suited for reengineering or reverse engineering a system. Sumner states that because legacy systems often lack appropriate documentation and technical data, reverse engineering will provide the requisite information to deduce design features with little knowledge about the original engineering design process. Therefore, in the case of identifying and reverse engineering a component to be redesigned for AM, a bottom-up systems engineering model is well-suited to derive higher-level requirements, while a spiral process model is appropriate to iteratively test and validate AM designs. Together, these models can improve supportability and provide needed spare parts to maintain Navy weapon systems.

The technical data available to engineers and logisticians in the sustainment phase of the system life cycle is often incomplete, which precludes a comprehensive evaluation for AM suitability. However, the Naval Supply Systems Command Weapon Systems

Support (NAVSUP WSS) and DLA can evaluate the spare and repair parts within the supply chain that satisfy the programmatic objectives for AM implementation; namely, the ability to reduce costs and lead times. From the initial screening, the cognizant engineering support activity (ESA) can utilize a bottom-up reverse engineering process to fill in missing technical data elements. Finally, a spiral model can be used to iteratively test prototype models to ensure the reverse engineered component will satisfy all physical, functional and performance requirements.

Additive manufacturing can provide value at any stage in the traditional system life cycle but incorporation early in system design provides greater potential for return on investment (ROI) in downstream logistics support. In the early stages of system development, AM design can leverage a systems engineering approach to validate designs through iterative prototypes, in which alternate designs can be manufactured and tested quickly in comparison to many subtractive manufacturing processes. In this sense, AM can be used to accelerate system development, reduce risks, enhance flexibility and improve system supportability. A 2012 article released by the Defense Acquisition University (DAU) states that "total ownership costs (TOC) incurred during the operations and support (O&S) phase may constitute 65 to 80% of total life cycle cost (LCC)" (Dallosta and Simcik 2012, 34–38). However, the early phases of system development solidify much of the system supportability costs. Therefore, use of AM prototypes early in the system development phase enables designers the flexibility to "design the support" and simplify downstream logistics support functions. This can greatly improve the supportability with regard to maintenance and spare part support for Navy weapon systems.

Additive manufacturing can also support on-demand manufacturing in a distributed supply chain network to produce components closer to the point of need. This leads to the potential for a reduced logistics footprint, reduced inventories, and reduced transportation costs. However, given the current state of the technology, it is often cost prohibitive to operate an AM supply chain as a decentralized network, as indicated in the research of Khajavi, Partanen, and Holmstrom (2013). Their research suggested, however, that distributed spare parts production becomes a viable configuration as AM machines become less capital intensive and more autonomous.

D. METHODS TO IDENTIFY AND PRIORITIZE AM APPLICATIONS

A 2016 publication by the Beta Research School for Operations Management and Logistics discusses the application of additive manufacturing in after-sales service supply chains. The selection and prioritization methodology of this study is based on the Analytical Hierarchy Process (AHP) and is dependent on information that is readily retrievable form internal or commercial databases (Knofius, van der Heijden, and Zijm 2016). The study suggests that AM offers numerous opportunities to aid in spare parts management, including reduction in manufacturing costs and increased supply chain responsiveness. The authors discuss how a bottom-up approach is employed to identify promising parts for AM in the after-sales supply chain. The bottom-up approach encourages an assessment of the benefits and technological feasibility to manufacture a part through an AM process. The authors note, however, that the bottom-up approach to identify AM candidates has its disadvantages. For example, the case-by-case evaluation will likely consider only a fraction of the parts in the supply system and many promising parts may be overlooked. Therefore, they propose a top-down approach to identify applications of AM if the spare parts supply chain.

The top-down approach proposed by Knofius, van der Heijden, and Zijm strives to rank candidate items based on various spare part attributes, as shown in Figure 12. Additionally, the authors suggest that process and material constraints that are imposed by the current state of AM technology must also be considered, which they refer to as "go/no-go" attributes. They identify material type and part size as the technical go/no-go attributes. If a candidate part can fit within existing AM machine build volumes and an AM available material can be substituted, then the candidate part would, at least from an initial technical feasibility standpoint, be considered a viable candidate. Decision makers would use the spare part attributes shown in Figure 11 as a first-pass method to prioritize potential AM parts.

		Improvement potential						
		Reduce manufacturing/ order costs	Reduce direct part usage costs	Reduce safety stock costs	Improve supply chain responsiveness	Postponement	Temporary fix	Reduce effect of supply disruptions
Spare part attributes	Demand rate	Low		Low		Low		
	Resupply lead time			Long	Long	Long	Long	
	Agreed response time			Short	Short		Short	
	Remaining usage period		Long					
	Manufacturing/ order costs	High						
	Safety stock costs			High		High		
	Number of supply options	Few			Few			Few
	Supply risk				High			High

Figure 11. Spare Part Attributes and Improvement Potential with AM. Source: Knofius, van der Heijden, and Zijm (2016).

The research of Knofius, van der Heijden, and Zijm uses a weighted system that took company goals into account, which could be motivated by different objectives. For example, industry may be interested in driving down component costs while the DON may be interested in reduced procurement lead-time. The weighted values will vary between organizations but the goals to be achieved through AM are likely similar, which include reduced material downtime, reduced costs, and secured stock. To test the top-down weighted selection process, Knofius, van der Heijden, and Zijm conducted a field study at a part supplier in the aviation industry with 40,330 spare parts. Using the go/no-go screening process based on company goals and part attributes, it was determined that 6,190 parts (15%) were technically feasible. Based on the findings of the top-down selection model, the surveyed company could already identify 1,141 cases that were technologically feasible and economically beneficial. Though this evaluation only constitutes about 2–3% of the part selected, the potential cost savings could be significant. These percentages will likely increase as AM technology matures and becomes increasingly integrated in system designs.

The work of Knofius, van der Heijden, and Zijm aids in the decision-making process regarding which spare parts may benefit from AM technology. Though qualitative in nature, the field study conducted with the top-down weighted selection model demonstrates the applicability of prioritizing large spare part assortments and makes the selection of spare part candidates more effective and efficient. Essentially, the most suitable candidates are those that are initially determined as technically feasible and then prioritized based on impact to organizational goals. When a technically feasible component aligns with organizational goals of reduced cost or reduced procurement lead-time, the item would be considered a viable component to evaluate for AM redesign. The field study revealed more than 1,000 technically feasible and cost saving opportunities for AM (2016). Additionally, this study reveals the practicality of using AM for after-sales service supply chains. This selection and prioritization model for commercial aviation spare parts is translatable to the aviation parts support needed to sustain naval aviation systems.

E. SIMULATION MODELS FOR AM COST EVALUATION

A 2015 dissertation from the University of Louisville J.B. Speed School of Engineering proposes a decision-making framework to decide whether use of additive manufacturing to produce spare parts on demand provides cost savings as compared to a conventional warehousing strategy (Jedeck 2015). The research study seeks to verify and gain new insight concerning the operations of AM and the associated cost implications in the spare parts supply chain. The conclusions of this study are supported by a discrete event simulation (DES) conducted in Rockwell Automation's ARENA simulation software program with the overarching goal to systematically verify the performance of additive manufacturing in the spare parts supply chain.

Jedeck's research (2015) includes a literature review of existing AM selection criteria and the development of a simulation model. Simulation provides a means to compare different configurations and material supply strategies using AM for spare parts supply. The variability of part attributes and supply data allow the simulation model to test multiple configurations and scenarios by means of adjustable parameters. The adjustable parameters of the model include part attributes, such a size and material, as well as AM machine attributes, such as cost and build volume. He determined that simulation was appropriate since a simulated model is inclusive of inherent supply system uncertainties that can be modeled with probability distributions. The simulation model proposed by Jedeck contributes to the body of knowledge for using quantitative analysis to assess AM suitability in the spare parts supply chain.

To understand the system, Jedeck presents a requisition process flowchart that incorporates an AM machine in addition to conventional warehousing procedures. This process flow diagram helps to visualize the flow of data and material, as well as identify the various elements pertinent to the simulation. This is a valuable first step in the simulation development process as it details the overall system, including functions and resource constraints. Figure 12 provides an overview of Jedeck's simulated system.

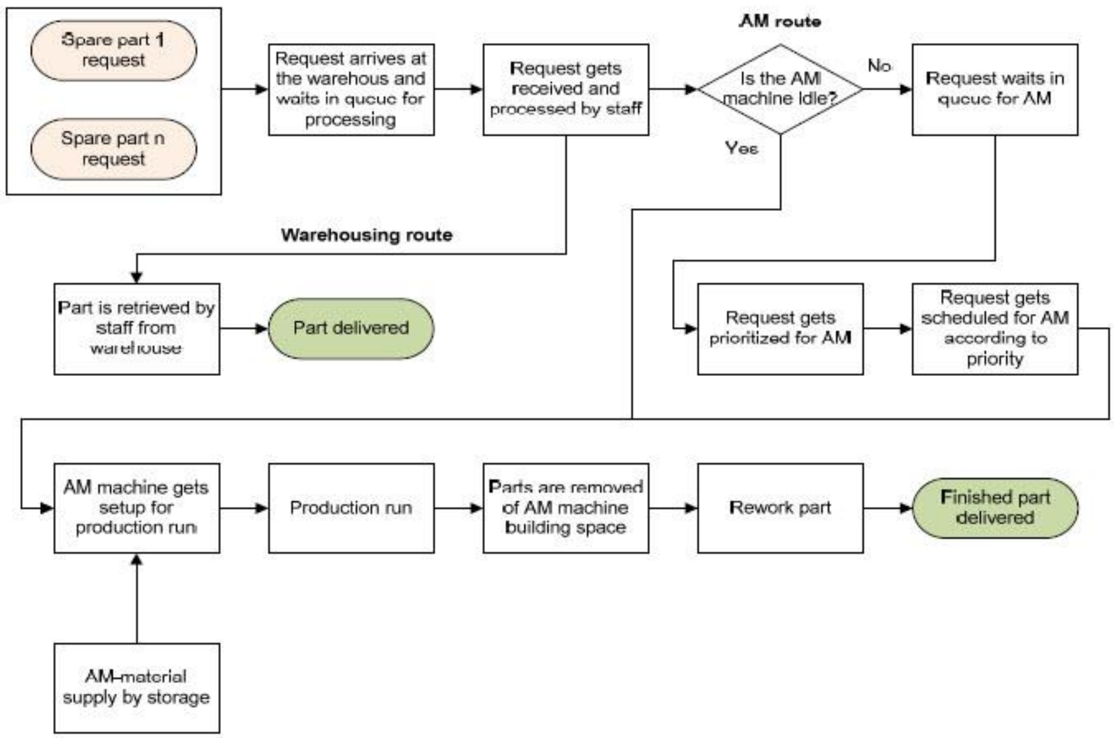

Figure 12. Process Flow of AM versus Warehousing. Source: Jedeck (2015).

After the creation of a model overview, Jedeck identifies the candidate part logistics attributes that are relevant to the model, including part description, stock on hand (SOH), material, unit cost, usage statistics, priority designation, geometric information, and procurement lead time (PLT). Warehousing data, such as inventory holding costs, are included when such data is available but otherwise will be approximated. Additive manufacturing data, including machine processing time, build volume, and materials can be incorporated into the model using data provided by the AM machine service provider. Finally, the model is translated into the ARENA software program to run a simulation. A sensitivity analysis is conducted by varying processing times, material costs, resource constraints and other attributes to see the effects of various AM scenarios and configurations. The simulation model is expandable to include multiple AM machines to process part requisitions.

The simulation model proposed by Jedeck provides a decision-making framework to evaluate cost-effective scenarios of using AM to manufacture spare parts, in comparison to traditional warehousing procedures. Additive manufacturing process performance and cost were evaluated to assess the viability of an AM process integrated within existing supply procedures. In his proposed scenario, the simulation model revealed that AM process performance performed equal to or better with the basic one machine solution than the warehousing configuration and was less costly. Jedeck noted that AM for on-demand production is more complex than traditional warehousing and the level of detail required for evaluation is much higher than traditional stock data. Therefore, a sufficient production strategy is necessary to incorporate AM and scenarios must be evaluated on an individual basis. However, the simulation model demonstrated that AM is a viable option to reduce part stock and associated inventory holding costs. For this thesis, this simulation model was adopted to evaluate potential cost and lead-time savings for aviation spare parts at Navy maintenance facilities.

III. THE NAVAL SUPPLY SYSTEM

A. OVERVIEW

An introduction to the current supply system and organizational structure is necessary to identify potential insertion points of AM technology into the Navy supply chain. The Naval supply chain is a complex system that involves the procurement, management, distribution and disposal of materiel assets. The Naval Supply Systems Command (NAVSUP) is responsible for all matters related to supply chain management and materiel support for the Department of the Navy and supports the Assistant Secretary of the Navy for Research, Development & Acquisition (ASN[RDA]) and the Chief of Naval Operations (CNO). Figure 13 provides a hierarchy of the Navy organization.

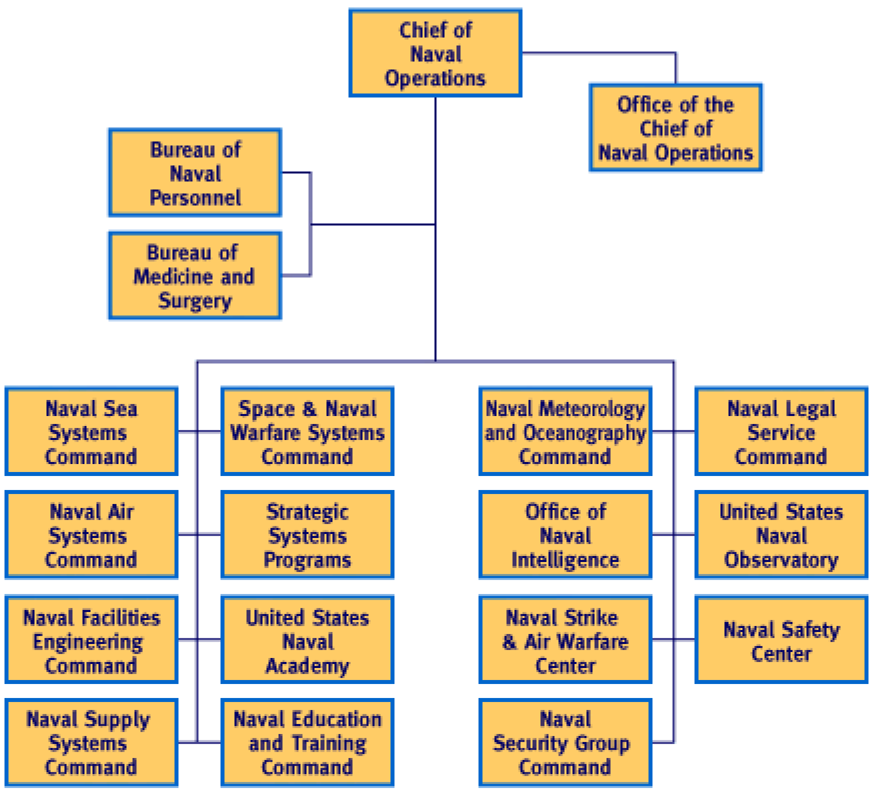

Figure 13. Navy Shore Establishment. Source: Department of the Navy (2006).

NAVSUP is responsible for the provisioning, cataloging, inventory management, distribution, material handling, transportation, packaging, preservation, receipt, storage, issue and disposal of Navy materiel (NAVSUP 2016). Within the NAVSUP command, the Naval Supply Systems Command Weapon Systems Support (NAVSUP WSS) is responsible specifically for the procurement and sustainment of military weapon systems equipment. NAVSUP WSS's stock management responsibilities include (1) position material at various locations based on demand, (2) retain inventory control of material assets, and (3) provide technical assistance to the supply system and the fleet (NAVSUP 2016). There are two NAVSUP WSS commands—NAVSUP WSS-Mechanicsburg, responsible for supply support for maritime weapon systems, and NAVSUP WSS-Philadelphia, responsible for aviation weapon systems. The eight fleet logistics centers (FLCs) stock and distribute NAVSUP WSS materiel assets. Together, the FLCs act as the primary point of contact to the operating forces for materiel support. Therefore, the FLCs are well positioned to stock and provide AM materials to sustain fleet operations.

When the fleet requisitions a material asset from the supply system, the designated FLC will issue the material from stock. There are, however, a number of avenues available to fill the order if material is unavailable at the supply center that received the initial requisition. If stock is unavailable, the FLC will refer the requisition to the cognizant NAVSUP WSS supply planner, who will then query the supply system for availability. If the desired asset is available at another supply center, that site will ship the material to the requisition point and issue a transaction report to NAVSUP WSS. After applying the issue transaction to its master record, the cognizant NAVSUP WSS supply planner will issue a contract to the appropriate original equipment manufacturer (OEM) or supplier to replenish the stock levels. After the receipt of contract from NAVSUP WSS, the material supplier will ship replenishment stock to the appropriate supply center and issue a transaction report to NAVSUP WSS to record the demand (NAVSUP 2016). In cases where the requisitioned material is unavailable in the supply system, the item will be labeled as backordered and the inventory control point (ICP) will pursue alternate methods of order fulfillment. Figure 14 provides an illustration of the requisition and issue process.

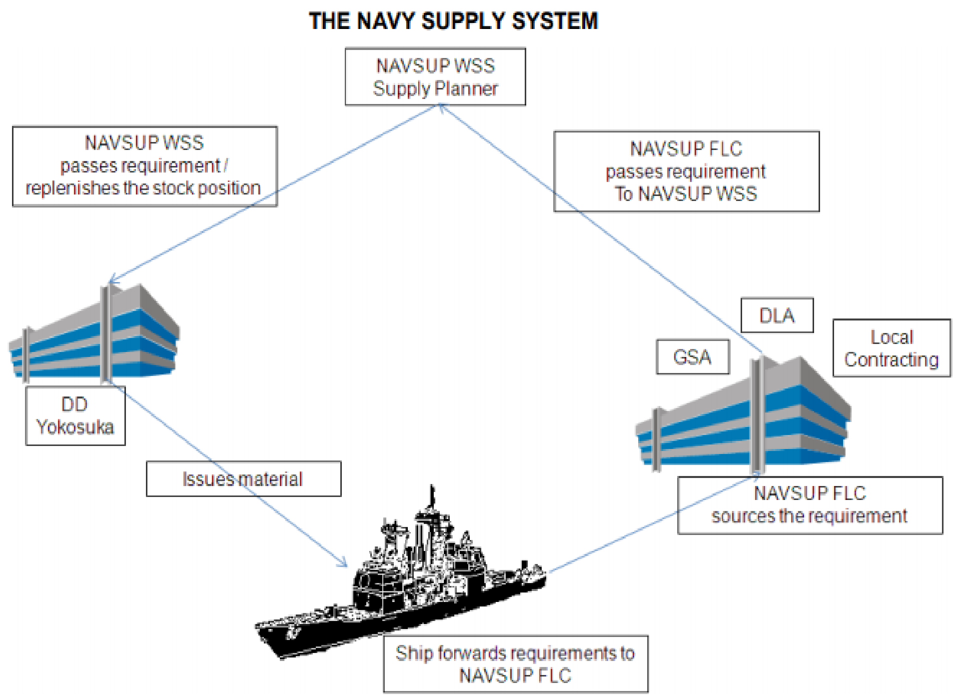

Figure 14. The Navy Supply System. Source: NAVSUP (2016).

The requisition and order fulfillment process illustrated in Figure 14 depicts the process for spares procurement and distribution; however, NAVSUP WSS is also responsible for the distribution and sustainment of repairable assets. The order flow process for repairable assets is similar, though instead of a requisition for material from the supply system, the requesting activity will return a failed asset to the supply system for disposition and will receive a credit for the value of the returned material. Fleet customers return assets that are beyond capable maintenance (BCM) to the supply system through the Electronic Retrograde Management System (eRMS). The repair facility for Navy-managed repairable assets could be a government-owned maintenance facility, such as a fleet readiness center (FRC), or a commercial maintenance facility. These maintenance facilities serve as potential insertion points for AM technology to improve material availability at the FLCs.

B. DOD AND NAVY AVIATION MAINTENANCE

The DOD maintenance system is comprised of three levels of maintenance: (1) organizational-level (O-level), (2) intermediate-level (I-level) and (3) depot level (D-level). O-level and I-level maintenance can be executed in forward deployed environments, whereas shored-based government or commercial repair facilities conduct depot-level maintenance. Figure 15 provides an overview of the levels of DOD maintenance. Depot-level maintenance can include the repair, purchase, or manufacture of repair parts and is often reserved for components that do not require frequent maintenance or for parts and assemblies that are highly complex.

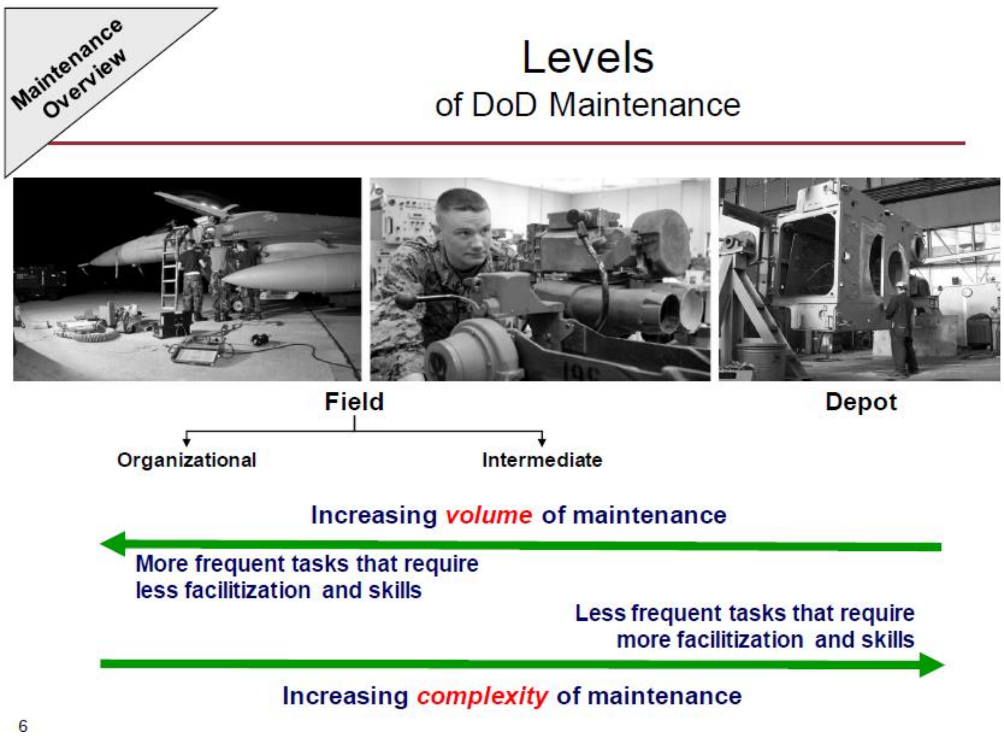

Figure 15. Levels of DOD Maintenance. Source: Defense Acquisition University (2011).

The Naval Aviation Maintenance Program (NAMP) details the maintenance and sustainment functions for naval aviation equipment. This instruction provides a standardized set of policies and procedures for the management of all Navy and Marine Corps maintenance activities. The fleet readiness centers (FRC), as well as industry suppliers and OEMs, complete aviation ***depot-level*** repairs for the Navy and Marine Corps. Together, the Navy FRCs and industry maintenance facilities overhaul and repair Navy weapon systems. Since AM has the potential to greatly accelerate spare parts production and tooling, these facilities are key insertion points for AM technology. Use of AM at maintenance facilities can greatly reduce the repair turnaround time for repairable assets and subsequently increase material availability at the FLCs. Figure 16 provides the locations of the Navy FRCs, which could be potential sites for government AM capability.

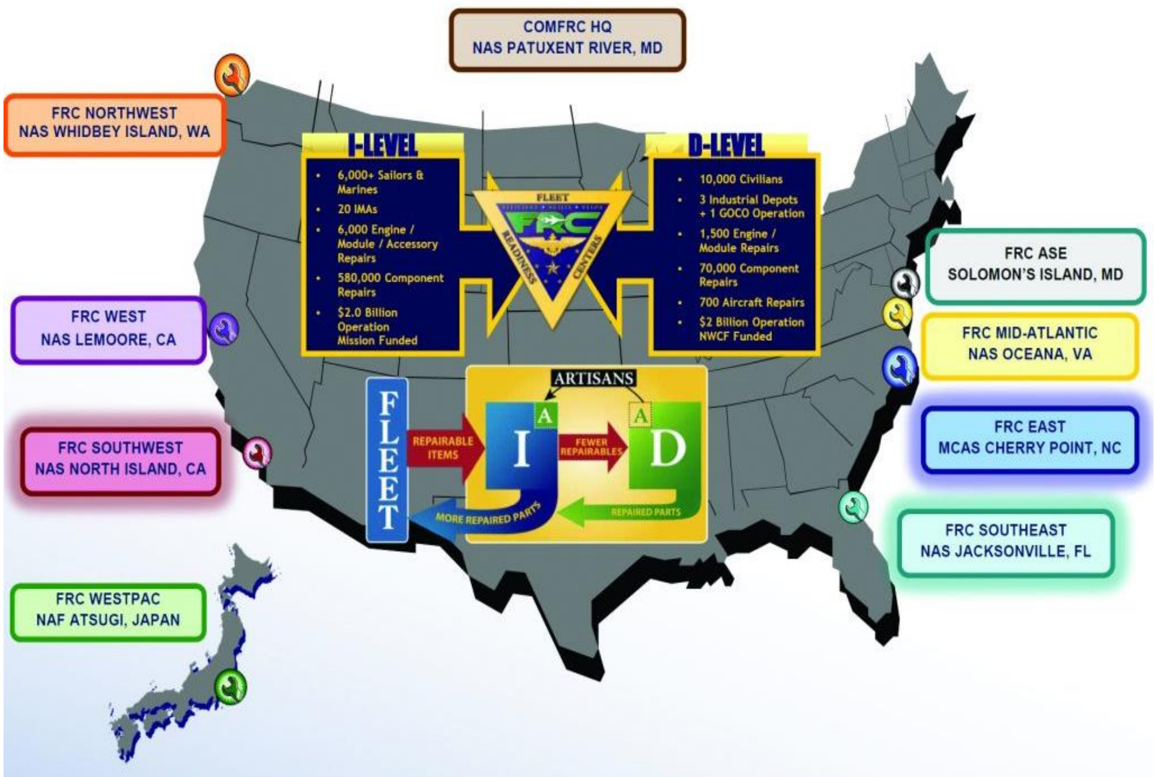

Figure 16. Map of Intermediate and Depot-Level Fleet Readiness Centers. Source: Ayers (2017).

The FRCs routinely requisition spare parts through the Defense Logistics Agency (DLA) to support the repair of failed weapon systems. When a fleet unit is in possession of an unserviceable AVDLR, the asset, also known as a "carcass," ships to the appropriate FRC for repair and disposition (Custard 2016). After a technician diagnoses the carcass, any repair spare parts that may be needed to restore the asset to serviceable condition are pulled from inventory. If there are spare parts that are not immediately available, the maintenance technician requisitions the needed parts through the supply system and places the failed asset in the awaiting parts (AWP) bin. Spare parts availability is a major problem for the Navy FRCs and a significant contributor to inoperability of equipment. AM provides an opportunity to accelerate spare parts manufacture to potentially reduce downtime of failed equipment.

NAVSUP WSS-Philadelphia is responsible for the management and distribution of AVDLRs, coded as 7R cognizance material, and Navy-managed aviation spare parts, coded as 1R. However, DLA manages most of the spare parts needed to restore 7R repairables to a serviceable condition; coded as 9B material (class IX repair spare parts). Therefore, the ability to restore failed weapon systems to a serviceable condition quickly and cost-effectively relies on the efficient operation of logistics support functions from NAVSUP WSS, DLA, and the FRCs. DLA maintains spare parts inventory at numerous distribution centers, both CONUS and OCONUS. Figure 17 provides a map of the DLA distribution centers.

Figure 17. Map of DLA Distribution Centers. Source: DLA (2017).

When a spare part is requested from an FRC to support a repair action, DLA issues the part from inventory. If there is no inventory available at a distribution center, DLA will purchase the needed component from industry through contracted acquisition procedures. A significant issue for DLA, and the NAE as a whole, are the unavailability of repair spare parts and the expansive operation of the Navy supply infrastructure, as highlighted in the map of DLA distribution centers. If the FRC needs a spare part, the cost and time associated with shipment from a distribution center may be well beyond budget and schedule requirements. Additive manufacturing provides an opportunity to produce needed spare parts closer to the point of need, which could greatly reduce transportation costs and delivery times compared to CONUS and OCONUS distribution.

C. ADDITIVE MANUFACTURING IN THE DON

To effectively communicate the benefits of AM and integrate the technology within existing operations, the DON chartered the Naval Additive Manufacturing Executive Committee (NAM EXCOMM) and developed an agency-wide implementation plan (SECNAV 2017). The Navy AM implementation plan was developed in response to a 2015 memo from the Secretary of the Navy (SECNAV) to explore additive manufacturing applications and how this technology could be used to improve readiness and sustainment of military systems as well as enhance warfighter capabilities. The AM implementation plan highlights key initiatives within the agency and articulates a strategy to incorporate AM technology across the organization. To accelerate adoption of AM technology, SECNAV tasked the Assistant Secretary of the Navy for Research, Development and Acquisition (ASN RD&A) and the Navy system commands (SYSCOMS) to develop an AM implementation plan that would outline strategies to achieve multiple objectives. The following objectives define strategic imperatives deemed necessary to effectively integrate AM within the DON:

- develop the capability to rapidly quality and certify AM components
- enable end-to-end process integration of secure on-demand manufacturing with integrated digital AM data, infrastructure and tools

- formalize access to AM education, training, and certification for the DON workforce
- develop responsive AM related business practices, contracting, intellectual property, legal and liability guidance
- enable manufacturing agility through low-volume production in maintenance and operational environments

The NAM EXCOMM is a stakeholder committee tri-chaired by the Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation (DASN (RDT&E)); the Deputy Chief of Naval Operations (CNO) for Fleet Readiness and Logistics (N4); and Deputy Commandant of the Marine Corps for Installations and Logistics (DC I&L)). The committee was chartered to advocate for resources to advance AM development, introduce AM capabilities across the DON, address necessary changes to DON policies, processes, and procedures, and outline the details of the AM implementation plan (SECNAV 2017). Additive manufacturing stakeholders across the DON convene annually at the Naval Additive Manufacturing Technical Interchange (NAMTI) to inform the NAM EXCOMM of current AM initiatives and to promote collaboration across the Navy SYSCOMS to achieve the objectives outlined in the implementation plan.

Since the inception of the NAM EXCOMM, the DON has taken steps to understand the benefits and limitations of AM and how to integrate this technology into existing processes to provide improved capabilities to the warfighter. The Navy organization has completed multiple projects to realize the strategic objectives outlined in the SECNAV implementation plan. In 2013, the Combat Direction Systems Activity (CDSA) Dam Neck, partnered with the Naval Supply Systems Command (NAVSUP) and OPNAV, led an initiative known as “Print the Fleet,” which was intended to provide AM capabilities to the fleet in a forward-deployed environment. The Print the Fleet initiative involved ashore support from CDSA Dam Neck as well as the installation of an FDM printer onboard the USS Essex (LHD-2) (Kohlmann and Lambeth 2014). As part of the Print the Fleet program, CDSA Dam Neck was able to utilize an iterative AM design approach to manufacture and supply a phone jack enclosure that was unavailable in the supply system. The phone jack enclosure was an obsolete component, yet widely used across surface ship classes. Through iterative AM prototypes, the CDSA Dam Neck engineering team was able to design, manufacture, and test a replacement part faster and cheaper than soliciting and qualifying an alternate source of supply. The ability to respond quickly to unforeseen system failures or spare part shortages would provide the Navy with a critical capability to enhance mission effectiveness. The Print the Fleet program was a critical step to enable manufacturing agility in maintenance and operational environments.

In July of 2016, the Naval Air Systems Command (NAVAIR) successfully flight tested additively manufactured safety-critical components on the MV-22 Osprey aircraft. As released in a 2016 new release, "this flight marked NAVAIR's first successful flight demonstration of a flight-critical aircraft component manufactured using AM" (NAVAIR 2016). The flight test conducted by NAVAIR was driven by the following objectives: to gain experience with AM technology and the associated post-processing; to establish an AM process to manufacture and test flight-critical components; and to assess avenues towards qualification and certification for additively manufactured parts (Kasprzak, Lass, and Miller 2017). The flight demonstration was a multi-phase effort that involved component identification, material and process characterization, component structural testing, including nondestructive and destructive testing, as well as flight testing in a controlled operational environment. Though many challenges lie ahead, the NAVAIR critical parts flight demonstration was a necessary step towards developing the capability to rapidly qualify and certify AM parts, as well as uncover the infrastructure and tools necessary to enable secure on-demand manufacturing with integrated digital AM data.

A key focus area of the SECNAV AM implementation plan is to enhance access to AM education and training for the workforce. Over the last few years, the DON has strongly promoted expansion of fabrication laboratories (Fab Labs) and makerspaces across the organization for both military and civilian personnel to deepen their understanding of AM and 3D manufacturing technology. In 2015, the Defense Advanced Research Projects Agency (DARPA) and the Navy deployed a Fab Lab at the Mid-

Atlantic Regional Maintenance Center (MARMC) in Norfolk, Virginia, under DARPA's Manufacturing Experimentation and Outreach Two (MENTOR2) program (DARPA 2015). In 2016, the Naval Surface Warfare Center, Carderock Division (NSWCCD) opened a facility for additive manufacturing, known as the Manufacturing, Knowledge, and Education (MAKE) Lab to provide its workforce with the tools necessary to design and build prototypes using 3D design and manufacturing technologies. The tools include access to computer-aided design (CAD) software and hobbyist-grade 3D printers. The MAKE Lab promotes an environment of knowledge sharing and collaboration to enable innovation through workforce development and facilitate greater science, technology, engineering and mathematics (STEM) outreach efforts (Diaz 2016). In addition to Fab Labs and STEM outreach, the DON has promoted joint-agency collaboration for AM projects and initiatives through knowledge sharing portals, such as the milSuite Navy AM working group and the Defense Acquisition University (DAU) Additive Manufacturing Community of Practice (COP).

One of the key focus areas identified in the 2017 release of the AM implementation plan is the development of a business case model to assess economic viability of AM components. This focus area includes the acquisition of new components as well as existing components in the Navy supply chain. While there has been a great deal of effort to operationalize AM within the Navy, there has been a lack of harmonized effort to evaluate Navy-managed in-service equipment for potential AM applications. While the vast majority of items within the Navy parts inventory were designed for conventional manufacturing processes, there may be opportunities to reduce inventory costs and improve part performance and reliability through AM processes. Without a standardized methodology to screen components, there may be numerous cost saving opportunities that go unrecognized. To support a business case analysis (BCA) for AM implementation, a proper selection methodology must be developed to analyze which components in the supply chain are most likely to benefit from the unique manufacturing flexibility provided by AM processes. Additionally, the various logistics elements, data rights and distribution networks within the Navy supply chain need to be identified to reveal insertion points for AM technology. This information will reveal opportunities to integrate AM solutions that align with DON supply support objectives, be they cost savings or improved materiel readiness.

The DON has recognized the many unique benefits offered by AM and how this technology could greatly improve warfighter readiness; however, there are many challenges the DON must overcome to effectively operationalize AM across the enterprise and identify opportunities that closely align with the department's strategic imperatives. Additionally, the DON must be cognizant of the current limitations with additive manufacturing and maintain realistic expectations for this technology. Gartner Inc., a business management consulting firm, releases an annual "hype cycle," which attempts to illustrate the transformation of the public's expectations for breakthrough technologies over time. As suggested by Gartner, many innovative technologies, such as 3D printing, experience a similar trend regarding expectations, where the innovation triggers rapid public interest, followed by a wane in expectations, and finally a gradual understanding of practical applicability. Figure 18 provides a diagram of the Gartner hype cycle. As illustrated in the hype-cycle diagram, 3D printing in the supply chain and 3D printing of consumable products are not anticipated to reach the plateau of productivity for another five to 10 years, as of 2015; however, there are realistic foundations the Navy can establish to be prepared for this technological evolution.

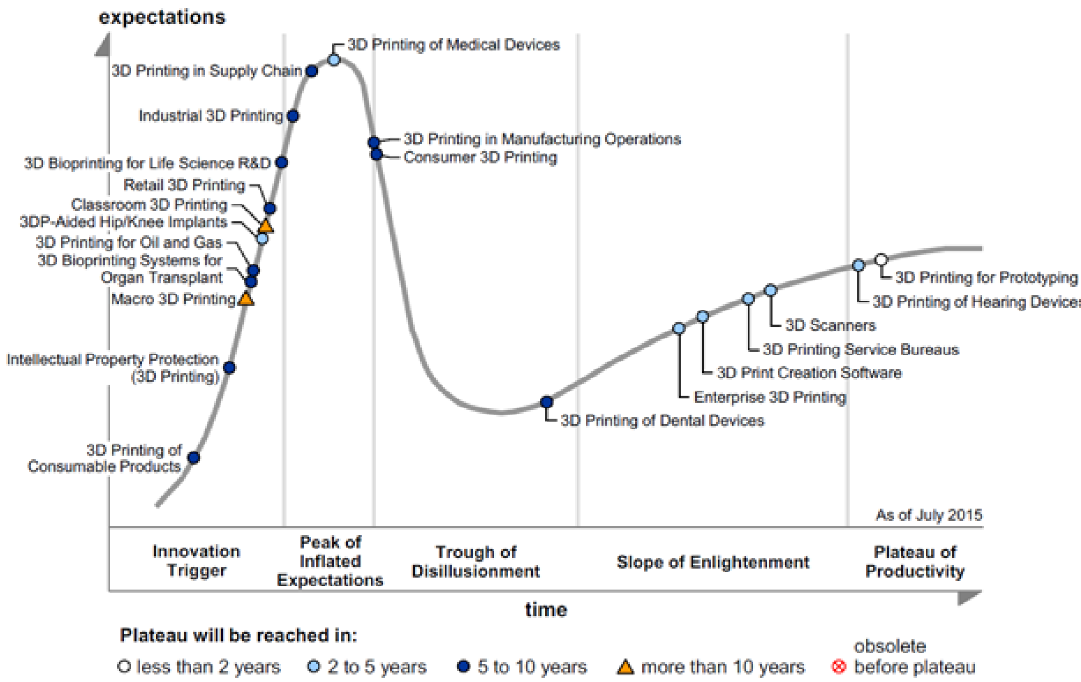

Figure 18. Gartner Hype Cycle for 3D Printing. Source: Gartner (2015).

Since AM technology is continuously evolving, the Navy must remain steadfast in its pursuit to align business practices to support AM, as well as develop the technical and logistics infrastructure necessary to enable integration of AM across the DON weapon systems life cycle. Additionally, the DON must develop solutions to address the supply chain and intellectual property (IP) infringement challenges imposed by AM. A 2015 GAO report entitled *3D Printing: Opportunities, Challenges, and Policy Implications of Additive Manufacturing* outlines several of these critical IP challenges (Persons 2015). The innovative business practices to adopt AM technology will require expertise from acquisition professionals across many career fields, including engineering, logistics, and contracting. In addition, successful development of the AM infrastructure requires collaboration among industry, government, and academia as well as between DON system commands (SYSCOMS). Consequently, in recent years, the DON has supported several initiatives to rapidly mature AM technologies and accelerate adoption of AM as an enhanced warfighter enabler.

D. IDENTIFICATION OF AM PARTS IN THE DOD SUPPLY CHAIN

In order to leverage the benefits of design flexibility and on-demand manufacturing provided by AM, it is necessary to understand the applications for which AM is well-suited. It is not always practical nor even possible to use AM to solve the many unique challenges faced by the Navy maintenance and sustainment communities. Spare parts within the Navy supply chain are components that were manufactured with conventional manufacturing technologies, including machining, forging, casting, and injection molding. Thus, components in the Navy supply chain are not optimized for an AM process, which makes it difficult for logisticians to parse the millions of components in the supply chain that may benefit from AM. To identify potential candidates, it becomes necessary to filter the inventoried parts based on technical as well as logistics attributes, if such data is available to the government. In most cases, the technical data available to the government is either not available or incomplete for competitive procurement.

In 2014, the DLA Research and Development (R&D) Manufacturing Technology Office supported the J34 Logistics Support Executive Directorate to investigate the applicability of using AM to manufacture DLA-managed class IX spare parts; categorized as consumable components used to support the repair of higher-level assemblies (Morris 2016). The research effort sought to develop a decision support process to identify which spare parts could be potential candidates for AM, as well as the technical and logistics information necessary to make an informed assessment of suitability. The Defense Logistics Agency funded a research effort with the Logistics Management Institute (LMI) in partnership with XSB, Inc. and the Penn State Applied Research Lab (PSU ARL), to develop a software tool that could screen the millions of components within the DOD spare parts supply chain for suitability for additive manufacturing (Parks et al. 2016). LMI had suggested that determination of whether legacy class IX parts would be suitable candidates for AM would require an in-depth understanding of both technical and logistics attributes for the millions of components in the DLA supply chain. LMI had identified material specifications, bounding volume and weight as critical technical attributes necessary to make an informed assessment.

Additionally, several logistics attributes were identified that were critical in the determination, including stock on hand, procurement contract type, procurement lead time (PLT), TDP availability, backorders, unit price and various acquisition codes.

To constrain the scope of the AM screening project, and given the limited availability of relevant data, LMI had made some simplifying assumptions. For example, the selection tool assumes that the legacy components screened would not be redesigned to take advantage of AM capabilities; that is, only items that could fit within existing AM machine build chambers and matched readily available AM materials would be identified in the selection tool. This assumption was largely due to the lack of a DOD certified specification, or "table of equivalencies" regarding AM feedstock materials that could be substituted for legacy part materials (Parks et al. 2016). Technical and logistics data was pulled from available resources, including the Federal Logistics Information Services (FLIS) database, the DLA Enterprise Business System (EBS) database, the Acquisition Streamlining and Standardization Information System (ASSIST) database, DOD E-MALL electronic portal, the General Services Administration (GSA) electronic portal, as well as from commercial data sources. The technical attributes, including material and bounding volume, were matched against AM machines and materials listed in the SENVOL database, a comprehensive online accessible database for industrial manufacturing machines and materials (SENVOL 2017).

The range of variables coupled with the scarcity of accessible online technical data inhibited the development of a fully automated decision support process. The Logistics Management Institute revealed that technical data was largely unavailable or was recorded in unintelligible 2D raster formats, rather the 3D parametric CAD files, which heavily restricted the autonomy of the process. However, LMI was able to develop an "AM prescreening" tool as a first-pass filter to quickly parse the millions of legacy parts in the DLA supply chain. The Logistics Management Institute noted, however, that potential candidates identified in the prescreening tool would still require an individual engineering review to assess a part's suitability to be manufactured through an additive process. The AM prescreening tool is accessible to authorized users as a web-based system and hosted by XSB, Inc. (Parks et al. 2016).

The maintenance and sustainment of military weapon systems is executed by a combination of government and private industry depots that receive repair and reissue material assets to the fleet to maintain mission readiness. However, the maintenance and supply functions executed by government and private partners during the operation and sustainment (O&S) phase are by far the most costly over the system life cycle, accounting for nearly 65–80% of the total life cycle cost (Dallosta and Simcik 2012, 34–38). Given the high costs of sustainment, both government and industry facilities are continuously looking to adopt innovative technologies that can drive down costs and minimize repair turnaround times. A 2016 Defense Acquisition University (DAU) article explains that opportunities for AM in sustainment apply to replacement parts as well as tooling and fixtures used to support repair procedures (Gaska and Clement 2016). Additive manufacturing technology also provides a unique opportunity to secure a distributed supply chain for rapid field delivery of components needed for forward-deployed maintenance purposes. Therefore, AM has many insertion points to support the sustainment of Navy weapon systems. This research effort, however, will focus on the opportunities to integrate AM within the aviation maintenance system; specifically in the support of aviation depot-level repairables (AVDLRs).

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IV. PROPOSED COMPONENT SELECTION METHODOLOGY

A. SCOPE OF RESEARCH EFFORT

This research effort investigated the applicability of using AM to manufacture naval aviation spare parts vice conventional warehousing procedures. The methodology proposed will not be a comprehensive evaluation of all parts in the naval supply chain, but rather, a down-selection of consumable components that have been identified as cost or readiness drivers within the maintenance and sustainment of AVDLRs. A top-down framework for evaluating all Navy and DLA aviation components is presented to encourage future research. To limit the scope of this effort, only Navy-managed aviation spare parts and those contributing to not mission capable due to supply (NMCS) AVDLRs at aviation depot-level repair sites were evaluated. Previous studies, such as the prescreening process demonstrated by LMI in the literature review, have evaluated DLA-managed spare parts. The spare parts selected in this research effort expand upon the data set of previous research efforts to include Navy-managed consumable material and FRC manufactured items. The data set, however, excludes repairables (7R material) and peculiar support equipment (PSE).

The item selection process for this research will be a two-fold effort. First, a selection process was developed that is structured around the research findings detailed in the literature review. A top-down selection process, similar to that of Knofius, van der Heijden, and Zijm was adopted to identify and prioritize spare parts that contribute to NMCS AVDLRs. Items were prioritized based on ability to achieve programmatic objectives. NAVSUP and DLA organizational objectives include reductions in cost and procurement lead-time (PLT). Thus, part cost and PLT were used as priority weight factors. Secondly, the relevant part attributes detailed in the LMI candidate parts selection study were used as an initial “prescreening” to filter the parts based on technical feasibility. Technical feasibility includes parts that match AM available materials and fit within existing AM machine build volumes. The technical characteristics of the down-selected parts will be screened against material and machine data within the SENVOL database to assess technical feasibility and serve as the "go/no go" decision; similar to that of Knofius, van der Heijden, and Zijm.

The alignment of manufacturing feasibility with organization goals will yield a list of viable items for further evaluation. A sample item with resultant attribute data was selected to run through an Innoslate discrete event simulation (DES), leveraging the ARENA simulation methodology developed by Jadeck, and is discussed in the next chapter. This component selection and subsequent simulation will provide the foundation for the development of a BCA model to assess economic and operational benefits of AM in the aviation spare parts supply chain. To begin the process, the relevant data elements, both technical and logistics, and data sources will need to be identified.

B. OVERVIEW OF THE COMPONENT SELECTION METHODOLOGY

To begin the component selection methodology, a process flow was developed to identify relevant data and data repositories. Figure 19 provides of graphical depiction of the envisioned data selection methodology. The component selection process was devised to extract batch logistics data from databases readily available to NAVSUP logisticians, including Navy Enterprise Resource Planning (ERP) and I.H.S. Haystack. This data would be filtered based on logistics attributes identified in the research of Parks et al. (2016) as relevant for AM candidacy. After the dataset is filtered, the components would be sorted by relevant programmatic objectives as discussed in the research of Knofius, van der Heijden, and Zijm; in this case, cost and procurement lead-time (PLT). Finally, technical data, if available to the DON, would be pulled from the Naval Air Technical Data and Engineering Command (NATEC) and Joint Engineering Data Management Information Control System (JEDMICS) aviation technical data repositories. Technical data includes data attributes identified in the literature review studies as relevant for an AM feasibility assessment, including material, component volume, and gross weight. The following sections detail the relevant logistics and technical data, and the mechanics of using the methodology.

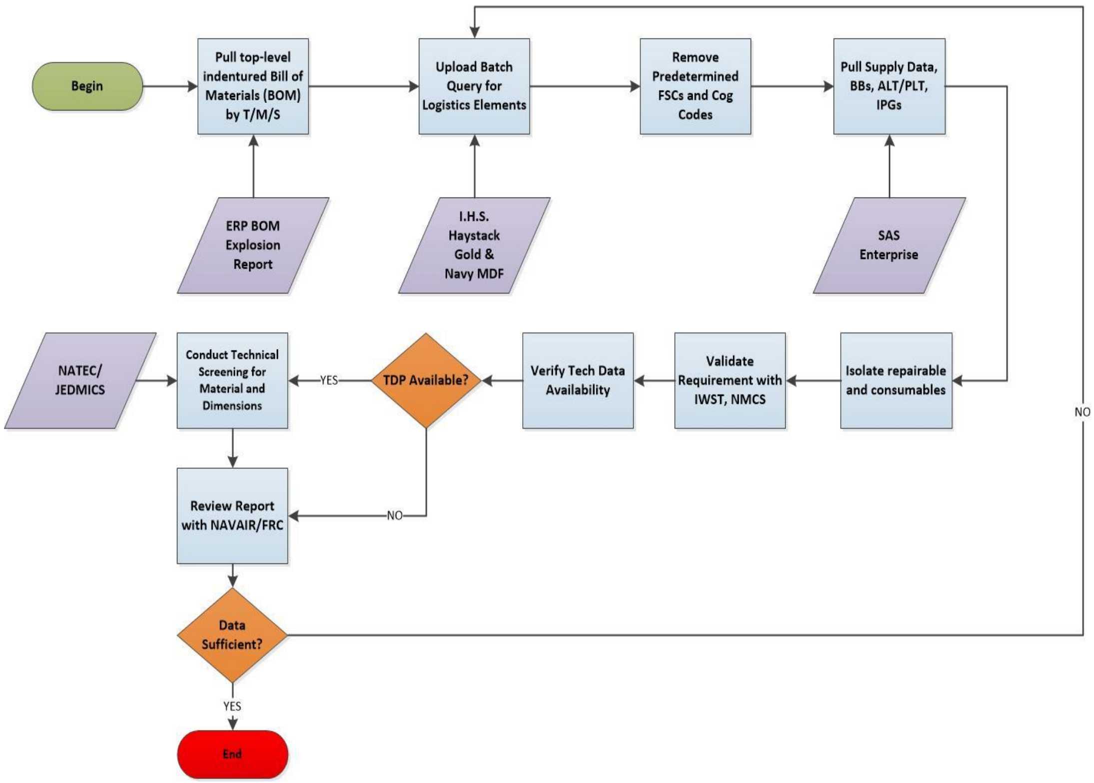

Figure 19. Envisioned AM Component Selection Methodology

1. Logistics Data Sources

Navy ERP and DLA Enterprise Business Systems (EBS) contain numerous logistics codes to identify acquisition, handling, distribution, and disposal procedures for stocked material. Some of the codes include acquisition advice codes (AAC), cognizance codes (COG), acquisition method codes (AMC), acquisition method suffix codes (AMSC), special material identification code (SMIC) and source, maintenance, and recoverability codes (SMR). Additionally, ERP and EBS contain information such as unit cost, lead times and demand. There are many logistics data elements needed to fully catalogue a component in the supply system, but only a select few will be necessary to screen for AM suitability. From a strictly logistics perspective, some of the most important data elements include cost, lead-time, demand, and data availability. The research effort between LMI and DLA presented in the literature review identifies several logistics elements as relevant for an AM prescreening. Table 1 provides a list of these data elements.

Table 1. Logistics Data Elements for AM Part Screening. Adapted from Parks et al. (2016).

Data Element	Code/Identifier	Description
Nomenclature	Nomen.	A description of the item
National Item Identification Number	NIIN	Nine digit code that uniquely identifies an item
Manufacturer Part Number	P/N	Part number assigned by OEM
Commercial and Government Entity Code	CAGE	Unique supplier identifier code
Cognizance	COG	Designated inventory management responsibility
Source, Maintenance and Recoverability	SMR	Procurement, maintenance, and disposal management for an item
Federal Supply Class	FSC	Identifies the commodity area and classification of the item
Procurement Lead Time	PLT	Time from purchase to delivery of an item
Administrative Lead Time	ALT	Time to process order from receipt of requisition
Local Routing Code	LRC	Identifies inventory manager
Acquisition Advice Code	AAC	How, and under what restrictions, an item is acquired
Acquisition Method Code	AMC	Purchasing technique assigned by inventory control activity
Acquisition Method Suffix Code	AMSC	Designated reason for AMC assignment; data rights/availability
Quarterly Demand	QTR	Number of requisitions for an item per quarter
Standard Price	Std Price	Unit cost to procure the item
Backordered	BB	Backordered item; no stock in inventory

2. Technical Data Sources

Much of the logistics data, including costs, distribution and packaging is contained within Navy enterprise resource planning (ERP). However, much of the required technical data is located within disparate systems. The Navy's primary repository for aviation technical data resides in NATEC, which contains technical publications, technical directives, engineering drawings, and associated data. Within NATEC, the JEDMICS repository contains detailed part drawings and associated lists. There are, however, several issues with these data sources. One challenge, in particular, is that even if the Navy is in possession of technical data, the data package may be incomplete or may not be easily converted into a 3D parametric CAD model to use for AM. Much of the legacy aviation data that resides in these databases are in raster graphics or PDF images, which are not seamlessly converted to 3D vector models necessary for AM machines. Therefore, the envisioned component selection process would first screen for technical attributes that can be pulled in batch queries from available government and commercial data sources. Such data sources include the DLA Federal Logistics Information Service (FLIS), I.H.S. Haystack Gold and the DLA Pin Point database. Any additional technical attributes that cannot be gathered from batch database queries must be pulled on a manual basis from the NATEC and JEDMICS data repositories.

3. Data Collection for Analysis

The conceived data collection process begins with a top-level bill of materials (BOM) data pull for each aircraft model managed by NAVSUP. This data query would include all Navy-managed material, both repairables and consumables, as well as DLA-managed material. This data pull consisted of thousands of line items for each aircraft model and would need to be extrapolated individually for each aircraft model. Rather than parse tens of thousands of items for each aircraft model, a sample dataset of Navy-managed aviation consumables was instead used for this research effort.

The data used to support this research effort was provided by the NAVSUP WSS Industrial Support department (code N983), and the Life cycle Management department (code N984). In total, three data sets were provided, totaling 10,162 items, which included all Navy-managed consumable aviation items, FRC local manufactured items, and DLA class IX (aka 9B) items that are contributing to NMCS AVDLRs. These data sets were combined into a single spreadsheet that was then used for further analysis. This combined data set was determined reasonable for the scope of this research effort for several reasons:

- The data set includes items that were excluded from previous studies, such as the DLA/LMI selection process discussed in the literature review.
- The data set includes all Navy-managed consumable aviation items, both stock numbered and serially managed (excluding PSE).
- The data is collected from repositories readily available to NAVSUP engineers and logisticians.
- The data set can be evaluated at the component level where material and geometric characteristics, when available, can be retrieved in batch queries.
- A bottom-up approach can be used to trace the data set to higher-level cost and readiness drivers.

4. Material Delay (G-condition)

One of the major contributors to delayed maintenance and not mission capable (NMC) aircraft is the unavailability of consumable spare parts to support repair efforts. Inventory management responsibilities of stocked materials are identified by their cognizance code, or COG. Navy-managed consumable aviation parts are designated as 1R and DLA-managed consumables are coded 9B. Navy-managed AVDLRs are coded as 7R. When a failed AVDLR (7R) is inducted and requires a new part for repair, the technician will pull available inventory from the shelf or requisition the material through either DLA, for 9Bs, or the Navy supply system, for 1Rs. If no inventory is available in the supply system, the item is backordered and the 7R asset is awaiting parts (AWP). Therefore, unavailability of consumable spare parts to support repair efforts is a significant contributor to degraded weapon system readiness and creates many work in process (WIP) cases. After assets are AWP for 45 or more days, they are labeled as "G-condition." The FRCs provide NAVSUP WSS with monthly lists of G-condition material. This list, referred to as *material delay*, is a good starting point for an AM suitability study for several reasons; namely, the parts are unavailable in the supply system, there is actual demand for the parts, requisitions are likely in low quantities, and the costs of inoperable higher-level systems may justify the costs of redesign for AM.

The G-condition material delay was used to screen for AM suitability, with some additional data elements pulled from other data repositories, including Navy ERP and DLA EBS.

5. Navy-Managed Spares and Organic Manufacture

In addition to G-condition spare parts, the NAVSUP WSS Life cycle Management department (N984) provided a list of Navy-managed aviation consumables (1R) and depot-manufactured items. The list contains all 1R items in Navy ERP, as well as non-catalogued items that are source coded as MD. Source, maintenance and recoverability (SMR) codes are used to communicate maintenance and supply instructions to the various logistics support levels for equipment and end-items (NAVSUP 2017). All DON supply parts contain an SMR code, which designates the lowest level authorized to remove, replace, maintain and dispose of an asset. Items that are source-coded MD are items that are manufactured at the depot maintenance level. These items are frequently referred to as “part number buys,” as they are not catalogued by national stock number (NSN) in the supply system. When an MD source coded item is needed, or a local manufacture requisition is received from DLA, the FRCs will follow a multi-step process to manufacture the part. The diagram shown in Figure 20 was taken from a Naval Postgraduate School (NPS) research study and shows the top-down process to manufacture a part at a depot facility (Kenney 2013).

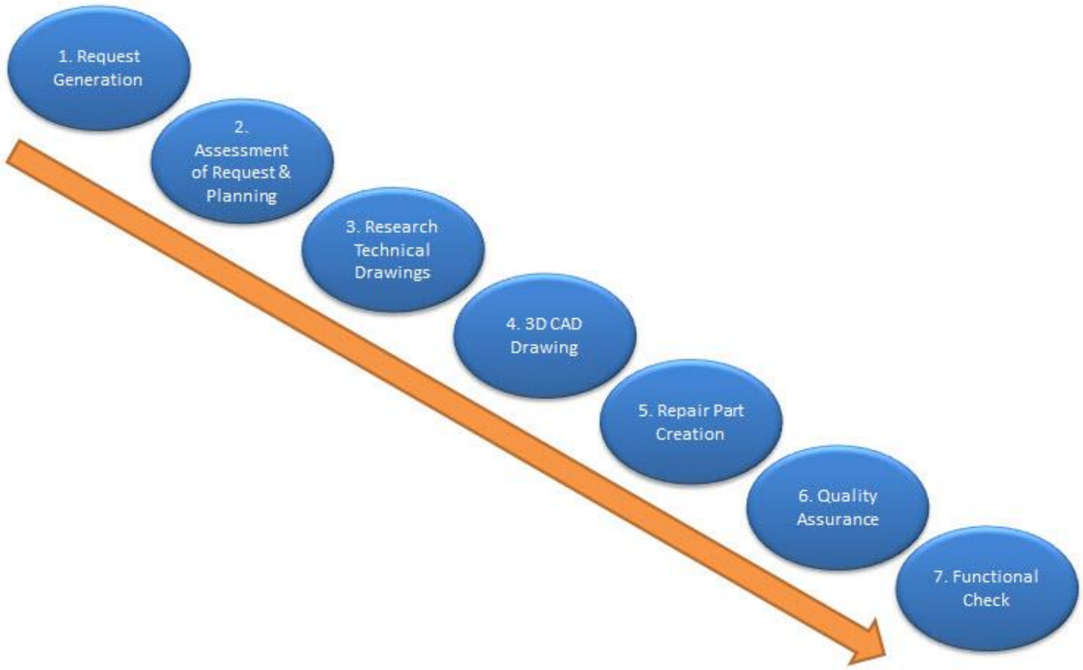

Figure 20. FRC Repair Part Manufacturing Process. Adapted from Kenney (2013).

As shown in the diagram above, the process is initiated when a request for manufacture is sent from DLA to an FRC. DLA initiates the process when there is a requisition for an item that is not available in inventory and the FRC is in possession of sufficient technical data and manufacturing capability to provide the item. The MD source coded items were determined to be a valuable data set to screen for AM candidacy, as these parts can delay repair capabilities and are generally fabricated in low quantities. Additionally, adequate technical data exists for these components to be manufactured at an FRC. Additive manufacturing may be a valuable alternative for such components, particularly those with complex geometries or manufacturing procedures.

C. APPLICATION OF THE METHODOLOGY

For this research effort, the technical and logistics data elements identified in previous studies are used as an initial screening for AM part suitability. Additional information such as quarterly demand and procurement cost over a two-year period were pulled form available data sources, including the Federal Logistics Information System (FLIS), Navy ERP, and DLA EBS. To begin, the data sets provided by NAVSUP WSS were combined into a single Excel spreadsheet; this includes the G-condition material, Navy-managed 1Rs and MD source-coded items. This spreadsheet was created so that the selected items and associated data elements could be uploaded into the subsequent simulation model. Figure 21 provides a graphical depiction of the data amalgamation.

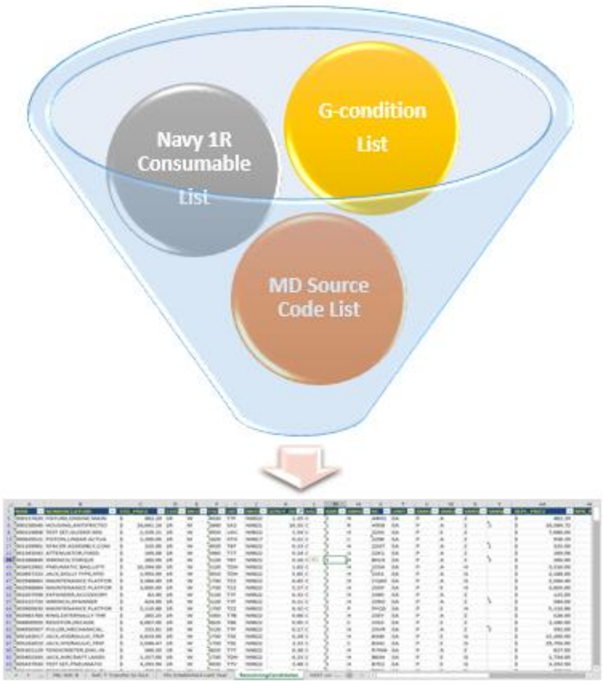

Figure 21. Combination of Consumable Aviation Data Sets

The data elements identified as necessary for initial parts screening will be used to filter down to several components that are amenable to AM from a technically feasible standpoint, as well as items that align with organizational goals of reduced cost and lead-time. To accomplish this, any missing technical and logistics data elements from the combined 1R, MD, and G-condition lists were obtained via a batch data query using the NAVSUP SAS Enterprise software program to extract data from the Navy ERP system. Data filters were then applied to the data elements in the spreadsheet to exclude nonstructural components, based on federal supply class (FSC) codes, and any items for which there was no quarterly demand (i.e., no material requisitions). Pivot tables were used to sort items based on unit cost and PLT to identify candidates that show the greatest potential to improve programmatic objectives of cost and lead time reductions. After the list was filtered and prioritized, technical attributes, including item material, gross weight, and bounding dimensions were added. In many cases, technical data, particularly part material, was unavailable in Navy ERP and could not be extracted via a batch query. Therefore, if material data was unavailable, it was extracted manually from the NATEC or JEDMICS technical data repositories. Items for which no technical drawings were available in JEDMICS were removed from the list. Finally, the material data and dimensions for the listed items were juxtaposed against AM materials and machines listed in the SENVOL database. Items that had an AM material match and fit within AM machine build parameters were considered technically feasible. An illustration of the item down selection process is provided in Figure 22.

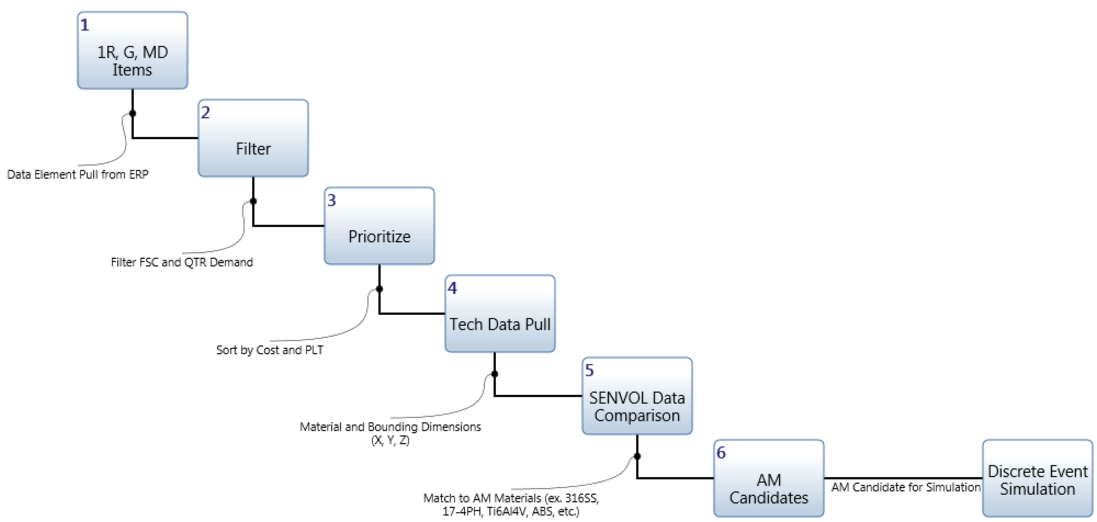

Figure 22. Sequence of Data Filter Steps

The down-selection process resulted in five potential items to be considered for further evaluation. A sample item was selected to run through a simulation model in Innoslate to assess economical and operational benefits compared to traditional supply processes. The results are discussed in the next chapter.

1. Additional Assumptions

Several key assumptions were made during the component selection process. First, items that had a quarterly demand of zero over a two-year period were assumed to be poor candidates, as there is no anticipated need for such items; however, there could be rapid spikes in demand for such items in the future. This assumption was made largely due to the labor-intensive manual technical data pull, so limiting the item selection to a manageable data set was determined necessary. Secondly, it was assumed that cost and procurement lead-time were the most highly valued programmatic attributes and were equally weighted, though this may not always be the case. Thirdly, items were selected based on matches with materials that are listed in the SENVOL database; however, new materials continuously emerge and may expand the set of parts in the future. It was assumed that the existing part material had to match a readily available AM material feedstock, though this ignores the possibility of material substitutions. Any component that would be selected for an AM process would inherently require some level of redesign and would be manufactured using an alternate precursor material than was used for the original part. For example, a 316 stainless steel component manufactured via an additive process with AM precursor materials would exhibit different properties than a 316 stainless steel component machined from bar stock due to variations in the process physics and precursor material characterization. Therefore, a material match is not a direct *equivalency* and will not always be necessary to consider a part for a legacy component to be considered for AM redesign. However, due to the lack of engineering data available to NAVSUP engineers and logisticians, a material match was assumed to be necessary.

2. Limitations of the Methodology

Availability and accessibility of technical data is a significant constraint in the component selection process and prohibits a comprehensive evaluation of the aviation spare parts supply chain by DLA and NAVSUP engineers and logisticians. However, there can be an initial evaluation of the Navy spare parts inventory that identifies high cost, long lead-time and low demand items that may be suitable to existing AM materials and processes. Though technical data availability is a limiting factor in the component selection process for NAVSUP engineers and logisticians, it does not preclude a complete evaluation of technical suitability, as that authority resides within the engineering support activity (ESA). Ultimately, a comprehensive technical feasibility assessment and “go/no go” concurrence would require support from the hardware SYSCOM ESA.

V. DISCRETE EVENT SIMULATION ANALYSIS

A. DATA AND COMPONENT SELECTION

Using the data retrieved from the component selection process, a candidate item was selected and run through a discrete event simulation (DES) model in Innoslate that simulates the cost to manufacture via AM compared to traditional part warehousing and order strategies. The model considers the cost and lead times associated with spare part procurement and local spare part manufacturing. The intent of this simulation is to provide a framework that can provide insight into AM costs and lead times vice traditional supply support strategies for naval aviation spare parts. The model employs a combination of empirical data and notional data. All parameters within the model are customizable to simulate alternate configurations and scenarios. The item chosen for simulation analysis has been down-selected using criteria that align with programmatic objectives and technical feasibility. The selected component is a high cost item with long lead time that fits within AM material and process constraints of existing AM technology, as taken from the SENVOL database. Part data is provided in Table 2. Additionally, the selected part exhibits a highly variable infrequent demand pattern, as illustrated in Figure 23.

Table 2. Sample Part Technical and Programmatic Attributes

Technical Attributes	
Material	17-4 PH Steel
Material Specification	SAE AMS 5643
X dimension (largest)	5.22 in
Y dimension	5.22 in
Z dimension (smallest)	3.164 in
Gross weight	6.5 lbs
Program Attributes	
Procurement Lead Time	545 days
Production Lead Time	365 days
Administrative Lead Time	180 days
Unit Price	$ 7004.77

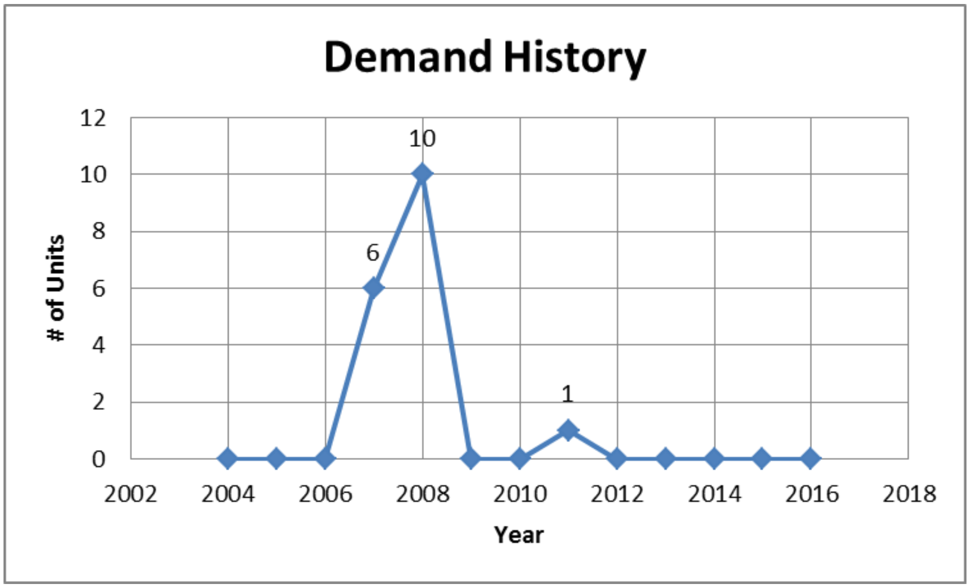

Figure 23. Sample Part Demand History

B. MODEL FORMULATION

An activity diagram is useful to map the process flow for a spare part requisition needed to complete a repair action at an FRC. A well-constructed process flow provides insight into the actions needed to complete a repair action, as well as the cost and resources consumed in the process. Figure 24 provides a process flow for a repairable asset received at an FRC. The activity diagram in Figure 24 was modeled in Innoslate. The model is a simplified representation of the spare part requisition process needed to complete a repair; however, actions can be further decomposed to provide deeper insight into the repair process. For example, labor and overhead costs can be incorporated and resource consumption can be expanded to include more than just the spare part needed to complete the repair. Such additions were determined to be outside of the scope of this model and were therefore not incorporated; however, additional information can be incorporated to improve the accuracy and robustness of the simulation model. In Figure 24, actions are denoted by grey blocks, resources are in purple, and any inputs/outputs, such as purchase orders and maintenance plans are denoted by green blocks.

The activity diagram begins with a repairable asset inducted for repair. At this point, the asset is in queue, awaiting a failure diagnostic assessment from the FRC technician. The FRC technician assesses the failure based on the equipment maintenance plan and provides disposition. The failure assessment will reveal if a spare part is needed to restore the asset to a serviceable condition. At this point, there is typically one of three routes that can be pursued to obtain the part. If it is assumed that the spare part needed is available locally, the part can simply be pulled from the shelf and the local inventory will be decremented. If there is no inventory readily available on the shelf, the technician can place an order through the supply system. There are a number of supply support options available to fill the order, including issue from inventory, lateral support, or direct vendor delivery. This model assumes that no inventory is readily available in the supply system and the requisition is backordered. The part order will be filled by an order to the OEM or other qualified sources on file. Lastly, if the part is not available in local inventory or through the supply system, the component can be manufactured, assuming the requisite technical data is available for the FRC or a component manufacture to produce the part.

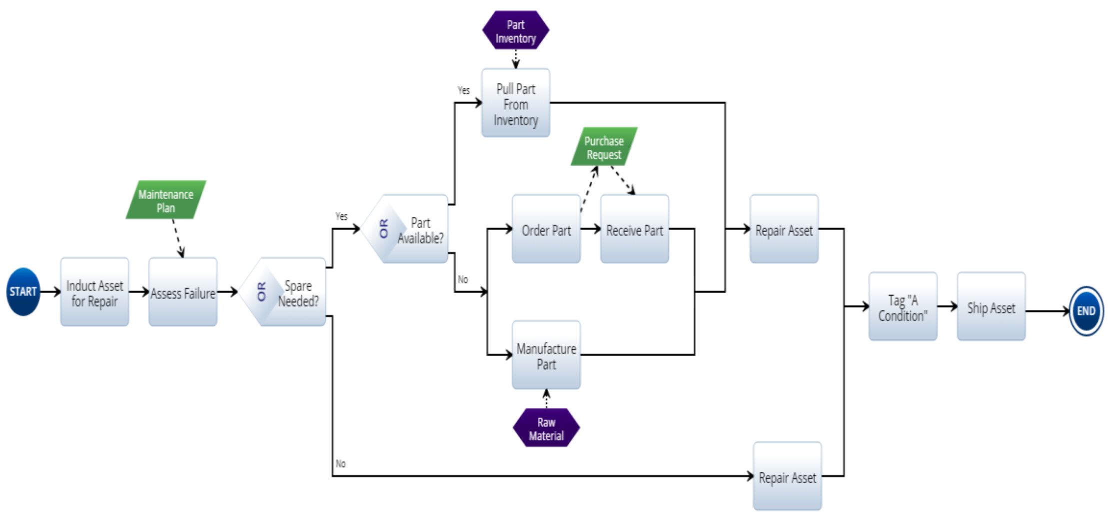

Figure 24. Activity Diagram for the FRC Repair Process

To gain insight into the costs and lead times associated with each supply option, a simulation was run, beginning with the spare part requisition. Cost and resource attributes were incorporated into the model for the various supply routes. The attributes of the AM manufacture route were decomposed to provide deeper insight into the costs and lead-times associated with the AM process. For the AM route, much of the cost and lead-time attributes were estimated based on data published by AM equipment and material providers. However, each of the attributes defined in the model can be modified to simulate alternate AM materials and processes.

1. General Assumptions

There are several key assumptions that were made in the development of the simulation model. First, it is assumed that the material requisition follows a probabilistic distribution. In this test case, a uniform distribution is used to simulate the requisition process. According to Kelton, Sadowski, and Zupick (2010), a uniform distribution provides a worst case setting when little data is available (Kelton, Sadowski, and Zupick 2010). Empirical data, when available, can be substituted into the model to improve lead-time accuracy.

Second, the model assumes that the requisite technical data is available to manufacture the part via an AM process and that it is technically feasible to do so. It assumes that a 3D parametric CAD file exists, all product manufacturing information (PMI) is available, and a production-level TDP is complete. This assumption neglects the cost and time required to reverse engineer a legacy component to obtain a 3D model and redesign for AM. An activity block with approximations can be incorporated into the model to account for costs and lead times associated with reverse engineering. The DOD SD-22 DMSMS Guidebook provides guidelines and estimates for alternate supply strategies (DSPO 2016). According to the SD-22, “many items can be reverse engineered in three to six months, but some take much longer.” (DSPO 2016, 65). Additionally, costs can vary considerably depending on the criticality of the item and the level of qualification that is necessary. Since much of the data necessary to conduct a reverse engineering assessment was unavailable to NAVSUP engineers and logisticians, it was assumed to be outside of the scope and omitted from the model. However, reverse engineering cost and lead-time data can be incorporated into the model to improve accuracy.

Lastly, the model assumes in the part order scenario that no stock is available in the supply system or at a vendor site. Therefore, the item is assumed to be backordered and a purchase order is issued to the OEM or qualified suppliers for manufacture. Production lead-time (PLT) and administrative lead-time (ALT) for the selected component is used to simulate the order fulfillment process. It is also assumed that the supplier provides the part and does not "no bid" the requisition.

2. Goals

Given the high degree of variability between parts in the supply chain, simulation was determined to be reasonable tool to assess an AM supply strategy. The goal of the DES model is to provide a framework to evaluate the cost and lead times associated with additive manufacturing in comparison to traditional material supply strategies. The model provides a simplified representation of the process flow to obtain a spare part to complete a repair action at an FRC and compares three supply support strategies, including local supply, requisitions filled through the Navy supply system, as well as local FRC manufacture. The model was designed to include flexible parameters that can be modified to simulate alternate parts and supply configurations. When available, empirical data was included to simulate a realistic test case. It should be noted, however, that the DES provides insight into costs and lead times associated with AM, though a real AM configuration would be required to validate the process. The simulation was designed to be expandable and any additional data elements, including labor costs, warehousing costs and machine performance parameters can be included to improve the robustness of the model.

3. Model Parameters

The action and resource blocks within the FRC repair process flow contain cost, lead time and material attribute data to simulate incurred costs and process time. Each material routing process in the DES model contains data relevant to the particular supply method. The sample part detailed in Table 2 was run through the model to evaluate cost and lead time tradeoffs among the various supply support strategies. In this model, there are three routes that can be taken to provide the part: (1) pull part from local inventory,

(2) order part from OEM/supplier or (3) manufacture via AM. Model parameters for each supply route are detailed below and can be adjusted to reflect alternate configurations.

a. Part Pulled from Inventory

The first route in the model, shown in Figure 25, assumes that the sample part is readily available in local inventory. The spare part is pulled from local inventory and the inventory resource block is decremented by one unit. The time required to pull the item from local inventory is approximated at 30 minutes. This time is arbitrary, but is considerably smaller than the time associated with part procurement or additive manufacturing. The cost associated with the local inventory supply includes the unit cost of the sample material and inventory holding cost. In this scenario, the sample part has a unit cost of $7004.77, as shown in Table 2. The inventory holding cost is approximated using an aggregated interest rate, as described by Nahmias and Olsen (2015), which can include cost of capital, taxes and insurance, cost of storage, and breakage and spoilage. This model assumes a total interest charge of 10%. This approximation falls within expected holding costs for aviation spares as proposed by Conklin and de Decker (1998). The following relationship provides the inventory holding cost per unit per year:

$$h = i \times c$$

h = inventory holding cost (\$/unit-year)

i = total interest charge (%/year)

c = unit cost (\$/unit)

$$h = 10\% \times \$7,004.77 = \$700.48\text{/unit/year}$$

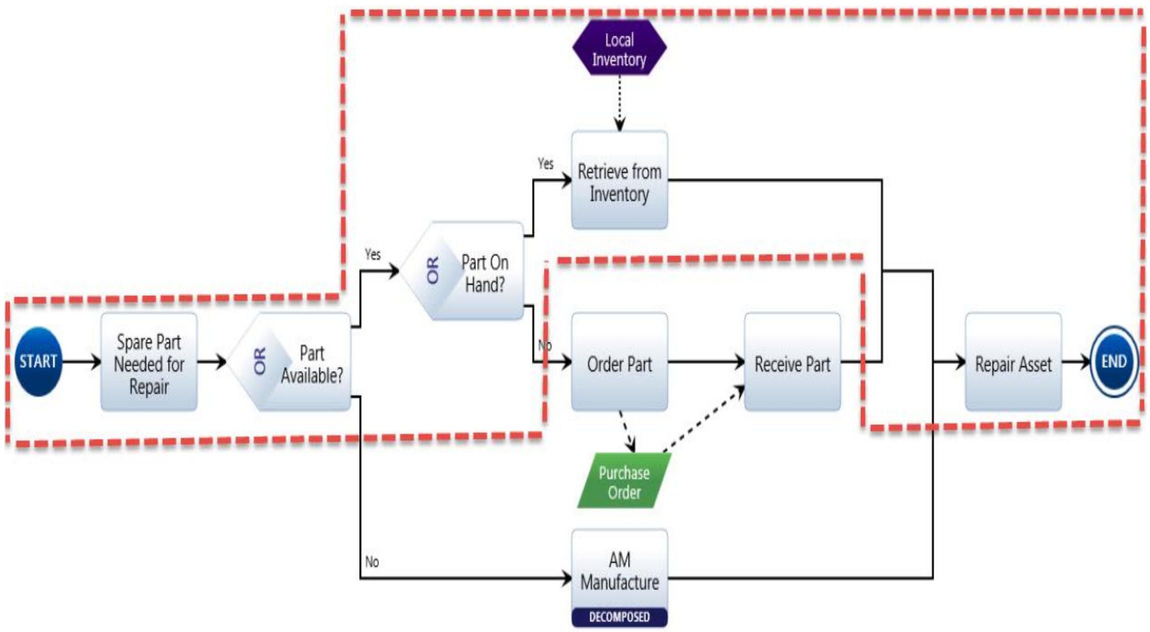

Figure 25. Spare Part Pulled from Local Inventory

b. Order Part from OEM or Supplier

The second route, illustrated in Figure 26, assumes that no inventory is available for the part, neither from local inventory nor from the supply system. This route assumes that the item is backordered and an order is submitted to a supplier to manufacture the part. Using the data from Table 2, the procurement lead-time is set to 545 days and the order cost is set to the unit cost of the sample material -- $7004.77. When the requisition is routed through the part order path, the purchase order input/output, denoted by the green block in the activity diagram, triggers an order for the spare part.

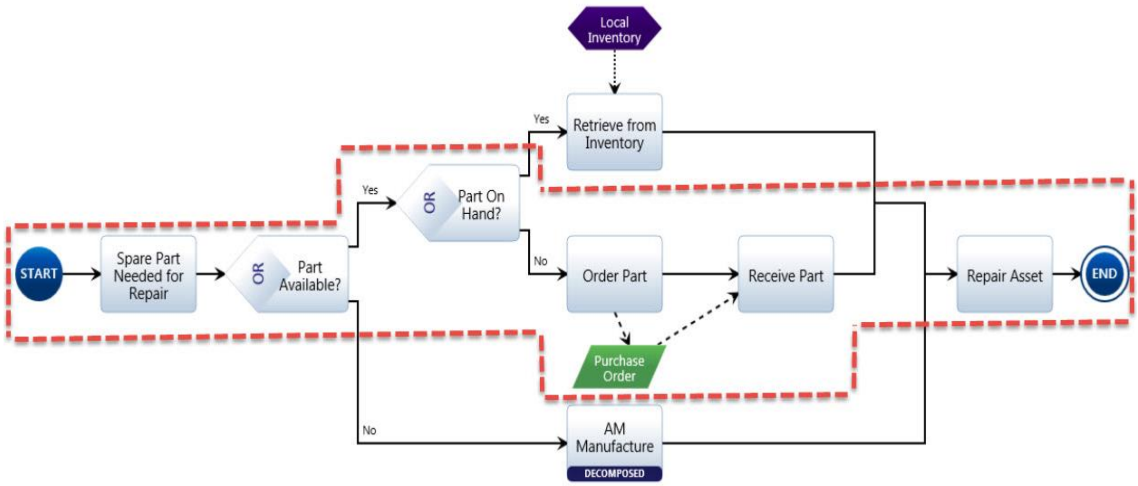

Figure 26. Spare Part Ordered from OEM/Supplier

c. Additively Manufacture Part

The third route, illustrated in Figure 27, assumes that the part is unavailable in inventory and will be manufactured via an additive process. Given the sample part material and build volume, it is assumed that the component will be locally manufactured on an EOS M290 DMLS machine using 17–4 PH stainless steel feedstock material. The EOS M290 is a PBF AM printer that is commonly used in the aerospace industry. This AM printer was selected for the simulation model since the candidate component is made from 17–4PH stainless steel, a material available on the EOS M290 and fits within the M290 printer build volume. Various technical attributes, including material density, material cost, build rate, build volume were collected from OEM data sheets. Table 3 provides the technical attributes used from the OEM data sheets.

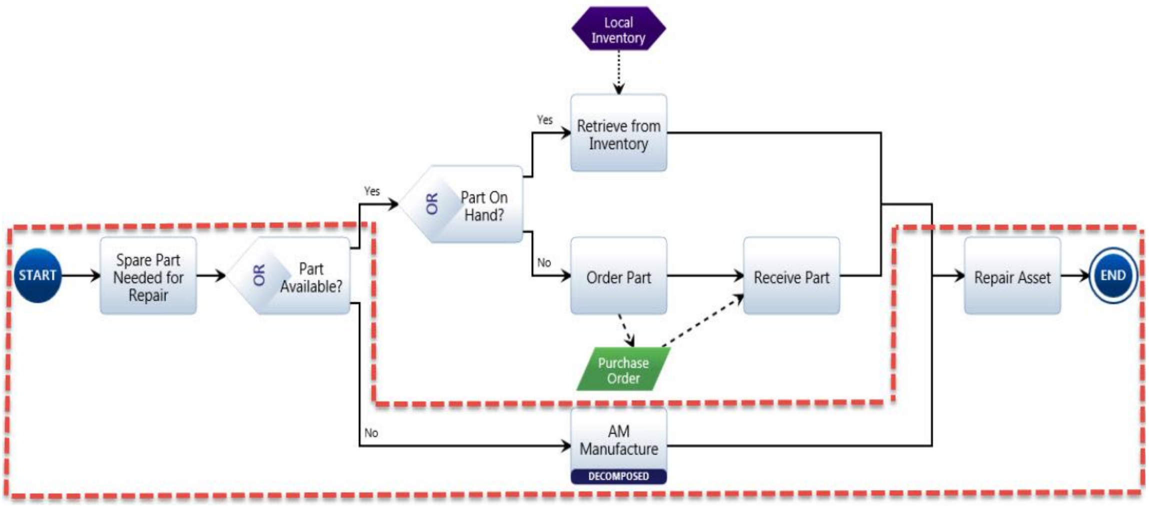

Figure 27. Spare Part Manufactured via AM.

Table 3. EOS M290 17–4PH Stainless Steel Process Data. Adapted from (EOS, 2016).

EOS M290, 17–4PH SS	
Build Rate (in^3/hr)	0.73
Part Material Density (lb/in^3)	0.28
Material Cost ($/lb)	$ 47.62

Using the data in Tables 2 and 3, the print time for the sample component is approximated. The volume of the sample part is calculated using the 17–4PH material density and gross weight of the selected part. The build rate for the component can then be approximated using the calculated volume and EOS M290 build rate.

$$\text{Density} = \text{Mass} / \text{Volume}$$

$$\text{Volume of part} = (\text{mass of part}) / (\text{material density})$$

$$\text{Volume of part} = (3.8 \text{ lbs}) / (0.28 \text{ lbs/in}^3) = 13.57 \text{ in}^3$$

$$\text{Build Time} = (\text{volume}) / (\text{build rate})$$

$$\text{Build Time} = (13.57 \text{ in}^3) / (0.73 \text{ in}^3\text{/hour}) = 18.6 \text{ hours}$$

The AM manufacture block in the activity diagram is decomposed to provide insight into the various actions required for AM manufacture. The activity decomposition includes machine setup, machine run time, part removal from the build plate, post-processing, and final inspection. In this DES simulation, the sample part is assumed to be the only part manufactured in the print run, that is, only a single component is printed during the AM build process, though this may not always be the case. Figure 28 provides the activity diagram of the AM build process. Table 4 provides the attributes assumed for this simulation test case.

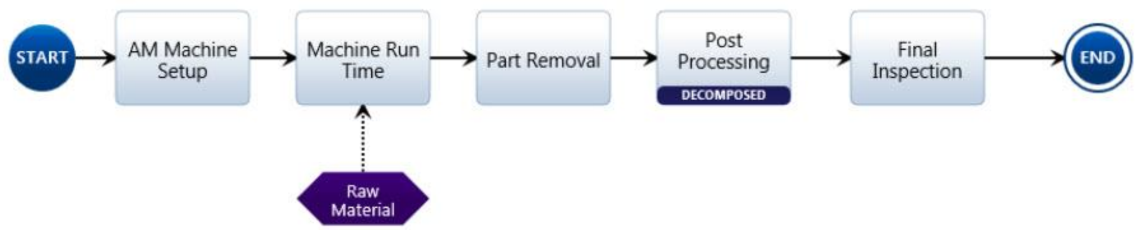

Figure 28. AM Process Flow Diagram

Table 4. Approximated Costs and Lead Time for AM Process

Action	Incurred Cost	Incurred Time
AM Machine Setup	$ 100.00	1 hour
Machine Run Time	$ 550.10	18.6 hours
Part Removal	$ 100.00	2 hours
Post Processing	$ 1,000.00	1 week
Final Inspection	$ 400.00	1 day

The values in Table 4 were estimated from the activity-based cost models of Jason T. Ray (2017) as well as Thomas and Gilbert (2014). The cost estimates were simulated as triangular distributions with a plus and minus of 25% of the estimated cost. The post-processing action block in Figure 29 is further decomposed to provide greater detail of the post-processing requirements for the part. To simplify the model, the post-processing in the sample part scenario was assumed to be $1,000 with a one week turnaround, though the degree of post-processing could vary considerably depending on the complexity and criticality of the part. Additionally, not all post-processing may be completed in-house. Post-processing can include removal of support material, heat treatment, including hot isostatic pressing (HIP), final machining, surface finishing, such as polishing or shot peening, and final coating or plating. In this case, the sample part is assumed to be manufactured via a powder bed fusion (PBF) process; specifically, direct metal laser sintering (DMLS) on an EOS M290. The cost and time parameters associated with each action block are fully customizable and can be adjusted to reflect different sample parts and different AM materials and processes.

Figure 29. AM Post-Processing Activity Diagram

C. SIMULATION RESULTS AND ANALYSIS

The discrete event simulation tool in Innoslate was used to simulate various part supply strategies as illustrated in the previous process flow diagrams. The intent of the model was to develop a framework to run simulations to compare alternative spare part supply strategies and capture the required steps for an additively manufactured part. The DES module within Innoslate provides analysis of the costs incurred and time required to execute each activity within the process flow. Figure 30 provides a sample of the Innoslate DES report. This report contains graphical representations of the time required to execute each activity within the model, as well as the incurred costs for each activity.

Actual data should be incorporated into a simulation model whenever available to improve accuracy, though probably distributions can provide reasonable results when data is unknown or highly variable. In this simulation model, for example, the time required to remove support material from an AM part could vary significantly, depending on the complexity of the part. To account for this variability, probability distributions would be used in this activity block in the simulation model. If an upper bound and lower bound were known for the time required to remove support material for a DMLS part, a triangular distribution would be reasonable to simulate the values within this range. In this simulation, a combination of probability distributions and empirical data was used. A uniform distribution was used to simulate the demand signal and triangular distributions were used for several AM processing steps, including machine setup time and part removal. The results shown in Figure 31 provide insight into the expected costs and lead times associated with the AM route in the process flow model. The results provide a Gantt chart illustrating the sequence and time required to progress through each activity in the model. The cost incurred over time is provided in the top right corner in Figure 30 and the cost allocation for each AM process is provided in the bottom-right corner. Figure 31 provides a cost breakdown for the various decomposed steps within the AM manufacturing activity block. When empirical data is available, the attributes within the model can be adjusted to more accurately reflect the simulated configuration. This can provide greater visibility into the expected costs and lead times associated with an AM supply support strategy compared to alternate conventional strategies.

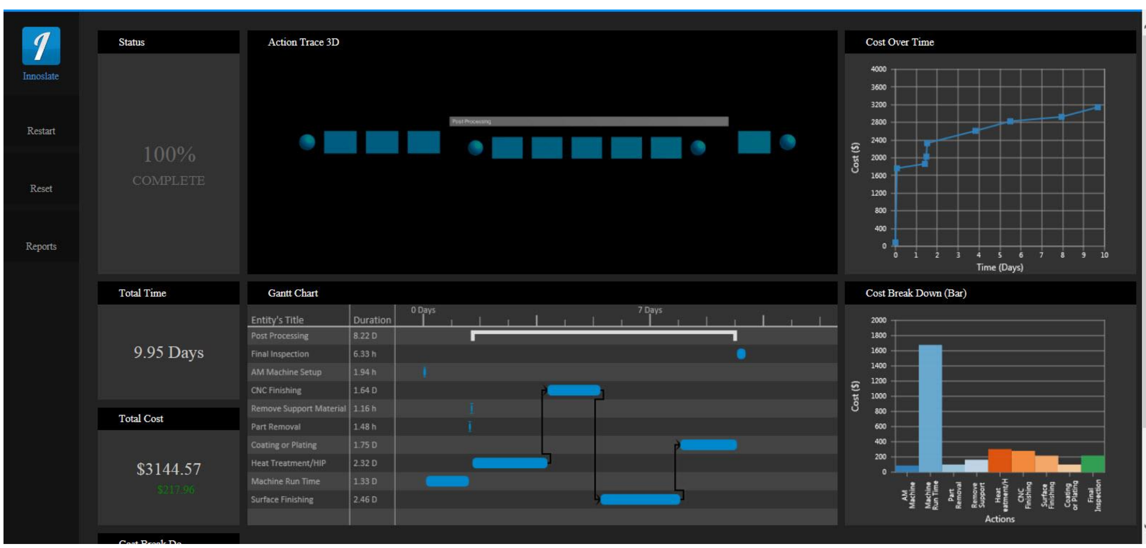

Figure 30. DES Results for AM Supply Branch

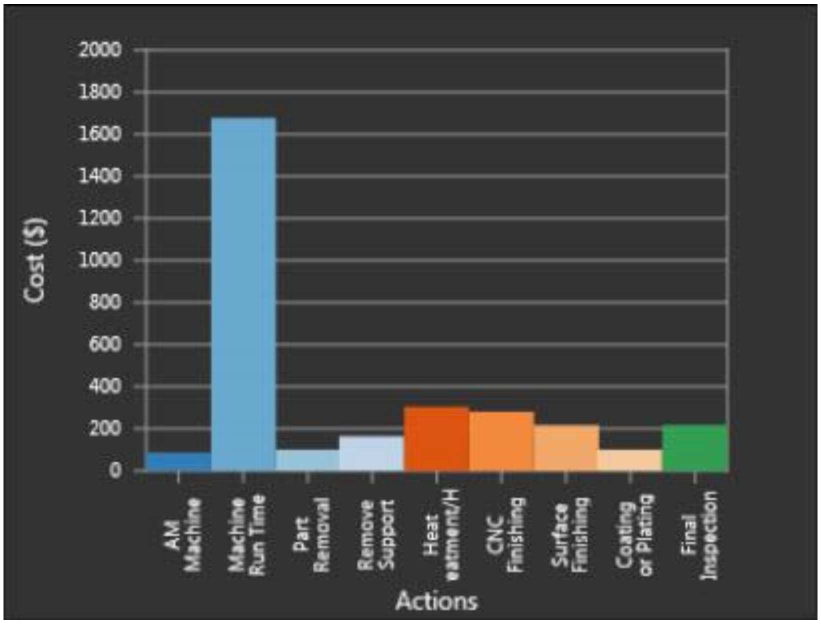

Figure 31. AM Cost Breakdown Bar Chart

The cost breakdown chart from the simulation run indicates that the majority of the costs are incurred during the AM build process—nearly 53% of the total cost. This spike in cost is largely attributed to the high costs for AM feedstock materials and the slow print speeds of the PBF process. As AM technologies mature over the next several years, it is anticipated that cost of feedstock materials will go down and printer speeds will increase. However, despite the high cost of AM manufacture, the simulated part still shows both cost and procurement lead-time reductions compared to the baseline. The baseline assumes that the component will be procured from the supplier at the conventionally manufactured unit price of $7,004.77 with a procurement lead-time of 545 days. The AM simulated model shows the AM manufactured part to be $3,144.57; nearly 45% of the traditional procurement cost and a significant reduction in PLT—about 10 days compared to 545 days.

D. SENSITIVITY ANALYSIS

The simulation model of the selected aviation spare part indicates that the highest costs of the PBF AM process can be attributed to the machine run time. In this test case, roughly 53% of the total cost falls within the AM build process of the activity diagram.

Suppose that an alternate machine or an alternate AM process were to be used to manufacture the selected component. Suppose that all other parameters are equal but the build rate of the alternate AM machine is half of the baseline print speed. The baseline print speed was 0.73in^3/hr with a total build time of 18.6 hours. A process with half of the build speed would require 37.2 hours—twice the print time of the baseline. The simulation model was rerun and showed that the per part unit price increased from $3,144.57 to $4,846.80, which is still 30% less than the original baseline unit price of $7,004.77. Figure 32 provides the Innoslate simulation results for a build time of 37.2 hours. Figure 33 provides the cost breakdown for the 37.2-hour build time.

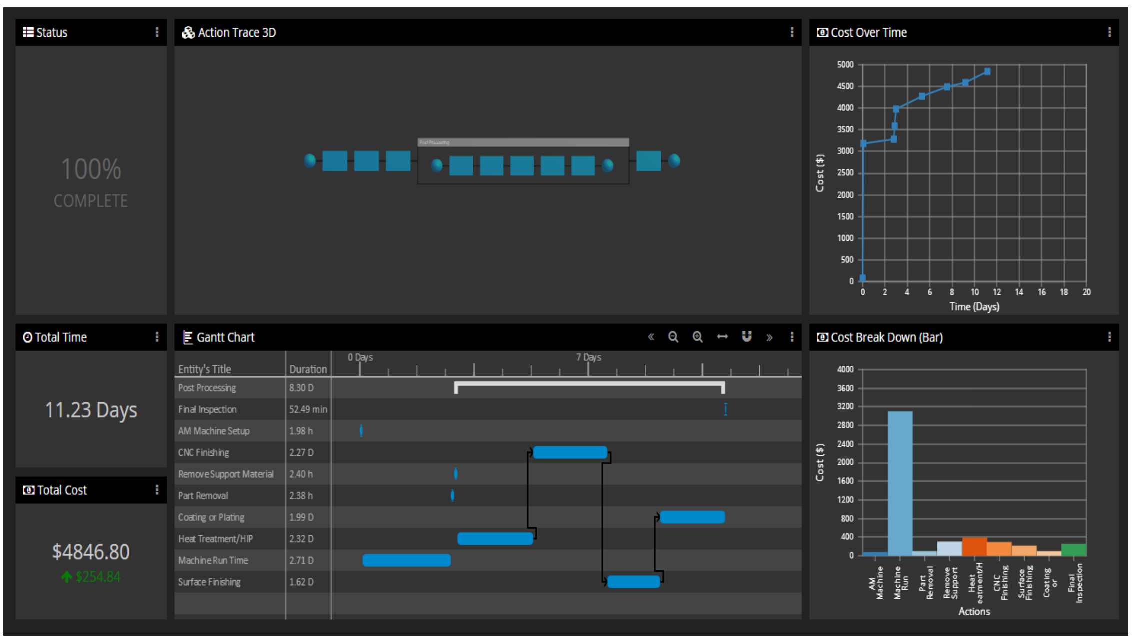

Figure 32. Innoslate DES Results for Half Print Speed

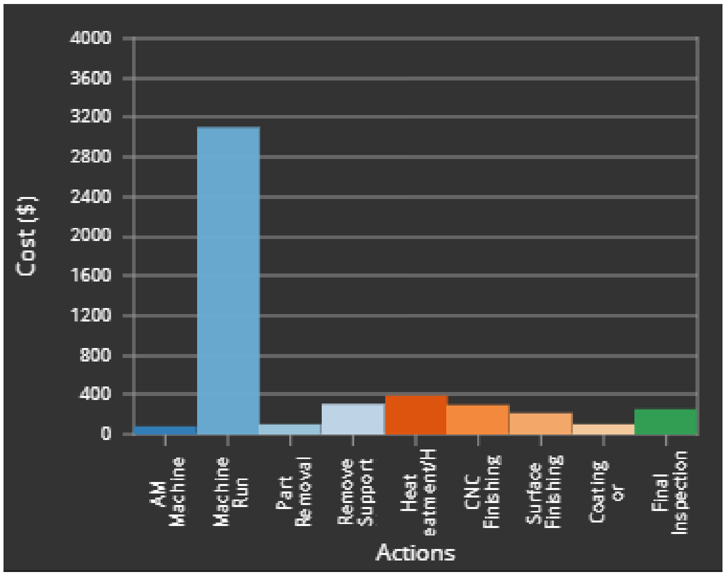

Figure 33. Innoslate DES Cost Breakdown for Half Print Speed

If the alternate AM machines print speed were one quarter of the baseline print speed, the time required to manufacture the component would be 74.4 hours. This scenario still provides significant time savings compared to the traditional PLT of 545 days; however, the simulation model was rerun and showed that the per part unit price increased to $8,158.26; a 17% increase from the standard unit price of $7004.77. This scenario indicates that significant time savings are still achievable with the AM process compared to traditional procurement, though part unit cost is heavily influenced by the machine specifications. Figure 34 provides the Innoslate simulation results for the 74.4 hour build time. Figure 35 provides the cost breakdown for the 74.4-hour build time.

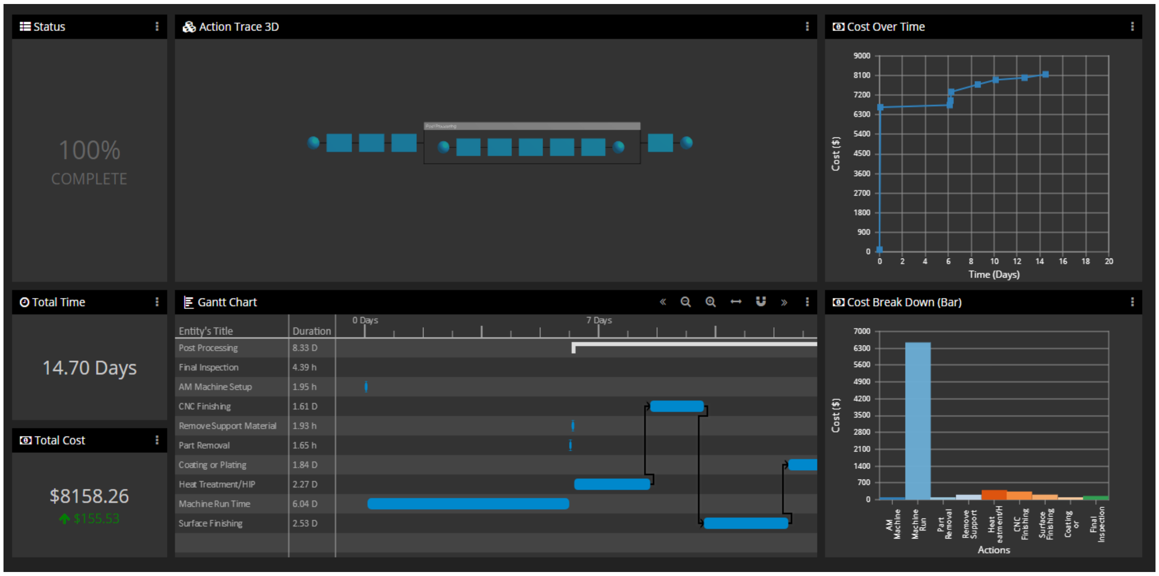

Figure 34. Innoslate DES Results for Quarter Print Speed

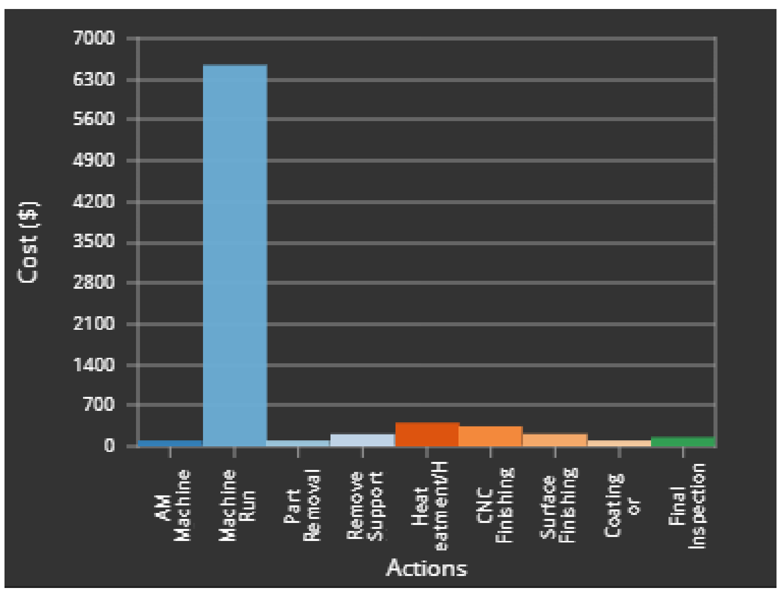

Figure 35. Innoslate DES Cost Breakdown for Quarter Print Speed

VI. CONCLUSION AND RECOMMENDATIONS

A. DISCUSSION

This thesis has presented a method to identify applications for additive manufacturing within the naval aviation spare parts supply chain and how component costs and lead times for AM can be compared to conventional supply support strategies. A background of the aviation supply system was presented, along with an overview of the maintenance organization to identify insertion points for AM. This thesis focused on use of AM to manufacture class IX spare parts to support the repair efforts of AVDLRs within Navy FRCs. A component selection methodology was discussed, providing insight into the relevant technical and logistics attributes necessary to identify potential item candidates within the Navy supply system, as well as the databases used to retrieve the requisite data. A prioritization method was presented, which aligns technical feasibility with programmatic objectives for an AM supply support strategy. For the DoN supply chain, opportunities to reduce material support costs and procurement lead times were identified as key programmatic objectives and were used as candidate item selection criteria. Technical feasibility was inferred based on data available to supply chain engineers and logisticians, including material and geometric characteristics.

A discrete event simulation model was constructed to evaluate cost and lead-time implications for an AM supply support strategy within an FRC material asset repair process flow. The process flow assumes that a spare part is needed to complete an AVDLR repair action and presents alternate supply scenarios, including traditional supply strategies, such as inventory pull and supply requisitioning, as well as an additive manufacturing supply strategy. The AM branch of the process flow model decomposes the activities required to manufacture a spare part using one specific AM technology. The values and parameters of the model are customizable, so alternate AM machines and processes can be substituted. If an alternate machine or process were to be considered, the machine build volume and material costs would need to be updated to reflect the alternate process. This model assumed that the manufacture of the selected item will be done locally at an FRC and a complete AM TDP is available. When available, AM machine and material process data was used from OEM datasheets. When data was unavailable for the given activities within the model, probability distribution functions were used to simulate the data. The model developed provides a framework to simulate the cost and lead time of alternate spare part support strategies for sustainment of AVDLRs. Each action block within the model activity diagram can be customized to include additional parameters, be they technical characteristics of the manufacturing process or warehousing costs. This customization provides flexibility within the model to conduct sensitivity analysis and evaluate alternate support strategies. Such a model can assist engineers and logisticians with the appropriate supply support strategy that aligns most closely with program objectives, given tradeoffs among cost and procurement lead-time.

This thesis sought to address the following questions:

- Can additive manufacturing technologies reduce costs and procurement lead times within the naval aviation supply chain that are unachievable with conventional supply support processes?
- How can the Navy systematically identify opportunities to integrate additive manufacturing within the aviation supply chain?
- What is the process flow and decision support system necessary to identify cost and lead time savings using additive manufacturing?

The DES model can be used to assess procurement lead-time and costs associated with an AM supply process, though attributes within the model will need to be adjusted on a part-by-part basis to account for the variations in manufacturing processes and supply configurations. The component selection process and subsequent simulation model revealed that many characteristics influence a spare part's amenability to an AM process. These attributes can significantly alter the costs and lead-times associated with an AM supply support strategy. Adjustments will need to be made to the model to reflect the attributes of the spare parts that are simulated; however, the model has revealed that an AM supply strategy can yield lower costs and lead times compared to conventional supply strategies. A sample part was selected using the component selection methodology discussed in chapter IV and was shown to reduce lead times in comparison to a traditional spare part ordering process. This sample simulation, however, had several assumptions. The sample simulation assumed that the candidate item was unavailable in the supply system and had a procurement lead-time (PLT) of 545 days, as taken from Navy ERP. Additionally, the cost and qualification time associated with reverse engineering the legacy component were not included in the model, which could significantly influence the results, depending on the complexity and criticality of the selected component. Inclusion of reverse engineering costs and qualification times would increase the fidelity and robustness of the simulation model and further research in this area would be beneficial.

To identify insertion points of AM in the aviation spare parts, a component selection methodology was presented. Realistically, there are many insertion points to utilize AM within the maintenance and sustainment of aviation weapon systems, though this thesis focused on AM manufacture of end-use, Navy-managed consumable aviation components. The selection methodology, based on the work of LMI (2016) and the Beta Research School for Operations Management (2016) revealed that only a subset of technical and logistics attributes available from DOD data sources are relevant to identify AM candidates in the spare parts supply chain. Further, these candidates can be prioritized based on technical feasibility and contributions to organizational objectives. The Navy data sources used to retrieve the relevant technical and logistics attributes were identified. Most of the logistics element needed to prioritize components can be retrieved from Navy ERP through a logistics interface tool, such as SAS Enterprise. Any missing data can be retrieved in batch queries from other DOD data repositories, including DLA EBS and Web FLIS, or commercial databases, such as I.H.S. Haystack. Technical data elements, on the other hand, are often incomplete in Navy ERP and are problematic to obtain via batch data queries. The inaccessibility of technical data emphasizes the importance of a collaborative product life cycle management (PLM) solution for the DON.

The simulated AVDLR repair process included alternate spare part supply strategies, including conventional warehousing, part replenishment, and local AM manufacture. The process flow and DES model was designed to include flexibility of component attributes so that alternate parts and support configurations can be modeled. The developed model utilized Innoslate, which can export customizable reports for further analysis. This information can be used to drive decision support strategies and develop a BCA for AM implementation.

B. RECOMMENDATIONS

The component selection methodology detailed in this research revealed several challenges with existing DON data retrieval systems; namely, the automated retrieval of spare part technical data. The unavailability and inaccessibility of materiel technical attributes poses a significant challenge to sustainment engineers and logisticians to make informed decisions regarding use of AM within the spare parts supply chain. Thus, a collaborative DON PLM system would greatly benefit the sustainment community with assessment of alternate supply support strategies; AM being just one potential solution space. This lack of data accessibility emphasizes the importance of a digital thread within the DON sustainment infrastructure to effectively operationalize AM across the enterprise.

To limit the scope of this research effort, only a subset of spare parts within the supply system were used to assess AM as an alternate supply strategy. A comprehensive framework would be beneficial to evaluate other insertion points of AM technology with in the operations and sustainment phase of the weapon system life cycle. A major challenge with such a model is the connection of the disparate systems where supply data is stored and methods to retrieve the data by automated queries. At present, the data necessary to conduct an AM evaluation for legacy components requires manual data pulls from disconnected data repositories. In the case of technical data, this is done on a component-by-component basis. An investigation of automated and batch data retrieval methods would provide broader assessment of the spare parts supply chain.

C. AREAS OF FUTURE RESEARCH

This research effort targeted the use of AM to supplement spare part shortages with regard to sustainment of AVDLRs. The selection methodology and simulation model considered only consumable aviation items and the manufacture of those components. However, the supply system includes repairable assemblies as well as peculiar support equipment (PSE), such as tooling and fixtures, which could benefit greatly from AM technology. An analysis of AM technologies and its impact on 7R repairable material would be beneficial. Future research could target the use of additive material repair processes, such as cold spray and directed energy deposition (DED) and how these technologies can reduce costs and improve readiness for 7R material. Additionally, indirect AM applications, such as mold tooling and PSE could be explored to address opportunities that are outside of the catalogued material in the supply system.

A key assumption of the DES model presented in this research is the exclusion of the costs and lead times associated with reverse engineering a legacy component. Since much of the technical data necessary to conduct a reverse engineering analysis was unavailable to NAVSUP engineers and logisticians, it was not considered within the scope of this model. Reverse engineering, however, could tremendously impact the costs to implement an AM supply strategy. Therefore, future research into the reverse engineering process to convert legacy data into an AM TDP would be beneficial to increase the fidelity of the simulation model presented in this research effort.

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