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AN ANALYSIS OF ITEM IDENTIFICATION FOR ADDITIVE MANUFACTURING (3-D PRINTING) WITHIN THE NAVAL SUPPLY CHAIN

December 2014

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13. ABSTRACT (maximum 200 words)

Additive manufacturing (AM) technology, known as three-dimensional (3-D) printing, was developed in the 1980s and has matured such that it is being implemented into modern business processes as a way to reduce prototype design and production lead times. Similar to companies in civilian industry, the U.S. Navy's Chief of Naval Operations Rapid Innovation Development Cell has been looking for ways to introduce this technology into the Navy's supply chain.

The Navy is operating in a continuously shrinking, budget-constrained environment and always seeks ways to save money and improve business practices. Implementing AM into the Navy's supply chain has the potential to reduce costs and improve acquisition processes. As the Navy continues to invest in AM, current inventories of material must be reviewed for applicability and compatibility to determine what is 3-D printable. This project's goal is to provide decision support criteria by identifying influential factors that determine the applicability of 3-D printing alternatives. The approach taken involves an analysis of the technology, its use in civilian industries, and a discussion of influential factors determining whether 3-D printing is a alternative to traditional supply chains. Moreover, it identifies potential uses and provides examples for printing 3-D material for the Navy.

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LIST OF ACRONYMS AND ABBREVIATIONS

3-D	three-dimensional
3-M	Maintenance and Material Management
A_o	operational availability
AM	additive manufacturing
BPA	blanket purchase agreement
BMW	Bavarian Motor Works
CAD	computer-aided design
CASREP	casualty report
CDSA	Combat Direction Systems Activity
cm	centimeters
CNO	Chief of Naval Operations
COSAL	Coordinated Shipboard Allowance List
CSC	Computer Sciences Corporation
cu. in.	cubic inches
D-level	depot level
DBI	demand-based inventory
DBS	demand-based sparing
DDG	guided missile destroyer
DLA	Defense Logistics Agency
DOD	Department of Defense
DON	Department of Navy
DSP	Defense Standardization Program
DUSD[L&MR]	Deputy Under Secretary of Defense for Logistics and Material Readiness
DVD	digital versatile disc
FAD	force/activity designators
FDM	fused deposition modeling
FLC	Fleet Logistics Center
GAO	Government Accountability Office
GE	General Electric

GEGRC	General Electric Global Research Center
GLS	Global Logistics Support
hh:mm	hours: minutes
I-level	intermediate level
IDIQ	indefinite delivery and indefinite quantity
in^3	cubic inches
LCDR	Lieutenant Commander
LEAP	Leading Edge Aviation Propulsion
LHD	Landing Helicopter Dock
LSD	Landing Ship, Dock
LT	Lieutenant
MDS	Maintenance Data Subsystems
MIL-DTL	Military Detail Specification
MIL-HDBK	Military Handbook
MIL-PRF	Military Performance Specification
MIL-SPEC	Military Specification
MIL-STD	Military Standard
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NAVSUP	Naval Supply Systems Command
NSS	Navy Supply System
NSWC	Naval Surface Warfare Center
O-level	organizational level
O&M	operations and maintenance
OCONUS	outside continental United States
OMMS-NG	Organizational Maintenance Management System-Next Generation
PD	priority designator
PMS	Preventative Maintenance System
RBS	readiness-based sparing
RFI	requests for information
RFP	requests for proposal
RMC	Regional Maintenance Center

R-SUPPLY	Relational Supply
SCM	Supply Chain Management
SKED	Automated Planned Maintenance System Scheduling Tool
SLA	stereolithography
SLS	selective laser sintering
TM	traditional manufacturing
TP	transportation priority
UMMIPS	Uniform Material Movement and Issue Priority System
USN	United States Navy
USS	United States Ship
UND	urgency of need designator
U.S.	United States
USD[AT&L]	Under Secretary of Defense for Acquisition Technology and Logistics
V_m	Volume of modeling material
V_s	Volume of supporting material
WFIRM	Wake Forest Institute for Regenerative Medicine
WSS	Weapon Systems Support

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I. INTRODUCTION

A. BACKGROUND

Additive manufacturing (AM), commonly referred to as three-dimensional (3-D) printing, represents an assortment of technologies that can convert modeled data into physical products layer-by-layer relatively rapidly and without difficulty (Gibson, Rosen, & Stucker, 2010). There are diverse AM technologies, characterized by different speeds, layer thickness, ranges of materials, accuracy, and cost; however, they are all using the same basic principles of layering source material one layer at a time (Gibson et al., 2010).

The U.S. Navy's deployment and operational strategy relies on increasingly complex logistical lines of communication to support their activities around the globe on a daily basis. The new AM technology has the potential to drastically reduce costs and increase the efficiency of logistical processes that society, and organizations such as the Navy, has come to know.

This report investigates the three methods of AM that are most common within the 3-D printing industry: Stereolithography (SLA), Fused Deposition Modeling (FDM), and Selective Laser Sintering (SLS). It also identifies the key parameters by which Navy decision makers can determine if such AM technologies can add value to their spare parts supply.

B. PURPOSE OF RESEARCH

The purpose of this research is to identify the key factors that influence the selection of AM technology candidates to be implemented in the Navy's spare parts supply chain. First, the report reviews the different techniques of AM that currently exist by exploring their capabilities and limitations, as well as reviewing applications of AM within the aerospace, automotive, healthcare, and manufacturing industries as examples of the technology's success.

Second, the report reviews three primary areas of focus that weigh heavily on the feasibility of additive manufacturing versus traditional manufacturing: the demand requirements of the part in question, the material specifications/requirements of the item, and the economic analysis of printing the item in 3-D. For each of the identified areas, the report examines the importance of that area on the decision to implement AM or not, and how it can be used to ensure a sound decision-making process.

C. RESEARCH QUESTIONS

As various techniques of AM are discovered and utilized within the aerospace, automotive, healthcare, and manufacturing industries, with the potential to be implemented into the Navy supply chain, the following questions will be addressed by this report:

> Primary Research Question: What are the influential factors to consider when detecting potential AM candidates from the existing Navy supply chain?
>
> Secondary Research Questions: What factors determine the economic feasibility of individual part candidates? What current initiatives are investigating the integration of AM into the Navy?

D. BENEFITS OF RESEARCH

In the article “The 3D Printed Supply Chain: Stronger, Faster, and More Flexible,” LT Jason Ray, United States Navy (USN) (2013) asserts that 3-D printing technology could potentially alleviate some logistics issues that the Navy experiences, such as long lead times for legacy parts that are no longer carried within the supply system, or even reduce the transportation costs of shipping repair parts needed throughout the world. While 3-D printing technology would be a welcome solution to the Navy, there are other questions and concerns that must be addressed before the Navy commits to investing in this technology. This research aims to investigate what these factors are and how they are likely to impact the decision to implement AM throughout the Navy’s supply chain. A thorough examination of these factors brings value to the Navy by helping ensure that 3-D printing is the most economical solution to the issues of long lead times and part obsolescence mentioned by LT Ray (Ray, 2013). The analysis of the identified critical factors is meant to serve as a model or template that a variety of organizational levels could use in order to aid the decision process of whether or not to implement AM technology.

E. LIMITATIONS OF RESEARCH

The field of AM has become quite large in recent years and encompasses a wide variety of techniques to accomplish a layer-by-layer construction; however, in an effort to focus the research, our analysis of AM is limited to a few primary methods commonly used within industry. Ideally, multiple examples to analyze and draw conclusions from would be provided. Unfortunately, due to the relative infancy of AM technology in a practical sense, its use within the Department of Defense (DOD) is further limited. Therefore, research is restricted to a single, real-world example of introducing 3-D printed parts into a Navy supply chain. This limited sample of AM use could lead to results that may or may not be the norm or commonly experienced.

Finally, research was limited to scholarly journals, reports, and instructions, as access to an AM machine was not made available. Access to the different AM machines could have allowed for a more detailed analysis of the technology's capabilities. Ultimately, the research was narrowed to the written accounts that others have had with these machines.

F. METHODOLOGY

The research was conducted by accumulating data from articles, scholarly journals, DOD regulations and instructions, and government research reports of past AM implementation initiatives. The review of how the Navy's supply system operates allowed us to identify three factors—demand, material specification requirements, and economic feasibility—that influence parts that exist within that system; thus, allowing one to determine the factors that must be considered when altering the current system to allow for the introduction of 3-D printed parts. The final cost calculations were based on methods used in a previous AM case study conducted by Mr. James Lambeth at the Navy's Combat Direction Systems Activity (CDSA) in Dam Neck, Virginia in 2014.

G. ORGANIZATION OF REPORT

This report is comprised of six chapters. The first chapter consists of a brief background on AM technology, describes the purpose of the research, identifies research questions, describes the benefits and limitations of research, and reviews the methodology used. Chapter II provides a detailed background, examines the current Navy supply system and how it works, the AM methods used, and how the methods are currently being used within the aerospace, automotive, healthcare, and manufacturing industries. Chapter III, the literature review chapter, investigates past economic analysis, reviews make-versus-buy decision criteria, and examines a case conducted onboard a U.S. Navy warship. The methodology chapter, Chapter IV, discusses the approach used to collect data, details the cost determination method, and describes specifications and standards that must be met by AM. Chapter V, the analysis chapter, includes calculations and analysis of the results. Finally, Chapter VI provides the discoveries of the research, makes recommendations based on those findings, and offers recommendations for related research.

H. SUMMARY

The purpose of this introductory chapter is to provide a brief background of the Navy supply system, AM technology, and identify the research questions. A discussion of the benefits and limitations of the research conducted and a brief description of the research methodology is introduced as an overall layout of the entire report. Chapter II will provide a detailed background of both the Navy supply chain and the AM technology.

II. BACKGROUND

A. INTRODUCTION

This chapter examines Navy supply processes. Specific areas reviewed include the organization of Navy supply, fleet support objectives, inventory methods, Navy maintenance as a function of supply support; and repair options for achieving operational availability (A_0). These supply processes inform the foundation of sparing objectives and priority designation discussed further in Chapter IV.

Next is a detailed look at the current state of AM technology that exists in the world today. The focus of which is centered on three specific and popular methods of AM that have been experiencing technological advancements over the years: SLA, FDM, and SLS. The report includes a brief description of how the individual processes accomplish a layer-by-layer construction of materials, capabilities, advantages, and disadvantages of each respective technique.

Then, analysis is conducted on how AM is currently being used and developed for industry-specific applications, particularly the aerospace, aviation, automotive, healthcare, and manufacturing industries.

Finally, Navy sparing is examined by means of priority designation informing readiness and demand requirements. These aspects of the Navy Supply System (NSS) are determined by specific policies and procedures that affect the higher-level processes of maintenance and inventory programs. In order to successfully implement AM into the Navy's supply chain, the available technologies need to meet certain standards and specifications of the equipment and weapons systems used throughout the Navy.

B. CURRENT U.S. NAVY SUPPLY SYSTEM

1. Introduction

Detailing Navy supply processes is beneficial to understanding the approach needed to integrate AM into a mature supply chain process. This can be initiated by defining the overarching products of weapons systems support and supply chain management within the context of the NSS provides scope for new and emerging technologies. Understanding the acquisition mechanics within the Navy provides insight into how the process flows and how new capabilities assimilate to existing systems is the next step for process integration. A requirement's prioritization, based on expected and actual need, is defined by readiness and demand profiles. Inventory management is explored to shed light on opportunities that AM integration provides to the Navy. Next, priority and speed of material movement unveil the nature of expediting requirements and the associated room for process improvement. Finally, the Navy maintenance program is essential for understanding the nature of repairs and sparing implementation strategies. This approach to understanding the flow of information is the primary means of identifying material suitability for AM as a supply chain solution.

2. Navy Supply System and Partners

The Naval Supply Systems Command (NAVSUP) organization is responsible for the integration of AM parts into the Navy supply chain. The NAVSUP mission is to deliver sustained global logistics and quality-of-life support to the Navy and joint warfighter (Department of the Navy [DON], 2014c). This is a separate, but connected, organization from the design, building, and maintenance functions of Naval Sea Systems Command (NAVSEA) and Naval Air Systems Command (NAVAIR). The intersection of NAVSUP, NAVSEA, and NAVAIR with regard to AM is realized by their shared visions of reducing operating and sustainment costs for fielded systems and implementing life-cycle cost reduction (DON, 2014b).

Short-term development and production costs of AM may certainly be higher than the immediate costs of parts manufactured by traditional means that are already fully integrated into the supply chain. The most impactful cost savings are realized in the long run and are best characterized within a life-cycle framework. Life-cycle parts support costs fall within the NAVSUP area of responsibility.

According to the NAVSUP website (2014c), Supply Chain Management (SCM) is the collection of processes that result in Navy customers receiving the parts they need, when and where they need them, anywhere in the world. The fleet supply support function includes allocating material, managing and contracting repairs, developing allowances, and providing customer support. Program support functions include life-cycle management, maintenance planning, configuration management, and reliability improvement. These facts are attributable to SCM having a dual focus of fleet supply support and program support in order to provide sustainment for the life cycle of the weapons systems (DON, 2014c).

3. Fleet Support Vision

Reducing operating and sustainment costs for fielded systems and implementing life-cycle cost reduction is the shared vision across NAVSUP, NAVSEA, and NAVAIR (DON, 2014b). This vision is framed in the singular term of "fiduciary responsibility." The mission of the Navy is "to maintain, train and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas" (DON, 2014a, para 1). NAVSUP, NAVSEA, and NAVAIR directly contribute to the Navy's mission within the context of maintaining and equipping weapons systems for the warfighter. Although maintenance and equipage share cross-functional duties, this section deals exclusively with equipping the warfighter.

4. Inventory Program

Inventories are defined by the Navy as being synonymous with the term "secondary items." A secondary item is "an item of supply that is not defined as a principal item and includes repairable components, subsystems, and assemblies, consumable repair parts, bulk items and material, subsistence, and expendable end items, including clothing and other personal gear" (Office of Under Secretary of Defense [Acquisition Logistics & Technology] [USD AL&T], 2014, p. 11).

The business approach to inventory management is primarily concerned with the trade-offs of dollars spent and mission readiness. According to the Office of USD[AT&L], "The size of secondary item inventories is determined by decision-making designed to minimize total DOD supply chain costs while meeting peacetime, war, and other high tempo requirements" (2014, p. 6).

a. Wholesale Inventory

Wholesale-level inventory items are visible and available to meet worldwide demand for all DOD customers. The Defense Logistics Agency (DLA) is the primary organization that procures and manages spares. The dollar average of DLA's wholesale inventory from 2008 to 2010 was $13.7 billion. A large portion of this cost is due to the role of wholesale inventories and the requirement to replenish retail-level inventories (Government Accountability Office [GAO], 2010). The goal for supply material availability at the wholesale level is to fulfill 85% of material requirements with ready-for-issue items. (Chief of Naval Operations [CNO], 2012). Availability, for the purposes of this report, is an item that is in current inventory, as opposed to not-in-stock and not-carried inventory.

b. Retail Inventory

Retail-level inventory is inventory held below the wholesale level, regardless of funding source (CNO, 2012). The Navy's Fleet Logistics Centers (FLCs) are the most common, intermediate-level inventory sources. Consumer-level inventories are limited to internally utilized items. The Navy defines locally available items as either retail or wholesale inventory items, depending on proximity to each type of distributor. Unless directed by type commander at a higher level, 65% is the supply material availability goal for ready-for-issue retail level inventories (CNO, 2012).

c. Other Inventories

Alternate means of procurement are necessary for spares that are not in inventory. Contractors and suppliers holding stock, stock purchased from commercial sources, and commercial or government sources that fabricate unavailable spares are all examples of not-carried inventory items that have varying significance of impact on the end-user.

Contractors, as part of material management or maintenance contractual agreements, hold some spares. This type of sparing support can either be bought as part of an already funded contract or the spares can be purchased on a pay-as-you-go basis.

Regardless of funding remedy, these inventories are visible to item managers and treated similarly to wholesale and retail inventory items.

The Navy purchases spares and repair parts that are not part of the Navy stock system in the open market. Some parts are readily available and not held in Navy inventories for the reason of financial prudence. The Navy procures items that are readily available through open market procedures of payment, through blanket purchase agreements (BPA), and through existing indefinite delivery and indefinite quantity (IDIQ) contracts. These types of procurement methods have less visibility and, thus, less certainty of availability.

The least preferred option is fabrication of parts. Fabrication for procurement is different than repair parts support, which will be addressed later in the report. Fabrication is normally required for parts, components, and assemblies that rarely fail and have not been demanded at high enough levels to necessitate spares. Despite lead-time concerns, this type of fabrication process can be remedied at a manageable level. The worst-case scenario in terms of part fabrication is of an obsolete or not-supported nature. This may be a catastrophic problem that either costs more than the value of the associated system or renders the parent system itself obsolete. Reverse engineering and creative solutions can be implemented with added cost risk.

5. Navy Maintenance

Maintenance and Material Management (3-M) is the Navy program that standardizes maintenance planning, scheduling, control, and performance for all systems and equipment (CNO, 2013).

a. Maintenance and Material Management

Preventative Maintenance System (PMS) is a major subsystem under the 3-M system. This subsystem is the tool that facilities the organization and coordination of 3-M (CNO, 2010). PMS utilizes the Automated Planned Maintenance System Scheduling Tool, commonly known as SKED, as the software that organizes unit-wide maintenance scheduling. SKED includes equipment configurations and parts allowance lists. As repairs are identified, within scheduled maintenance actions or otherwise, Organizational Maintenance Management System-Next Generation (OMMS-NG) is the application within SKED that reports maintenance requirements for identified repairs. OMMS-NG interfaces with Relational Supply (R-SUPPLY) to identify, report, and requisition parts for routine or corrective maintenance actions. R-SUPPLY and OMMS-NG comprise the two parts of the Maintenance Data Subsystems (MDS) units utilized to document and provide follow-on action to achieve A_o (CNO, 2013).

b. Repairs

Component and part repairs are a facet of the Navy supply chain process that are not included as a traditional sparing solution, but certainly contribute to performance, readiness, and cost decision making. Repairs are a facet of the maintenance process. The three levels of maintenance are organization, intermediate, and depot. The relationship of volume and complexity of maintenance actions is illustrated in Figure 1.

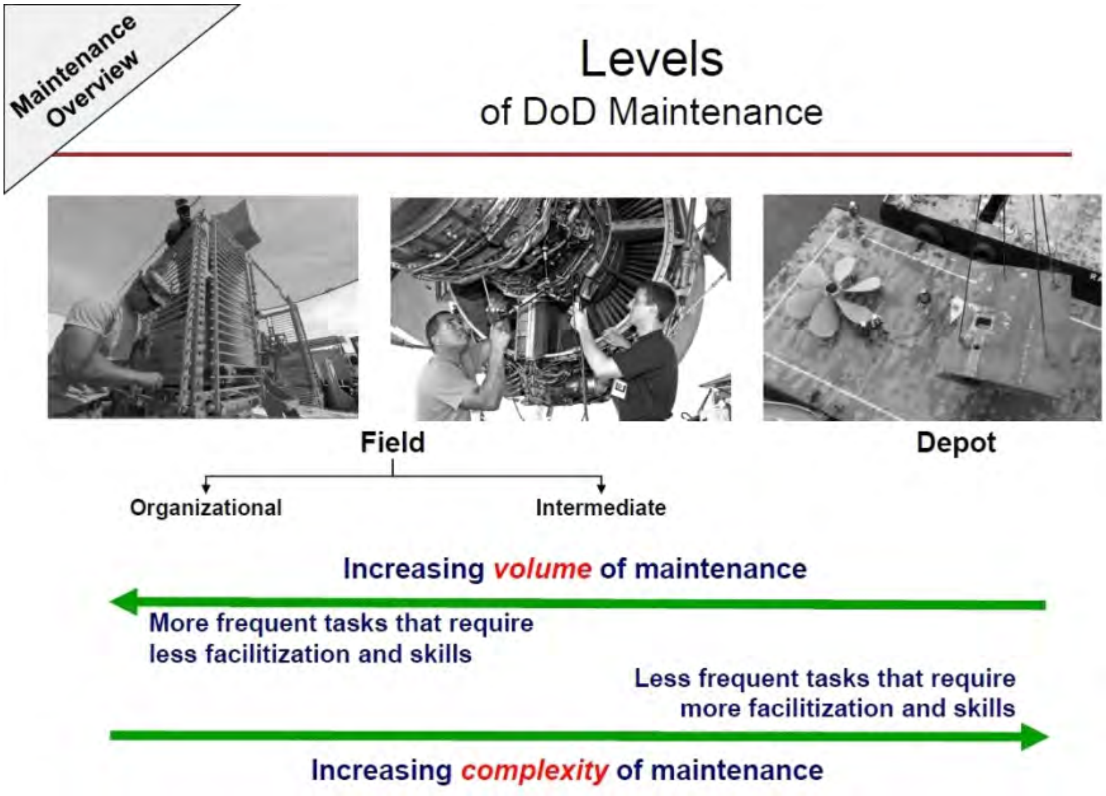


Figure 1. Levels of DOD Maintenance (from DOD, 2012).

Organization-level maintenance (O-level) is the lowest level of maintenance based on complexity and is performed exclusively by unit personnel. Routine maintenance actions such as cleaning, preservation, calibration, and operational testing typify O-level maintenance (CNO, 2010).

Intermediate-level maintenance (I-level) is the second level of maintenance that normally requires assistance from personnel outside the unit. These maintenance actions are normally O-level maintenance of a more complex nature or involving equipment of a higher order of complexity, as well as corrective maintenance actions (CNO, 2010).

Depot-level maintenance (D-level) is the most complex of the three maintenance levels and requires support, knowledge, and capabilities above what is available at the O-level and I-level. D-level support is normally executed by Regional Maintenance Center (RMC) personnel for catastrophic and highly complex system failures (CNO, 2010). The most common D-level support provides a scheduled maintenance period for weapons systems-level or unit-wide equipment availability periods.

C. ADDITIVE MANUFACTURING

AM, commonly referred to as 3-D printing, represents an assortment of technologies that can convert modeled data into physical products layer-by-layer, relatively rapidly, and without difficulty (Gibson et al., 2010). Contrary to subtractive manufacturing technologies that can leave up to 90% of waste material behind, AM is considerably more efficient and produces practically no waste (Freedman, 2012). The AM process of building 3-D parts and material layer-by-layer, as described above, has the benefit of customizing the output products. McNulty, Arnas, and Campbell (2012) use a specific example to highlight the benefits of customization:

> . . . if a customer wanted a wrench to be fashioned with a grip unique to his hand, he could scan his hand by computer and modify the existing design accordingly before the 3D printer begins production. Additionally, since the wrench is not assembled from preexisting parts, it would be a complete entity—unable to break into component parts as there is only one ‘part.’ Since the wrench is made by additive manufacturing as opposed to conventional ‘subtractive manufacturing’—taking a block of

> raw material and removing excess until the finished product remains—the process as a whole is more efficient and less wasteful. (p. 1)

A generalized AM process and the benefits described by McNulty et al. (2012) are illustrated in Figure 1. As seen in Figure 2, the item produced is scanned and digitized; the supporting software creates a series of files that represent individual layers; then the filament is liquefied and extruded through the print head, one layer at a time, until the final product is achieved.

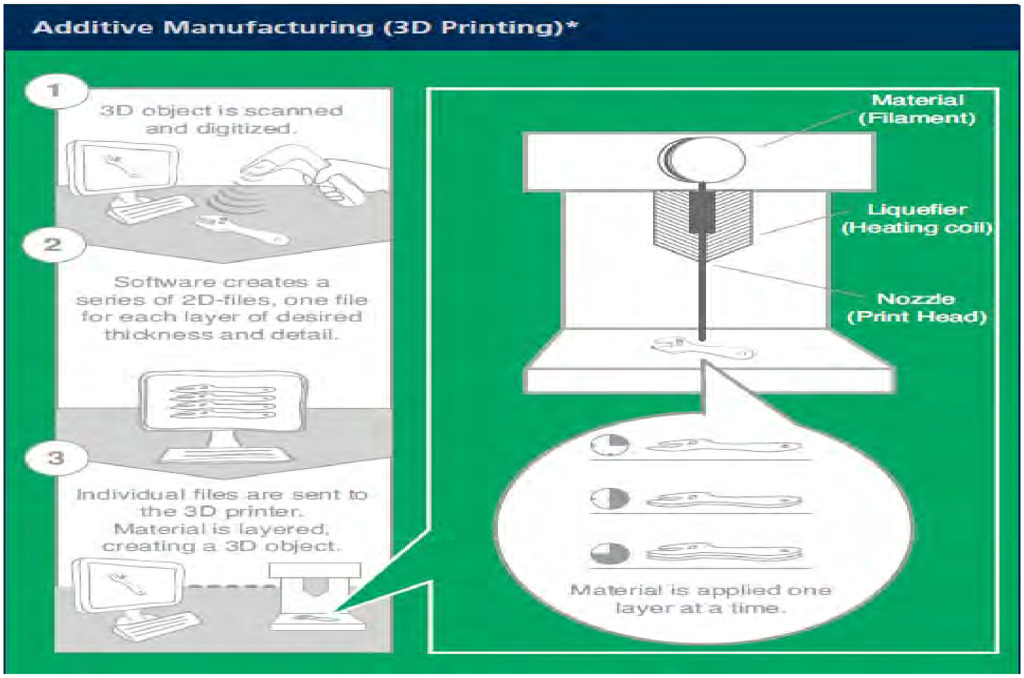


Figure 2. Illustration of the AM Process (from McNulty et al., 2012).

While there are variations between the different AM technologies, such as speed, layer thickness, range of materials, accuracy, and cost, the basic principles of layering source material one layer at a time drives almost all types of AM mechanisms (Gibson et al., 2010).

D. ADDITIVE MANUFACTURING METHODS

This discussion reviews the three most prominent forms of AM that are also the most common within the aerospace, automotive, healthcare, and manufacturing industries. Additionally, brief descriptions and graphical illustrations of each form of AM provide background information of these technologies. Finally, the primary advantages and disadvantages of each method are examined.

1. Stereolithography

SLA was one of the first techniques developed and is considered to be one of the most popular technologies available. SLA utilizes an ultraviolet laser that is scanned across the surface of a liquid photosensitive polymer to harden layers upon layers of cross-sectioned resin (Bartolo, 2011). Minor and Lasater (1997) provide a further detailed description:

> The build process uses these cross-sections of the part as patterns. A laser beam traces out and fills in each of these cross-sections on the surface of a vat of liquid photocurable resin. Wherever the laser traces, the liquid resin is cured to a solid, to a depth of approximately 0.006 to 0.009 inches. Once the entire cross-section is cured, the part is dipped into the liquid to recoat the part with liquid resin. The laser then traces out the next cross-section on top of the previous one. This process is repeated until all of the cross-sections of the part have been cured. At which time, the completed prototyped part emerges from the liquid. (p. 3)

Figure 3 is a graphical illustration of the SLA process. As seen in this figure, there is an elevator that dips the part into a vat of resin, which is cured by a laser, layer-by-layer, until the final product is achieved.

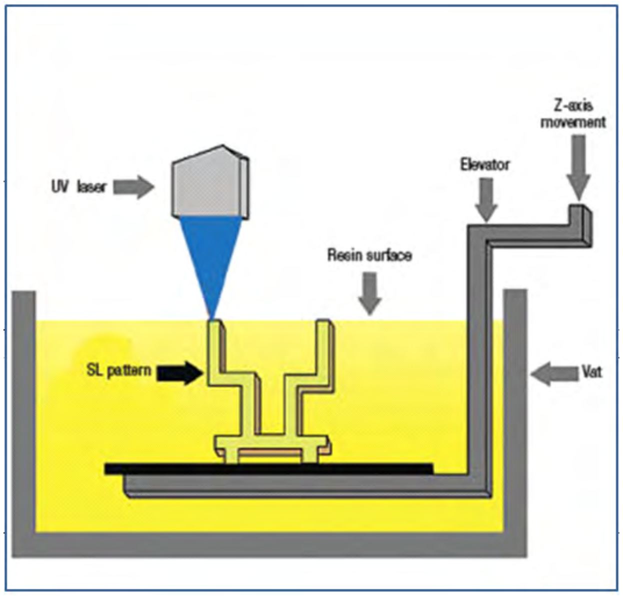


Figure 3. Illustration of the Stereolithographic Process (from Connelly, 2010).

In the article, “Means of Transportation in the Next Generation of Supply Chains,” Hormozi (2013) highlights a wide variety of applications available with the use of SLA, ranging from medical implants, to jewelry, to complex mechanical devices such as a grandfather clock. This technology has the ability to significantly increase the rate of production for prototypes and add an almost limitless level of customization during the product development process (Hormozi, 2013). As mentioned, prototype production time is significantly reduced. Gibbs and Winkelmann (2006) quantify exactly how fast this production rate can be, by stating, “The build rate for SLA parts is approximately 1 cu.in./hour (2.54 cu.cm/hour), which for most parts makes it the fastest process available” (p. 24). They continue to illustrate that “It is also capable of building the largest parts available” (p. 24).

Despite the seemingly endless benefits and capabilities of this technology, SLA is not without its limitations. The parts created with this technique can be brittle and are susceptible to distortion over time (Gibbs & Winkelmann, 2006). Additionally, they can have a somewhat tacky surface due to the fact that some of the resin used during the production process does not completely cure, which can lead to hazardous conditions, as uncured material can be toxic (Gibbs & Winkelmann, 2006).

2. Fused Deposition Modeling

The next technique of AM reviewed was the FDM method. Vartanian (2013) describes FDM as “a plastic filament is unwound from a coil and supplies material to an extrusion nozzle, which can turn the flow on and off. The nozzle is heated to melt the material and is moved in both horizontal and vertical directions by a motion control mechanism, driven by a tool path created directly from CAD model” (p. 52). The nozzle that moves across the production area produces a small bead of the heated material, which hardens practically instantly to create bonds that form the product layer-by-layer (Gibbs & Winkelmann, 2006). The capabilities of the FDM process are similar to the SLA process. Gibbs and Winkelmann (2006) describe these capabilities: “FDM parts can achieve a layer thickness of 0.004 to 0.020 in. (about 0.01 to 0.051 cm), and the build rate for this process is approximately 1 cu. in./hour (2.54 cu. cm/hour) with a maximum envelope of 24 x 20 x 24 (61 x 50.8 x 61 cm)" (p. 25). Figure 4 shows the FDM process. As seen in this figure, a heated filament extrudes through a nozzle in a specified pattern that is predetermined by a computer aided design (CAD) model until the final product is achieved.

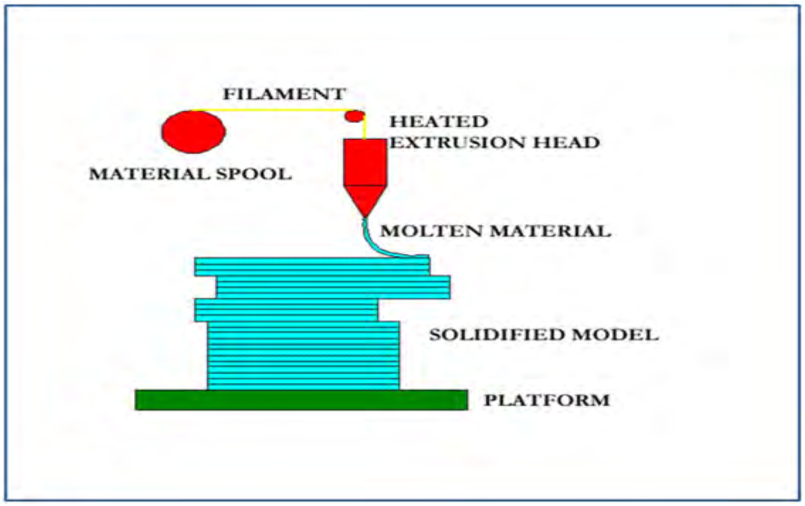


Figure 4. Illustration of the Fused Deposition Modeling Process (from Fused Deposition Modeling, 2012).

A couple of apparent advantages are associated with the FDM technique of AM. First, this process is the cleanest, quietest, and most environmentally friendly (Gibbs & Winkelmann, 2006). Additionally, the investment costs in this technology are relatively inexpensive when compared to the competing techniques (Gibbs & Winkelmann, 2006). For these reasons, FDM could potentially be the AM process of choice when one is determining the most cost-effective route.

On the other hand, despite the cost advantages and environmental efficiencies that FDM techniques offer, there are downsides. While the FDM process is considerably fast for small parts, once the product exceeds a few cubic inches or is designed with exceptionally large cross sections, the process can be much slower than other AM methods available (Gibbs & Winkelmann, 2006). Furthermore, "The finish of parts produced by FDM has been greatly improved over the years, but isn't quite on par with SLA parts" (Gibbs & Winkelmann, 2006, p. 25).

3. Selective Laser Sintering

The final AM technique reviewed was SLS, which is a technology that is highly suitable to the use of composites and functionally graded material (Silva & Rezende, 2013). Silva and Rezende (2013) provide a detailed description of the SLS process:

> SLS is a process where a laser beam transfers energy into a surface containing a thin layer of pre-heated powder material. A computer automatically controls the movement of the laser beam focus. The energy transferred by the laser beam fuses specific areas of the surface. After fusing one layer, another one is deposited and again the laser fuses this layer that will glue in the previous ones. This is repeated until the physical model is finished. (p. 2)

Figure 5 illustrates the SLS method of AM, which shows a laser that follows a predetermined route to trace out each layer into the powder of material that will become the final product.

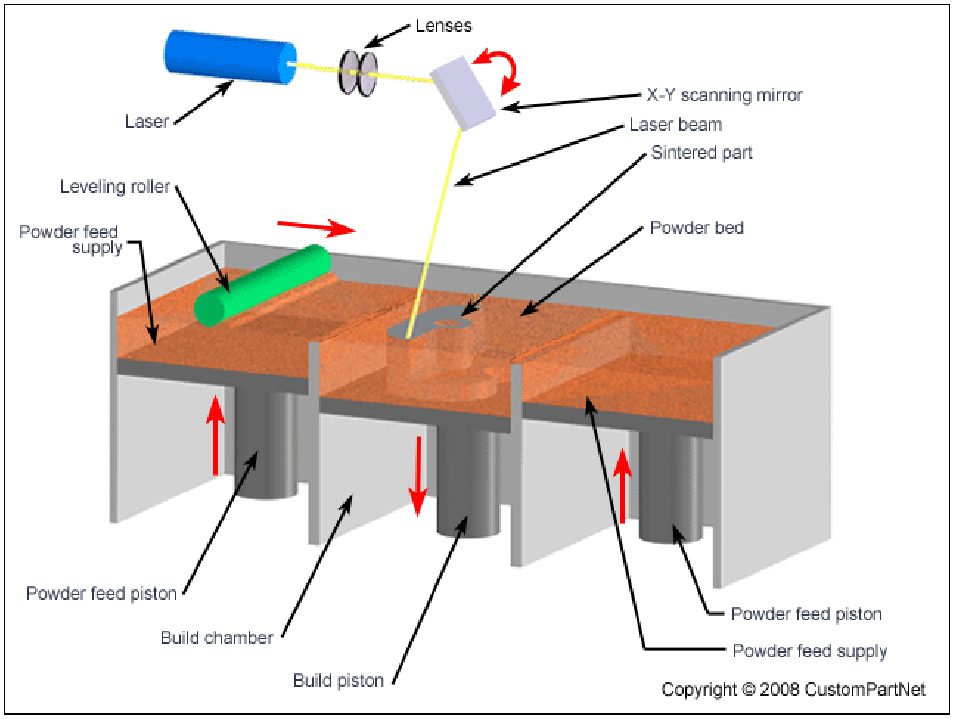


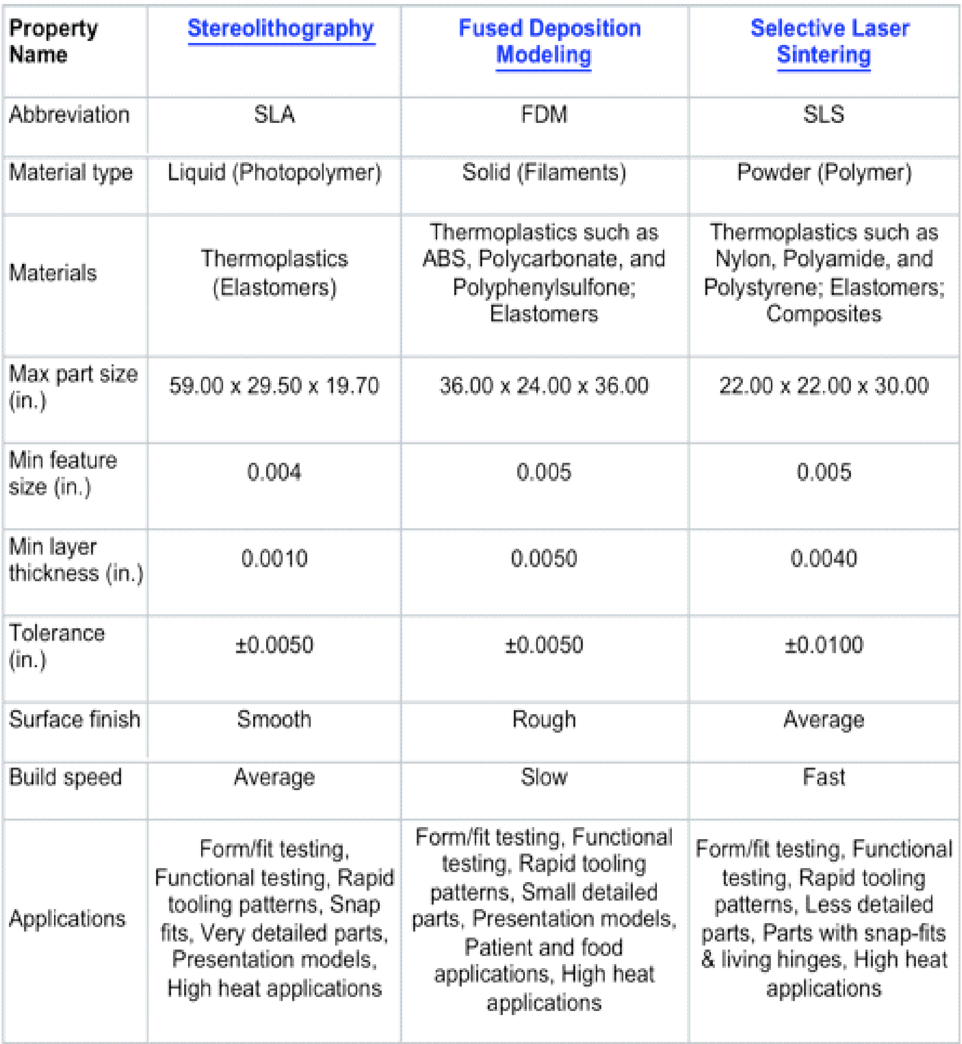
Figure 5. Illustration of Selective Laser Sintering Process (from Selective Laser Sintering, 2009).

One primary advantage of SLS technology is that it has a relatively fast production speed. The production speed that this method attains is primarily because the temperature inside the fabrication chamber is just below the melting temperature of the powder, allowing the laser beam to deliver the minimum amount of energy required to raise the temperature enough for the sintering process to take place (Gibbs & Winkelmann, 2006). Additionally, this technique of AM is quite versatile in the types of material that are compatible with its process. Gibbs and Winkleman state that "Powders can be inexpensive, produce high yields and offer faster part finishing" (Gibbs & Winkelmann, 2006, p. 25).

A few disadvantages of the SLS method were apparent when reviewing this technology. The first of which is the time required for cool down after the sintering process is complete. Before the product can be removed from the SLS machine, it must be allowed to cool to a temperature that allows it to be handled, which can take up to two days for larger parts with thin sections (Gibbs & Winkelmann, 2006). Another drawback associated with this process relates to the reduced quality of the finish and accuracy of the final product. Gibbs and Winkelmann state that " . . . surface finishes and accuracy are not as good as those of SLA, due to the grainy way in which the powder is sintered" (Gibbs & Winkelmann, 2006, p. 25).

The AM industry consists of multiple methods or techniques that have varying capabilities and limitations. Each of which has its individual strengths and weaknesses. Table 1 is a side-by-side comparison of these technologies that highlights the different material types, maximum product sizes, minimum layer thickness, tolerances, quality of finish, speed of production, and potential applications within the aerospace, automotive, healthcare, and manufacturing industries.

Table 1. Comparison of AM Methods (from Process Comparison, 2014).



Property Name	Stereolithography	Fused Deposition Modeling	Selective Laser Sintering
Abbreviation	SLA	FDM	SLS
Material type	Liquid (Photopolymer)	Solid (Filaments)	Powder (Polymer)
Materials	Thermoplastics (Elastomers)	Thermoplastics such as ABS, Polycarbonate, and Polyphenylsulfone; Elastomers	Thermoplastics such as Nylon, Polyamide, and Polystyrene; Elastomers; Composites
Max part size (in.)	59.00 x 29.50 x 19.70	36.00 x 24.00 x 36.00	22.00 x 22.00 x 30.00
Min feature size (in.)	0.004	0.005	0.005
Min layer thickness (in.)	0.0010	0.0050	0.0040
Tolerance (in.)	±0.0050	±0.0050	±0.0100
Surface finish	Smooth	Rough	Average
Build speed	Average	Slow	Fast
Applications	Form/fit testing, Functional testing, Rapid tooling patterns, Snap fits, Very detailed parts, Presentation models, High heat applications	Form/fit testing, Functional testing, Rapid tooling patterns, Small detailed parts, Presentation models, Patient and food applications, High heat applications	Form/fit testing, Functional testing, Rapid tooling patterns, Less detailed parts, Parts with snap-fits & living hinges, High heat applications

E. ADDITIVE MANUFACTURING WITHIN INDUSTRY

1. Aerospace

The aerospace and aviation industries are ones that can benefit greatly from the advancements that AM processes bring to the production of state-of-the-art components. General Electric Global Research Center (GEGRC) has been one of the leading companies in the development of AM for aviation components and has dedicated an entire lab towards the progression of AM (General Electric [GE] Capital, 2013). Combined with other technologies developed at GE, parts produced with AM technology will reduce the overall weight of GE's Leading Edge Aviation Propulsion (LEAP) engine by up to 1,000 pounds (GE Capital, 2013). In the article titled "Additive Manufacturing: Redefining What's Possible," GE states that "Each LEAP jet engine will incorporate 19 additive manufactured fuel nozzles" (GE Capital, 2013, p. 6). GE recently acquired two companies that specialize in the utilization of metals in AM, in order to ensure that they continue to stay on the leading edge of this technology as it continues to mature into the aerospace industry's next manufacturing practices (GE Capital, 2013).

2. Automotive

AM is also having a major impact in the automotive industry in the form of a two-passenger vehicle called the "Urbee." According to the Computer Sciences Corporation (CSC) report, *3D Printing and the Future of Additive Manufacturing*, the automotive industry is on the verge of being revolutionized by Kor, the maker of the Urbee (CSC, 2012). The CSC report asserts that by producing the shell of the Urbee via AM technology, they have "planted the seed for mass customization of large-scale car companies" (CSC, 2012, p. 12). The report goes on to emphasize advancements at automotive giant Bavarian Motor Works (BMW), where engineers have utilized current AM technologies to design customized and ergonomic tooling in an effort to reduce the amount of weight carried by workers on the production line (CSC, 2012).

3. Health Care

Another fascinating example of how AM is currently being utilized is an amazing feat that was accomplished by applying this technology to the health care field. Dr. Anthony Atala presented a summary of the work he conducts at the Wake Forest Institute for Regenerative Medicine (WFIRM) in which he uses a 3-D printer to replicate and generate human tissue in the form of a human kidney (Atala, 2011). McNulty et al. (2012) state:

> Dr. Anthony Atala of WFIRM has demonstrated an ongoing effort to grow human kidneys using 3D printers. To describe the process succinctly, the 3D printer constructs a frame from organic material and then places human tissue into the frame so that it grows and connects to form a functional human kidney. Creating an implantable kidney would represent

> a quantum leap in medical progress. At present, Atala's team has produced a kidney, however, additional research is needed before this process can be used clinically. (p. 5)

Figure 6 shows recent products of the AM processes at WFIRM. They include a kidney, ear, and finger bone.

Figure 6. Images of 3-D-Printed Kidney, Ear, and Finger Bone (from CSC, 2012).

This example of creating a complex human organ, while years away from implementation, does represent the tremendous accomplishments that AM has made possible and the boundless potential for the use of these technologies in the field of human medicine.

4. Manufacturing

The various forms of manufacturing that exists throughout the world has unlimited potential uses for AM. While the technology has not yet reached a stage in which it can compare to the strength and durability of current manufacturing technology, it has shown that it has the potential to drastically reduce costs in the form of product design, elimination of waste, and reduction in final production times (CSC, 2012). Table 2 illustrates the financial implications of implementing an FDM process into the production of a few sample specialty parts. Specifically, the CSC report states:

> Thogus Products, a custom plastic injection molder, found that for a particular specialty part, 3D printing (the Fused Deposition Modeling or FDM method) reduced the cost of manufacturing from $10,000 to $600, the build time from 4 weeks to 24 hours, and the weight of the object by 70-90 percent. (p. 6)

Table 2. Illustration of Benefits Realized with FDM Technology (from CSC, 2012).

PART/ TOOL	FDM	ALTERNATIVE METHOD
End of arm robot	$600 24 hours	$10,000 4 weeks
Automated turntable	$8,800 2 weeks	$50,000 8 weeks
Steel plates	$20 2 hours	$200 2 weeks

As the technology continues to advance, there are more materials available for use within the various AM techniques. McNulty et al. (2012) assert that as lasers continue to be enhanced, their operating temperature is allowing for the use of metals, such as titanium, which greatly expands the capabilities and range of candidates for 3-D printing.

F. NAVY SPARING SYSTEM

1. Readiness and Demand

The Deputy Undersecretary of Defense [Logistics & Material Readiness] [DUSD L&MR] (2003) states:

> The DOD components shall plan for and resource all elements of the supply chain to meet customer demand by developing and establishing support strategies that effectively and efficiently provide supply chain resources to meet supply chain requirements for future time periods. Material managers should collaborate with their customers or their representatives and maintenance and distribution and transportation managers to determine optimal support strategies that meet documented performance requirements. (p. 23)

This statement lays the groundwork for the expectation of service-level support required to adequately meet the equipping portion of the Navy’s mission. This process is executed by means of identifying, prioritizing, and aggregating customer demand. As stated by the Office of the DUSD[L&MR] (2003),

> Identification includes item classification and coding for requirements and requires collaboration with customers on their future needs. Prioritization entails setting parameters and goals for computing inventory levels so that those levels meet documented performance requirements. Aggregation involves accumulating and forecasting customer demand for products or services at the appropriate category, organizational level, and time interval. (p. 23)

The Navy quantifies customer demand in relation to parts support by either the readiness-based sparing or demand-based sparing approach. The methodology of each approach relates directly to the optimization support strategy, which is a trade-off between performance and cost. The fleet and program parts support initiatives are collectively managed by a number of methods and distributed across strategic locations to realize the complimentary benefit of end-user demand requirements in a manner that minimizes costs. Demand and readiness requirements are also tracked at the wholesale inventory level. The results of readiness and demand requirements drive the funding that is allocated to wholesale inventory holding costs.

a. Readiness-Based Sparing

Readiness-based sparing (RBS) is a method of inventory management that meets end-item performance requirements at minimum cost through strategic investment solutions (CNO, 2012). System readiness is a quantified metric that incorporates operational availability and mission capability rates. The computation for system readiness includes data of all components within a system as they relate to failure rates, repair requirements, cross-functionality, substitutability, and indenture structure (Office of the DUSD[L&MR], 2003). The financial investment aspect of readiness, relative to order and holding costs, determines the level of resource commitment that a program deems necessary.

This sparing method incorporates the above parameters and defines the range (type of parts) and depth (number of each part) of stock to reduce cost and maximize readiness for weapons systems (CNO, 2012). Mathematical models are used to calculate the optimal range and depth levels, and take into account the change of life-cycle costs over time (Office of the DUSD[L&MR], 2003). These mathematical models are not readily available to end-user logisticians and operators, but program-level points of contact can be reached for clarification and explanation of perceived issues or anomalies. RBS is the preferred method of sparing for both wholesale and retail inventory operations (Office of the DUSD[L&MR], 2003). In addition to range and depth, location of spares is an important determinate of RBS optimization.

RBS data is derived from data compiled and processed by Weapon Systems Support (WSS). As illustrated on the NAVSUP website, NAVSUP is divided into three business units: WSS, Global Logistics Support (GLS), and Sailor and Family Support (DON, 2014c). WSS is the business segment of NAVSUP that exclusively relates to this topic of discussion.

WSS employs 3,000 civilian, military, and contractor personnel, with $21 billion of inventory on-hand and an annual material budget of over $3.5 billion within its Navy SCM business segment (DON, 2014c). This support extends throughout the NAVSUP footprint to over 110 locations and 14 time zones. WSS utilizes RBS to provide life-cycle level sustainment and support to all Navy weapons systems.

b. Demand-Based Sparing

Demand Based Sparing (DBS) is utilized as the primary inventory management method in the absence of RBS or when RBS is determined to be not cost-effective for the purpose of inventory management (Office of the DUSD[L&MR], 2003). In the absence of weapons systems readiness as a quantifiable metric of performance, A_o is the primary metric used for establishing sparing requirements for system reliability, maintainability, and supportability (Office of the DUSD[L&MR], 2003). Optimal sparing methodology is a mathematical approach to compute item allowances based on balancing the priority of level of performance and associated costs (CNO, 2012). The DBS process is accomplished through assignment of demand-based items (DBIs). DBIs are generally defined as having relatively high issue rates. This rate is measured as a frequency of need that is greater than two occurrences per six months initially and once every six months thereafter (CNO, 2012). DBIs supplement the allowance of spares that are categorized as non-DBI. Non-DBIs are items that do not have a history of demand, but are stocked-based on insurance or program-level identification (CNO, 2012). DBIs are the stock that satisfies a requisition objective by accounting for parts of a consumable nature or high-failure parts that do not comport to existing forecasting models.

Sparing location determinations are as important a piece in the Navy supply chain process as sparing methodology. Wholesale, retail, open market acquisitions, and repairs all constitute system sparing solutions that involve availability and lead time decision-making analysis.

G. PRIORITY DESIGNATION

1. Priority and Urgency

Optimal sparing methodology is a mathematical approach to compute item allowances based on balancing the priority of the level of performance and associated cost (CNO, 2012). Part of that decision analysis entails urgency and priority designation. Urgency and priority determination inform Navy supply chain levels of risk associated with time and price.

The Uniform Material Movement and Issue Priority System (UMMIPS) details the movement and issue of material because it is necessary to establish a common basis of determining the relative importance of competing demands for resources within logistics systems such as transportation, warehousing, requisition processing, and material assets (NAVSUP, 2005). Urgency and importance are the two parameters used to assign relative importance. Urgency assigns a degree of system performance failure. Importance separates units by mission criticality.

Force/Activity designators (FADs) define military units or organizations on the basis of mission importance. The five levels of mission importance range from Roman numerals I to V. The Naval Supply Procedures Publication 485 (2005) defines FAD levels consistent with the following descriptions: FAD I is the highest importance and encompass U.S. forces in combat, national priority assignments as describes by the President, or declared emergencies. The second highest level is FAD II and pertains to combat-ready forces deployed outside the continental United States. (OCONUS). Forces maintaining combat readiness or direct support readiness are characterized as FAD level III. Units that are between 30 and 90 days before deployment are designated FAD level IV. All other forces are designated as the least relatively important units and utilize the level-V FAD designation.

Urgency of Need Designators (UNDs) define the degree of system degradation that is realized in the absence of required material. UND categories range from A to C, ranking highest to lowest level of urgency, respectively. UND A is for primary weapons systems and equipment that are degraded to prevent mission performance; material of this UND category is required immediately. UND B material is for auxiliary equipment failure that degrades primary mission performance at present or in the immediate future. UND C material is designated for administrative and support equipment, as well as material stock replenishment. The UND A through C descriptions above are all in accordance with the NAVUP P-485 (2005).

Priority designators (PDs) range from 01 (highest) to 15 (lowest) in precedence and are determined by the application of urgency and force/activity designator metrics, illustrated in Table 3. Priority designators are the backbone of UMMIPS and determine the time in which the requirement is processed (cradle to grave) by the supply system.

Table 3. FAD and UNDs to Priority Designators (from NAVSUP, 2005).

URGENCY OF NEED	**FAD**				
	I	**II**	**III**	**IV**	**V**
	Priority Designator				
A – Unable to Perform	01	02	03	07	08
B – Performance Impaired	04	05	06	09	10
C – Routine	11	12	13	14	15

Examples of priority designators include: PD02 for casualty repair in an operational theatre, PD03 for emergency medical supplies or riot/civil disobedience, and PD06 for essential clothing (NAVSUP, 2005). These PD examples illustrate the applicability of requirement fulfillment by creating categories of material support.

There are limitations on the amount of high priority (PD01-08) material that a unit can designate. Aircraft carriers, large amphibious ships, submarines, and regional maintenance centers can only designate 70% of all requisitions as PD01-08. Surface ships are allowed to assign 55% of all orders as high priority and FLCs can only designate 15% as PD01-08. For shipping and delivery, transportation priorities (TPs) are assigned utilizing the PD numbering system. TP1 is for PD01-03 material, and TP2 is for PD04-15 requisitions. All the limitations listed in this paragraph are provided in the NAVSUP P-485 (2005).

Weapons systems degradations of a catastrophic nature routinely have their priority categorized higher than PD03-06, depending on deployment status and the severity of the casualty. This designation is initiated by a casualty report (CASREP). CASREPs are utilized regardless of material corrective requirements, but often require material support (DON, 2014b). CASREPs that require material support are forwarded to a team of CASREP-dedicated expeditors who fulfill material requirements by moving them to the “front of the line.” This action essentially moves the priority of material handling to PD02-03 with regard to relative material wait time.

H. SUMMARY

The NSS meets mission objectives with maintenance and inventory programs. Maintenance is divided into repair and inventory processes. This chapter provides a top-level examination of Navy supply processes. The next chapter focuses specifically on describing the support functions of inventory and maintenance programs.

It is apparent from the description of the AM technologies mentioned above that there are varying degrees of capabilities and limitations between the machines available. This will undoubtedly be a crucial decision point for any potential introduction of AM into a supply chain. That being said, proven examples of successful introduction of AM into several industries illustrate the potential that this technology can have on a Navy supply chain.

The current NSS and its partners, as well as the parts and acquisition sections noted above, take a “big picture” look at Navy material support. Readiness, demand, inventory, priority, and speed discussions look at application-level supply issues. All of the above facets of Navy supply examined in this section will be further addressed as cornerstones of a methodological process to determine the applicability and feasibility of AM technology integration within the NSS.

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III. LITERATURE REVIEW

This chapter reviews the Navy equipment and weapons systems standards, and the specifications required for successfully implementing AM into the Navy supply chain.

In addition, recent case studies that evaluated costs associated with AM technology projects are reviewed. In the 2014 *Case Study: USS Whidbey Island* (LSD-41), authored by James Lambeth from the CDSA in Dam Neck, Virginia explored the possibilities of 3-D printing onboard a Naval ship. The other relevant case is the 2014 Aalto University, Finland cost analysis for AM-produced spare parts in the aeronautics industry.

A. DEFENSE STANDARDIZATION PROGRAM

Manufactured parts go through a standardization process to establish a baseline of industrial objectives for system and parts applications. The objective of this process is "to ensure that the contents of specifications cover only the requirements and testing for a product, preferably in terms of performance, to verify that those requirements are met; specifications should not include contractual provisions, such as data requirements, quality assurance, packaging, or contract administration" (DOD, 2003, p. ii).

A standard establishes the formats, contents, and procedures for the preparation of performance specifications, detail specifications, and associated documents, prepared either by government activities or under contract. Listed in Table 4 are associated documents that the U.S. Navy uses as policy guidance.

Table 4. Definitions of Standardization Guidance (from Office of USD[AT&L], 2000).

Acronym	Type	Definition
MIL-HDBK	**Defense Handbook**	A document containing standard procedural, technical, engineering, or design information about the material, processes, practices, and methods covered by the DSP. MIL-STD-967 covers the content and format for defense handbooks.
MIL-SPEC	**Defense Specification**	A document that describes the essential technical requirements for purchased material that is military unique or substantially modified commercial items. MIL-STD-961 covers the content and format for defense specifications.
MIL-STD	**Defense Standard**	A document that establishes uniform engineering and technical requirements for military-unique or substantially modified commercial processes, procedures, practices, and methods. There are five types of defense standards: interface standards, design criteria standards, manufacturing process standards, standard practices, and test method standards. MIL-STD-962 covers the content and format for defense standards.
MIL-PRF	**Performance Specification**	A performance specification states requirements in terms of the required results with criteria for verifying compliance, but without stating the methods for achieving the required results. A performance specification defines the functional requirements for the item, the environment in which it must operate, and interface and interchangeability characteristics.
MIL-DTL	**Detail Specification**	A specification that specifies design requirements, such as materials to be used, how a requirement is to be achieved, or how an item is to be fabricated or constructed. A specification that contains both performance and detail requirements is still considered a detail specification.

From an acquisition prospective, the Office of the USD[AT&L] (2000) states:

> The program manager must balance the decision to standardize against specific mission requirements, technology growth, and cost effectiveness. Under the DOD’s performance-based acquisition policies, it is primarily the contractor’s responsibility to recommend the use of standard materials, parts, components, and other items needed to meet performance requirements and satisfy other program elements, such as parts management and logistics support. However, interoperability, compatibility, and integration are key standardization goals that must be satisfactorily addressed for all acquisitions. These goals shall be specified and validated during the requirements generation process and throughout the acquisition life cycle. (p. 20)

There are questions that address the suitability of standardization for new technology. These questions relate to considerations that directly affect AM technology as well. Technological stability, manufacturing to solely satisfy customer approval, and inhibiting design flexibility and innovation are all concerns that acquisition professionals must address before pursuing standardization certification to serve the best interests of the supply chain process (Office of USD[AT&L], 2000).

Chapter three in the Defense Standardization Program (DSP) Policy and Procedures Manual, DOD 4120.24-M (2000), provides guidance on the types of issues and questions that buying commands need to address when deciding where, when, how, and to what level to standardize. These issues and questions are primarily intended to relate to the procurement of end items or reprocurement of components and piece parts (Office of USD[AT&L], 2000). Six applicable questions for this program include:

> Is physical uniformity a minimum essential requirement?
>
> Is uniform configuration necessary for ease of operation or safety?
>
> Must form, fit, function, or interface be defined to permit interoperability or connectivity between discrete items?
>
> Will the item be used in a variety of applications?
>
> Is design control necessary because predictable performance is a minimum essential requirement (reliability, maintainability, survivability, and safety)?

If the answer is "yes" to any of these questions, then consideration shall be given to standardizing the item (Office of USD[AT&L], 2000).

This section sets the precedent for AM integration into the existing Navy supply system. Standardization benchmarks and requirements must be satisfied by AM items for consideration for Navy supply chain inclusion. The above information provides an overview of the tests that must be satisfied by AM items.

B. USS WHIDBEY ISLAND CASE INTRODUCTION

1. Background

CDSA in Dam Neck Virginia, is spearheading an additive manufacturing initiate known as “print the fleet.” This is an exploratory endeavor that contributes to advancing technology in an effort to increase productivity, decrease costs, and improve warfighter support. Staging parts on afloat platforms, rather than using an intricate global supply chain, is an important Sea Basing initiative, mentioned by Federal Executive Fellow LCDR Mike Llenza’s presentation at a 2013 Washington, DC AM conference.

The *USS Whidbey Island* is utilizing 3-D printing onboard and serves as a test platform for substituting direct manufactured parts for routine sparing requirements. As the crew of the ship identifies part candidates that can be potentially fulfilled by means of 3-D printing, the engineering staff at CDSA generates requirements by means of additive manufacturing and assesses the production, installation, and success of utilizing requirements by AM means.

AM projects like these enjoy high visibility, which reach the highest ranks of Navy leadership associated with the cost savings and process efficiency that results from decreasing the organic supply chain footprint while improving readiness. A November 2013 CNO memorandum directs resource allocation toward developing additive manufacturing capabilities to improve the Navy, and this project is a direct reflection of following that order.

2. Rationale

CDSA engineers conducted a case study for one identified AM requirement in March 2014. This case study involved the replacement of sound-powered phone jack boxes. Brass boxes where discontinued for shipboard use due to their highly corrosive nature. Composite thermoplastic boxes are being installed as replacements, but the bolt hole locations are not in the same location as the brass box models. Rather than performing a ship alteration by cutting, grinding, welding, and painting the studs, a request to produce adapter brackets by means of additive manufacturing was made. The two facets of this project that add value to Navy AM are determining the feasibility of accomplishing small batch production successfully and creating ways to measure production and labor cost savings.

The outcome of this study helps establish a baseline for further research and assessment. Documenting the steps of the production process and identifying the analytics to measure project success and usefulness are dynamic endeavors. Creating a standardized approach to AM production and subsequent analysis helps the growth and monitoring of the Navy AM enterprise and is an essential step in the early stages of this process.

3. Shipboard Use Material Performance Requirements

As CDSA engineers continued developing this project, they soon realized that there were other barriers to overcome in order to implement this newly designed phone box adapter. Specifically, there is an extensive process of certifying a part of this nature for use in a shipboard environment. Mr. James Lambeth (2014) stated in its report, "Approval for meeting performance requirements are needed from multiple technical warrant holders. From past experience, a material scientist from Naval Surface Warfare Center (NSWC) Carderock Division estimated that this entire qualification process may take one to two years (p. 2)."

Table 5 is a summation of the performance requirements that must be met for a nonmetallic object, such as this adapter, to be considered for use onboard a U.S. Navy ship. The table illustrates a wide variety of testing and minimum requirements essential for shipboard use. These tests vary from shock and vibration to heat and corrosion.

Table 5. Nonmetallic Material Performance Requirements (from Lambeth, 2014).

TEST	ISSUE	REQUIREMENT
MIL-S-901	Shock	Grade A, Class 1, No failure
MIL-STD-167-1	Vibration	2-hour test, No failure
MIL-STD-1344	Impact / Random Drop	Six times, 4 ft drop, No failure
MIL-STD-1344	EMI / EMP	Min. 60dB
MIL-STD-810	Salt Fog	96 hr wet/dry, No corrosion
MIL-STD-810	High and Low Temperature	-28 F to 149 F, 3 days, Function, No cracking or sagging
MIL-STD-810	Solar Radiation	56, 24 hr cycles, no color change
ASTM E 162	Flame Spread / Dripping	25, self-extinguish, no drip
ASTM E 1354	Smoke / Heat Release	Cone 25, 50, 75 kW/m2
ASTM E 662	Smoke Density	Smoke < 200

4. Cost Elements and Equation

CDSA Dam Neck documented most data elements associated with the sound-powered phone-jack box adaptors during the project. Costs of input materials include tip sets, individual tips, foundations, modeling material, support material, and miscellaneous items. Applying the following equation to the cost data and volume requirements of production results in the cost of production:

$$P = \frac{V_m \times P_{fm}}{V_{fm}} + \frac{V_s \times P_{fs}}{V_{fs}}$$

Formula 1. CDSA Material Cost Formula (from Lambeth, 2014).

The variables in the equation are:

P – price of the part

V_m – estimated volume of the required model material

V_{fm} – volume of a full canister of model material

V_s – estimated volume of required support material

V_{fs} – volume of a full canister of support material

P_{fm} – price of a full container of model material

P_{fs} – price of a full container of support material

This equation captures the cost analysis of production for direct material costs. Other direct and indirect costs, such as overhead, labor, and various fixed costs, are not included in this calculation. CDSA compared total material costs for the production batch for each AM material solution to the traditional manufacturing anodized aluminum solutions. Additionally, CDSA Dam Neck documented production lead times to allow the assessment of time constraints of each solution as cost elements. A number of cost elements remain undisclosed in this case study. Further discussion on this missing facet of the project will be discussed in the next section.

5. Current Status

The Navy AM program is currently in the initial stages of growth and has immature elements within its analytical processes. Large amounts of data have been collected over the last calendar year, since the inception of the "print the fleet" program. The data has not been converted into numerous case study reports, but case studies are scheduled for preparation in 2015. Generating reports and program-wide analysis are currently secondary concerns. Production success and applicability are the primary areas of interest. This is because establishing viable production continuity must preclude result analysis for programs that intend to grow into a high-volume, immediate response process. Extrapolating and transferring raw data into information is not an easy process due to the technical nature of the software. The interface is not user-friendly and data processing is designed for users with a familiarity in the data inputs that normally necessitates an engineering background. This section is the starting point and provides background for facilitating cost estimates for economic feasibility analysis.

C. ECONOMIC ANALYSIS INVOLVING COST DATA

An academic report titled *Additive Manufacturing in the Spare Parts Supply Chain* by Khajavir, Partanen, and Holmstrom (2013) addresses 3-D printed parts, and tests whether this emerging technology can find its footing in the sparing supply chain from a technological and economically feasible standpoint.

1. Purpose of Research

Khajavi et al. (2013) compares current and future AM technology of F-18 Super Hornet fighter jets' air-cooling ducts with centralized and distributed supply chain configurations, producing four separate scenarios of AM capabilities. Examining centralized and distributed production facilitates assessment of another level of trade-offs—transportation and lag time costs versus speed of support and turnaround time.

Demand uncertainty and quality responsiveness are the elements defining the struggle between low operating costs and customer satisfaction. Quantifying the size of military logistics and parts, measured in dollars, is very important information included in the Aalto University study conducted by Khajavi et al. (2013).

The outcome of the Khajavi et al. (2013) report identified cost drivers that differentiate production methods as material costs, AM machine depreciation, and personnel costs of operation. Manufacturers do not normally determine material costs technological advancement and process improvement operational initiatives typically control machine and personnel costs. Ultimately, as machine and labor costs per machine drop, distributed production becomes a feasible means of supply chain sparing. This point was the primary take-away of the Khajavi et al. (2013) report.

2. Cost Analysis Approach

The research process, illustrated in Figure 7, represents the logical flow of how economic analysis is approached for investigating additive manufacturing scenarios and alternatives. Assessing demand and all associated costs as data inputs is essential for conducting a study that determines economic feasibility of additive manufacturing. There are a large number of assumptions in this report with regard to production and future technology costs. Without comprehensive cost data, the results of the study turned into a theoretical analysis of capabilities, rather than a timely quantitative summation.

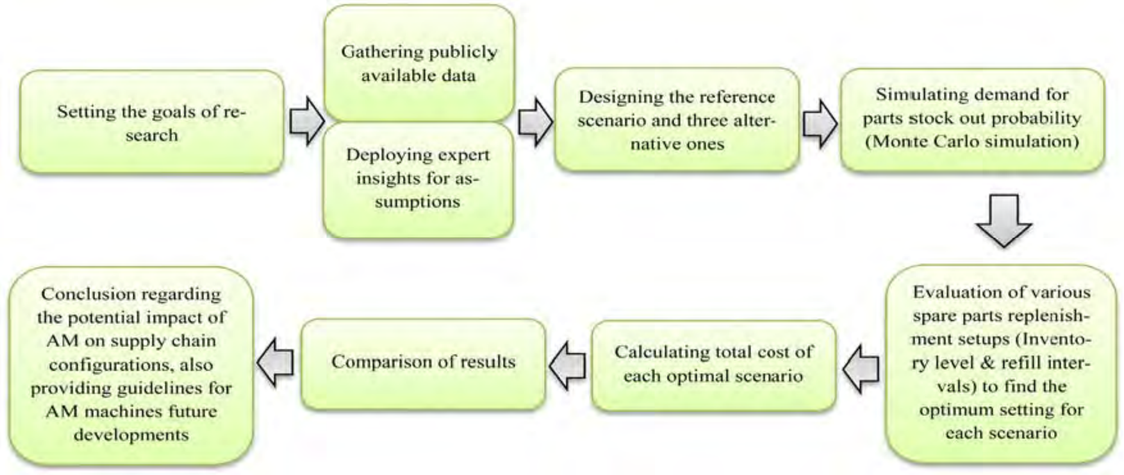


Figure 7. Economic Analysis Flow (from Khajavi et al., 2013).

The following 11 cost categories represent the cost data: personnel, material, spare parts transportation, inventory carrying, aircraft downtime, inventory obsolescence; initial machine investment (depreciation), total machine investment, annualized initial inventory production, total initial inventory production, and expected total scenario per annum. These data compare each scenario's depth of financial operational obligation.

3. Scenario Information

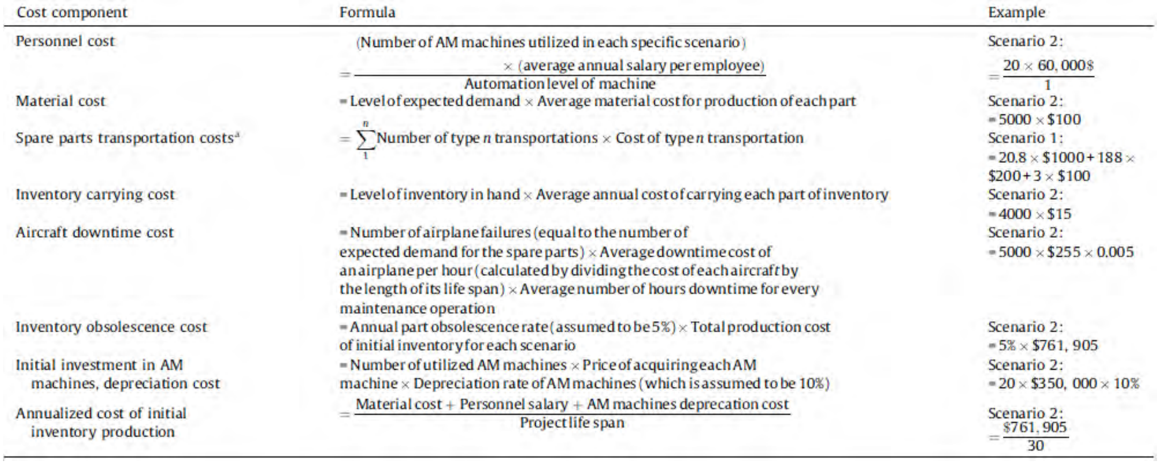
Khajavi et al. (2013) included 18 items of information for each scenario to determine a "best value" solution. A number of items were excluded that directly pertain to distribution decision-making information because they are outside the scope of our report. The information Khajavi et al. (2013) quantified is: expected spare parts demand, machine automation level (number of operators per machine), machine lifetime, machine depreciation rate, spare parts inventory level, average inventory carrying cost per part, annual inventory obsolescence rate, required time to produce one spare part, production capability of each machine, and average downtime cost.

Demand for spare parts, assumed inventory levels, and replenishment time intervals were determined by using Monte Carlo simulation. All the above data were utilized in spreadsheet-style statistical models to provide scenario outcomes. The number of assumptions made in this report was a limiting factor in the analysis of AM in spare parts supply chain conclusions.

4. Calculations Applied

The calculation methods of each cost component are of the most relevance to this report’s economic feasibility study. Table 6 illustrates the Khajavi et al. (2013) method and examples.

Table 6. Methods and Examples of Cost Calculation Method (from Khajavi et al., 2013).



Cost component	Formula	Example
Personnel cost	$= \frac{(\text{Number of AM machines utilized in each specific scenario}) \times (\text{average annual salary per employee})}{\text{Automation level of machine}}$	Scenario 2: $= \frac{20 \times 60,000\$}{1}$
Material cost	= Level of expected demand × Average material cost for production of each part	Scenario 2: = 5000 × \$100
Spare parts transportation costs[a]	$= \sum_{1}^{n}$ Number of type *n* transportations × Cost of type *n* transportation	Scenario 1: = 20.8 × \$1000 + 188 × \$200 + 3 × \$100
Inventory carrying cost	= Level of inventory in hand × Average annual cost of carrying each part of inventory	Scenario 2: = 4000 × \$15
Aircraft downtime cost	= Number of airplane failures (equal to the number of expected demand for the spare parts) × Average downtime cost of an airplane per hour (calculated by dividing the cost of each aircraft by the length of its life span) × Average number of hours downtime for every maintenance operation	Scenario 2: = 5000 × \$255 × 0.005
Inventory obsolescence cost	= Annual part obsolescence rate (assumed to be 5%) × Total production cost of initial inventory for each scenario	Scenario 2: = 5% × \$761, 905
Initial investment in AM machines, depreciation cost	= Number of utilized AM machines × Price of acquiring each AM machine × Depreciation rate of AM machines (which is assumed to be 10%)	Scenario 2: = 20 × \$350, 000 × 10%
Annualized cost of initial inventory production	$= \frac{\text{Material cost} + \text{Personnel salary} + \text{AM machines deprecation cost}}{\text{Project life span}}$	Scenario 2: $= \frac{\$761,905}{30}$

There were efforts made to mitigate the amount of assumed costs; but without weapons systems program office involvement, subject matter experts must fill in the informational gaps with varying degrees of assumption.

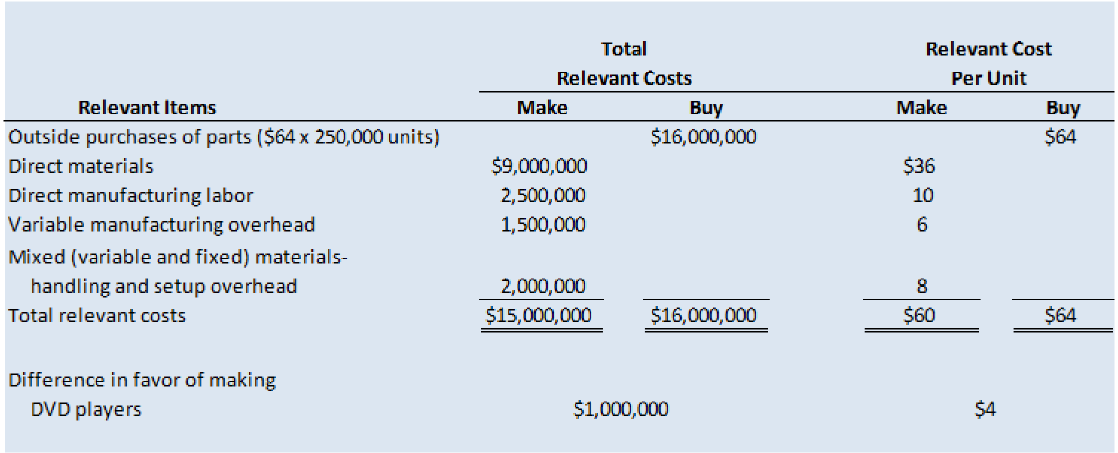
This section illustrates previous academic and research efforts directed toward cost estimation alternatives. Although the data required for comprehensive analysis were not collected, the approach is worth noting for further efforts included in this report.

D. MAKE VERSUS BUY DECISION CRITERIA

As the Navy continues to grow its organic manufacturing capabilities, it will inevitably be faced with the decision to make a product in-house (insource) or buy that product from within industry or outside manufacturing facilities (outsource). Datar, Horngren, and Rajan (2012) infer that common decision criteria for managers include quality, dependability of suppliers, and costs as the most influential factors over this crucial decision. On the other hand, there are other considerations, such as qualitative factors, that management must weigh in their decision-making process (Datar et al., 2012). For DOD, these qualitative factors typically equate to speed of acquisition or availability of material in a forward-deployed environment and must be considered on a case-by-case basis.

For the purposes of standardizing decision criteria, qualitative considerations are excluded, as they are case-specific and considered separately. When determining whether to make versus buy, management should attempt to answer the question, “What is the difference in relevant costs between the alternatives?” (Datar et al., 2012, p. 398). Datar et al. define relative costs as “expected future costs that differ among the alternative courses of action being considered” (2012, p. 393). Table 7 provides an example of relative costs compared between alternatives of insourcing or outsourcing a digital versatile disc (DVD) player. As seen here, there is $2,000,000 of future materials-handling and setup costs that are added to the make alternative buy, not under the buy alternative, because this is a future cost that is only incurred when the product is manufactured in-house and, therefore, is a relevant cost (Datar et al., 2012). Additionally, it should be noted that certain fixed costs, such as leases, insurance, or administrative costs, are not considered under either alternative because these are examples of costs that will be incurred by the firm despite the chosen alternative. Therefore, this is an example of an irrelevant cost.

Table 7. Example of Make vs. Buy Criteria (from Datar et al., 2012).



	Total Relevant Costs		**Relevant Cost Per Unit**	
Relevant Items	**Make**	**Buy**	**Make**	**Buy**
Outside purchases of parts ($64 x 250,000 units)		$16,000,000		$64
Direct materials	$9,000,000		$36	
Direct manufacturing labor	2,500,000		10	
Variable manufacturing overhead	1,500,000		6	
Mixed (variable and fixed) materials-handling and setup overhead	2,000,000		8	
Total relevant costs	$15,000,000	$16,000,000	$60	$64
Difference in favor of making DVD players	$1,000,000		$4	

Make versus buy determinations are important for economic feasibility analysis of costs. This can be applied to AM versus TM insourcing analysis, as well as insourcing versus outsourcing determinations. The scope and simplicity of this tool is essential for analysis at the individual item level or at a class-wide or bundled production level.

E. SUMMARY

Navy sparing and priority designation are the lower-level processes that inform the maintenance and inventory NSS programs of the required level of support. Sparing and priority designation policies and procedures applicability is crucial in determining AM applicability for meeting mission A_0 requirements. This chapter discussed the requirements, standards, and specifications that exist to introduce an item into the Navy supply chain, with intentions to integrate that item into Navy equipment and weapons systems. The 2014 Aalto University study(Khajavi et al., 2013), CDSA Dam Neck program details, and the make versus buy decision system set the foundation for the method of approaching and analyzing decisions in how individual AM parts can become an economically feasible Navy supply chain solution. Standardization program decisions relate to technological capability constraints and subsequent decisions for program support. The CSDA Dam Neck case illustrates current initiatives and cost data decision methods for analyzing individual item costs. The 2014 Aalto University study illustrates production-wide decision and cost data for program-level consideration. Finally, make versus buy concepts are applied to current manufacturing, and sourcing alternatives form a cost perspective. This chapter informs both the methods and analysis of economic feasibility for AM part candidate decision making.

IV. METHODOLOGY

A. INTRODUCTION

First, this chapter analyzes the relationship between NSS's maintenance and inventory processes, sparing theory, and priority designation criteria as a means to assign AM parts candidate necessity for each part identified. This provides a contextual description of the analysis on the three approaches for identifying AM parts candidates: (1) frequently replaced parts, (2) parts that are not readily available to end-users, and (3) parts that are deemed critically essential.

Second, this chapter presents the steps used to collect and analyze the data used in this report.

Next, we discuss the relative importance of three factors: (1) demand requirements, (2) material specifications/requirements, and (3) economic feasibility that influence decisions to introduce AM into the Navy supply chain.

This chapter also details the method for calculating costs and how those costs can be applied to AM part candidate determinations. This is accomplished by applying the quantitative specifics of the USS *Whidbey Island* case, traditional manufacturing, cost of time, and factors not considered within the context of this report.

B. NAVY PARTS SUPPORT PROCESS STRUCTURE

The NSS AM parts candidate decision-making flow chart (see Figure 8) is divided into programs and processes. Programs include maintenance, repair, and inventory. These programs are defined as plans for mission requirements that are informed by the lower-level processes. The processes are sparing theory and priority designation criteria. The processes work together to define the requirements of higher-level program goals.

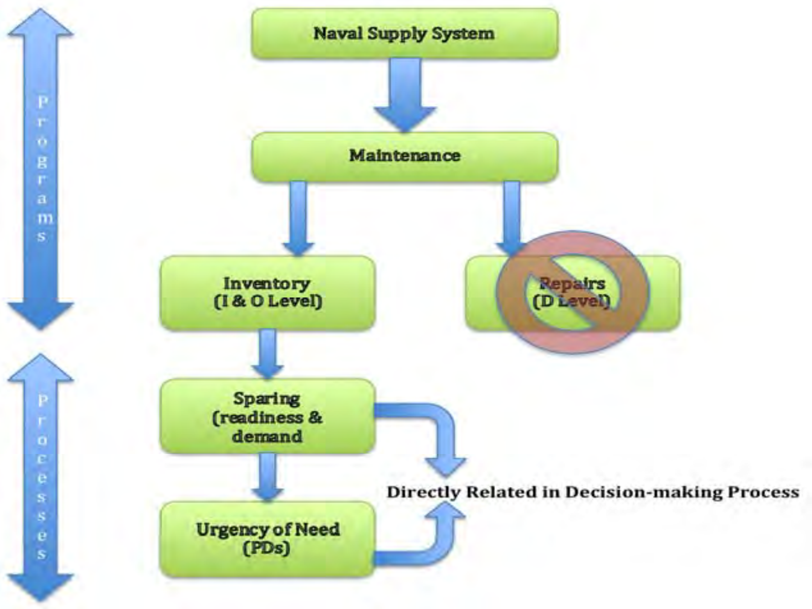


Figure 8. Navy Supply System AM Part Candidate Flow Chart

1. Maintenance

The maintenance program is the starting point for operational troubleshooting. Software programs, including maintenance logs, are recorded in the local supply system, which are uploaded to the Coordinated Shipboard Allowance List (COSAL) and WSS) mainframes. This upward reporting informs programs of trends and quantifiable requirements. Maintenance software also queries parts necessary for repairs and facilitates communication with related software that searches for parts inventory. Systems, subsystems, and parts that require repair can be assessed for AM candidacy.

a. O-Level and I-Level Maintenance

O-level, and most I-level, maintenance actions are best suited for examination for AM part candidacy. This is because routine preventative maintenance and less complex maintenance actions are conducted at these two levels. These relatively simple maintenance actions generally necessitate simple parts. The method for determining suitability of parts that require maintenance, rather than replacement, is based on comparing man-hours expended and associated material costs. Fabrication and modification times are compared with additive and traditional manufacturing processes. Calculating the difference in production time required for each process yields cost data used to determine whether AM is advantageous for each maintenance action studied on an individual basis. The primary differentiating factor of repairs between the two manufacturing methods is the lead time required to fulfill material or component delivery. Input material that is readily available for AM eliminates lead time concern and also provides additional cost savings. This savings is realized from reduced holding costs associated with storing numerous raw materials. AM implementation eliminates buying, maintaining, and utilizing a number of fabrication machines tool sets.

b. D-Level Maintenance

D-level maintenance actions are the most complex and are mostly handled at the manufacturer or under the supervision of engineers. Supply support solutions, including inventory and sparing, are unlikely to occur with D-level maintenance actions. For the purposes of this report, complex and expensive maintenance actions are excluded from further AM part candidacy consideration.

2. Inventory

Wholesale and retail inventory programs are informed by sparing theory and priority designation. It is assumed that wholesale inventories are congruent with centralized AM processes, and that retail inventories are similar to distributed AM. The range and depth of parts in wholesale inventories is determined by examining sparing theory. The range of parts is most related to readiness-based parts, and the depth of part inventories is predicated on demand. The range and depth of parts in retail inventories is realized by examining each part’s priority designation. The driving force of retail inventories is determined by demand-based sparing. Class-wide retail inventories include readiness-based mandated parts to be onboard, but the total number of parts is small in comparison to demand-based totals.

3. Sparing Methods

Sparing is the central concept of AM part candidate determination. It is assumed that a majority of demand-based parts are held at the retail inventory level, and that a majority of readiness-based parts are held at the wholesale level. Sparing is manifested through inventory profiles that are informed by documented maintenance requirements. The inventory levels required is a direct function of sparing methodology; therefore, AM part candidacy must be determined within the context of Navy-wide sparing objectives.

a. Readiness

The primary decision-making driver for AM part suitability for NSS program evaluators involved each requirement's current readiness and demand profile. Readiness encompasses predetermined required levels of sparing that are derived from insurance agreements and program-level mandates, based on mission criticality and operational availability policy. Mathematical models also inform readiness by anticipating failure rates by system/component risk reduction. Range and depth retail inventories are predicated on these mathematical models. Most spares defined as readiness-oriented are of a repairable nature. Current AM technology can only support a limited portion of repair parts. This small category of parts is limited to requirements produced with one composite material, limited material alternatives, and the most basic mechanical performance characteristics. Consumable materials possess little to no mechanical process characteristics. They are also designed to operate within a limited usage or time frame, thus possessing higher relative turnover and demand profiles. There are predetermined range and depth requirements for spares of a consumable nature. These part candidates are ideal for AM in the short run and would serve as the primary justifying cost from a readiness perspective.

b. Demand

Demand-based sparing is reactionary in nature; not based on anticipation, but on realized replacement rates. DBS inventory controls directly combat system "gremlins" that are caused by misalignment, an unbalanced load, gear meshing, resonance, flow-related, or electrical issues. Navy shipboard demand is unique for each ship, based on the failure rate of systems, which is also unique for each ship. The common aspect of shipboard demand, across ship classes and among each ship in a class, is the demand for consumable items. Gaskets, casings, washers, and screws are all examples of common consumable items. Spares such as these are ideal candidates of AM from a demand perspective. Certain repair parts also have a high demand, like valves and cylinder heads. The mechanical complexity of these parts is what drives AM candidacy of repair parts, not demand profile.

c. Priority Designation

Priority designation is directly related to the sparing methods of readiness and demand. Together, these two concepts inform inventory program's appropriate levels of support required for operational availability. Priority and speed are what drives various levels of urgency. It is assumed that onboard spares are defined as "must carry" and stocked at the retail level of inventory management. For other COSAL-based parts, the priority and speed required for correcting failed parts and its relationship to mission criticality determine the inventory type that is most appropriate. Mission criticality does not play a role in wholesale or retail inventory determinations. Just as urgent requirements get delivered at a higher cost and more expeditiously, urgent AM requirements would move up in the queue, rather than enter at the back of the line. For AM requirements that are not produced locally, urgency rules of delivery apply like all other part requirements.

C. PARTS CANDIDATE APPROACH

Three methods of approaching parts candidate determination are assumed in this report. Parts that are frequently demanded, parts that are unavailable, and parts of a critical nature are examined in further detail to determine the extent of relevance that they each have in AM part candidate determinations.

1. Frequency

Frequency is assessed in terms of the number of requirements demanded for a period of time. This may be due to high failure or consumption rates. For this approach, reviewing demand-based information is most appropriate. Current inventory levels are assessed for each part candidate. Priority designation reports are compiled by segregating individual part candidates to determine trends in demand and urgency. Frequency is the AM parts candidate determination approach that yields the highest number of parts candidates.

2. Availability

Availability is assessed by the lack of readily available parts for weapons systems and subsystems—also termed "unsupported parts." Another form of availability concerns immediacy of disposition. System obsolescence, manufacturer evanescence, and vendor discontinuation are all common reasons for part unavailability. COSAL queries of WSS data can be processed to generate a master list of unsupported parts. CASREPs and historic requisition, queried by part, also yield a demand profile. The resulting information is to be used in decision making for AM candidacy.

3. Criticality

Criticality is defined in terms of the amount of degradation that the absence of a functional part contributes to the operational objective. This may be due to system dependence on one part or the mission dependence on a system. For this approach, the review of readiness-based information is most appropriate. Insurance stock, program mandated spares, and criticality codes all serve as information sources for parts inventory requirements. It is assumed that criticality is already a major priority of weapons systems program professionals, and most critical parts are either too complex for AM candidacy or inventory levels are already satisfied with traditional manufacturing for the duration system life cycles. The analysis of these approaches will be ancillary to the purposes of this report.

D. TECHNICAL CAPABILITIES AND MATERIAL REQUIREMENTS

One of the foremost factors to consider when applying any AM technology to a potential project for use within a Navy supply chain is the end material requirements and the specifications needed to adequately function in the target system of use. Additionally, the AM technology available for use must have the capability to meet those material requirements and specifications. For example, a deck drain printed for use on a Navy ship must be able to withstand the shock and vibration stresses that are constantly present when a ship is operating at sea.

In order to appropriately ensure that military specifications and standards are met, we propose a process of comparing the material performance requirements that are described in the publications summarized in Table 4 to the technical capabilities and limitations of the AM processes described in Table 1.

Table 4 is a list of associated documents that the Navy uses to establish standard formats, contents, and procedures for the preparation of performance and detailed specifications of material that is prepared by the government or by contracted agents. The standards and specifications that make up these documents drive the quality of fit, form, and function of material destined to be integrated into Navy equipment and weapons systems. Ultimately, these standards maintain the integrity and reliability of the equipment and weapons systems that our Sailors operate on a daily basis throughout the Navy. As we consider the introduction of 3-D printing into the Navy supply chain, there is an ever-present set of criteria represented in these documents that must be met in order to successfully adopt AM as a viable process and supply solution.

Table 1 compares three common forms of AM side-by-side, showing the capabilities and limitations of each 3-D printing technique. This information makes it possible to identify what types of source material is possible in these AM processes and what the expected outcomes will be of the items produced. Additionally, Table 1 offers a quick and easy way to determine the most appropriate method of 3-D printing for an individual project.

When considering any particular item as a potential 3-D project, comparing the information in these two tables will ensure that the technologies available for use have the capabilities to meet the standards and specifications required for integrating printed material into Navy equipment and weapons systems.

E. DETERMINING COSTS

The method to approaching cost determinations include examining the USS *Whidbey Island* case, explaining the approach to traditional manufacturing cost, factoring in the cost of time, and costs not applied to this report for various reasons.

1. Calculations and Formulations

ASB-ESD7 is the base or modeling material used in the USS *Whidbey Island* AM process. The supporting material used is SR-30 (Lambeth). For the remainder of this report, all associated material costs will be limited to the production of sound-powered phone jack boxes made with ABS-ESD7 model material and SR-30 support material. The material cost formula introduced in Chapter III is:

$$P = \frac{V_m \times P_{fm}}{V_{fm}} + \frac{V_s \times P_{fs}}{V_{fs}}$$

Formula 2. CDSA Material Cost Formula (from Lambeth, 2014).

For the purposes of this report, some variables are renamed to avoid confusion. P-type variables are converted to C-type variables, such that price and cost are not abbreviated or used interchangeably. This report utilizes the following formula:

$$C = \frac{V_m \times C_{fm}}{V_{fm}} + \frac{V_s \times C_{fs}}{V_{fs}}$$

Formula 3. NPS Project Formula.

The variables in the equation are defined as:

C – material cost of each unit produced

V_m – estimated volume of the required model material

V_{fm} – volume of a full canister of model material

V_s – estimated volume of required support material

V_{fs} – volume of a full canister of support material

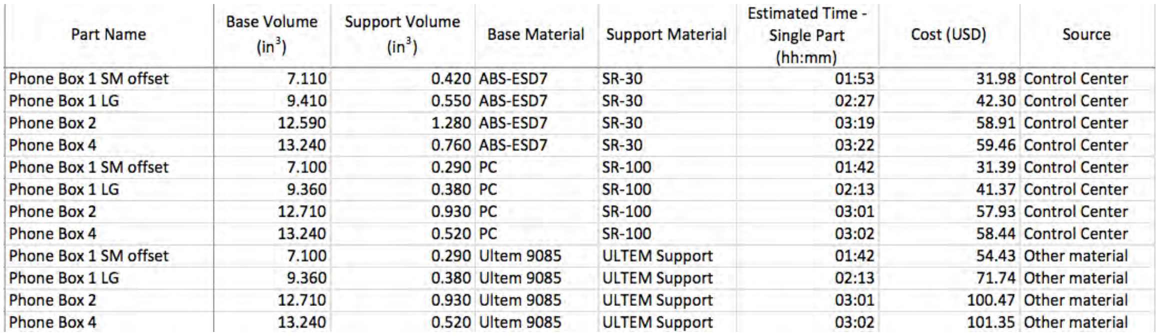
C_{fm} – price paid for a full container of model material

C_{fs} – price paid for a full container of support material

CDSA Dam Neck uses the same economic analysis flow approach as Aalto University's approach (see Figure 9), with the exception of applied demand simulation and replenishment setups.

In applying the total material cost formula, volumes of model material (V_m) and support material (V_s) must be measured. CDSA engineers generated the following report from AM analytical software:

Table 8. Modeling and Support Material Volume, Time, and Cost Data (from Lambeth, 2014).



Part Name	Base Volume (in^3)	Support Volume (in^3)	Base Material	Support Material	Estimated Time - Single Part (hh:mm)	Cost (USD)	Source
Phone Box 1 SM offset	7.110	0.420	ABS-ESD7	SR-30	01:53	31.98	Control Center
Phone Box 1 LG	9.410	0.550	ABS-ESD7	SR-30	02:27	42.30	Control Center
Phone Box 2	12.590	1.280	ABS-ESD7	SR-30	03:19	58.91	Control Center
Phone Box 4	13.240	0.760	ABS-ESD7	SR-30	03:22	59.46	Control Center
Phone Box 1 SM offset	7.100	0.290	PC	SR-100	01:42	31.39	Control Center
Phone Box 1 LG	9.360	0.380	PC	SR-100	02:13	41.37	Control Center
Phone Box 2	12.710	0.930	PC	SR-100	03:01	57.93	Control Center
Phone Box 4	13.240	0.520	PC	SR-100	03:02	58.44	Control Center
Phone Box 1 SM offset	7.100	0.290	Ultem 9085	ULTEM Support	01:42	54.43	Other material
Phone Box 1 LG	9.360	0.380	Ultem 9085	ULTEM Support	02:13	71.74	Other material
Phone Box 2	12.710	0.930	Ultem 9085	ULTEM Support	03:01	100.47	Other material
Phone Box 4	13.240	0.520	Ultem 9085	ULTEM Support	03:02	101.35	Other material

The utilized volumes in Table 8 are for all four AM phone box variants produced. Relevant data is limited to the first four rows of information, which include ABS-ESD7 and SR-30 material only. These volumes will be applied and analyzed within the context of AM part production decision making in the next chapter.

Modeling and support material canister volumes were provided by CDSA Dam Neck engineers in separate correspondence. The price paid for CDSA Dam Neck engineering staff also provided full containers of modeling and support material. For the purposes of this report, it is assumed that the price paid for full containers of material is treated the same as the total cost of a canister of material.

2. Traditional Manufacturing Costs

For the purposes of this report, traditional manufacturing costs are either the price paid for parts bought from commercial sources or total material cost of producing parts in-house by means of traditional manufacturing. CDSA Dam Neck derived commercial part sourcing from market research and in-house TM costs from the same method illustrated above in AM material cost determinations. Detailed analysis is not available from CDSA Dam Neck for TM material costs. It is assumed, for the purposes of this report, that comparative analysis of TM and AM processes is limited to raw material input costs and total labor hours per unit. Other fixed and indirect costs are not included in economic feasibility determination, but are certainly notional factors in AM decision-making determinations.

3. Cost of Time

For the purposes of this report, the cost of time is defined two ways. First, the labor costs directly associated with in-house production of a part has a quantifiable cost. This cost is calculated by multiplying the time, measured in hours, required to produce one unit of product by the hourly labor rate, times the number of people required to produce one unit. Labor includes only the direct effort of manufacturing, while excluding indirect labor efforts.

The second cost of time involves lead-time estimates and how they relate to priority and urgency requirements associated with material delivery. Table 8 includes estimated production time for a single part in hours and minutes. In-house production is estimated to be one to two weeks for AM, and two to five weeks for traditional manufacturing ™, according to CDSA Dam Neck estimates. The quantifiable data associated with these stated lead times do not exist because set-up, change out, and material replenishment times are known. The full scope of how urgency and priority requirements are assessed is addressed in next section of this report.

4. Costs Not Considered

Semi variable costs, not included in CDSA Dam Neck's cost data, are tip sets, foundations, and setup kits. These items are direct machine expenses, but the consumption rate is spread over time and not isolated to individual part production application.

As noted previously, there are a number of indirect and fixed costs that are difficult to measure. Some costs in the USS *Whidbey Island* case are unknown and cannot be applied to this report; for example, there were production lead-times documented for this report, but man-hours of production remain unknown. The labor component of cost is essential for determining accurate cost data of production. Transportation and inventory holding costs are undisclosed in this analysis.

F. APPROACH TO APPLYING COSTS

Two costs are essential in determining the economic feasibility of AM as a Navy supply chain solution: material costs and labor costs, as they drive the overarching AM program costs. AM and TM comparisons need to be made on an individual part basis to determine feasibility. All other costs are negated, with respect to feasibility determinations, due to the immaturity of the Navy AM program and the early stages of analysis being conducted.

Some direct and fixed costs are difficult to assign to specific organizational processes. On balance, negating indirect and fixed costs when conducting AM and TM comparative analysis does not invalidate the decision-making process, as it relates to including AM parts into the organic Navy supply chain, but without all costs being implemented into the methodology.

G. SUMMARY

This chapter details cost calculations and associated applications for the determinations of part candidate decision making. Maintenance, inventory, sparing, and priority approaches inform the necessary aspects and available information that decision makers use. Ultimately, these elements are used to assess the relative importance of the three factors in AM part candidacy.

The method of calculating costs and how those costs apply to AM part candidate determinations will be applied in the following chapter. Quantitative findings in traditional manufacturing, cost of time, and other costs not considered will be fully extrapolated and summarized to identify the factors and how they apply to making decisions in selecting AM part candidates for inclusion in the Navy supply chain.

V. ANALYSIS

A. INTRODUCTION

The purpose of this chapter is to quantify the costs of introducing AM and how those costs apply to part candidate determinations. Quantitative findings in TM, cost of time, and factors not considered apply to the decision-making process that determines AM part candidacy as an economically feasible Navy supply chain solution.

In this chapter, we narrow the scope of AM part candidate identification to three approaches and apply NSS programs and processes to AM part candidate suitability decision making to provide the most effective means to determine AM supply chain applicability. This analysis determines individual AM part candidate inclusion as a supply chain solution by identifying inventory demand necessity.

In addition, examine a real-world example of the USS *Whidbey Island,* where AM was utilized. First, we discuss the demand requirements that were present in our example. Next, we discuss the physical standards and specifications that exist and how that information is used to select a suitable AM technique for the application. Finally, we conduct a cost analysis to determine the economic feasibility of the 3-D printing project that took place onboard USS *Whidbey Island*.

B. NAVY SUPPLY SYSTEM PARTS SUPPORT PROCESS STRUCTURE

The following analysis serves as an approach for selecting individual AM part candidates on the basis of Navy operational availability objectives. Individual AM parts support within the NSS must be determined as sensible and as a necessary supply chain solution.

1. Parts Candidate Determinations

a. Frequency

Frequency of parts demanded is the most common approach for determining AM part candidacy. Frequency directly correlates to demand-based sparing methodology. A query of demand data should occur based on weapons systems platform type, weapons systems location, and quantity per application. These three demand-querying approaches inform inventory requirements and are driven by priority designation tendencies.

An example of weapons systems platform query is filtering a search by ship class. All Arleigh Burke-class destroyers (DDG-51) have the same systems and subsystems installed onboard. Running demand data filtered by ship class will inform wholesale and retail inventory requirements, based on the location and grouping of ship homeports and deployment zones. Weapons systems location queries in this example disclose the ideal inventory location strategy when combined with priority designation data. Quantity per application is important because the depth of part support is a critical facet of demand-based sparing. Inventory items with significant depth are ideal for satisfying the demand aspect of successful AM part candidacy.

After frequent parts are identified for manufacturing, its technical complexity is taken into account. If a part candidate qualifies as technically capable, the economic feasibility of supply chain inclusion is determined. Frequently demanded parts are stocked at higher rates in wholesale and retail inventories due to the routine and urgent nature of their demand, respectively. Because AM may reduce inventory and holding costs, frequently demanded parts is the starting point for AM part candidacy determinations. AM programs also have the opportunity to function at higher usage rates if high demand parts are the majority of supply chain AM requirements.

b. Availability

Availability is determined in a short- and long-term perspective. Short-term availability is the immediacy of a part’s disposition. For the purposes of this report, short-term availability is most appropriately addressed as a priority designation issue. If a part is available in the short-term and the lead-time is unacceptable, two alternatives exist: either the priority of requisitioning needs to be increased or the part needs to be assigned as an inventory allowance item. In both cases, AM does not apply for the purpose of supply chain improvement.

Long-term availability issues directly relate to this report. Unavailable parts are mostly attributed to system obsolescence, manufacturer discontinuation, and vendor stock outs. Determining the lack of existing contracted or manufacturer support is the first step in parts candidate identification. Submitting contract actions, such as Requests for Proposal (RFPs) or Requests for Information (RFIs), are the primary means of identifying industry capabilities and levels of interest. Investigating the demise of the discontinuation of part support and manufacturer production through market research is a more immediate means of gaining perspective. If research yields that the cost of replacement cannot be determined or is greater than the parent system, investigation of technical capability for AM is warranted. Unsupported parts that have no history of failure and replacement should be treated as the lowest priority for AM candidacy. Experimentation is suggested for parts with no means for production on an "as time permits" basis.

Complexity and technical production limitations should be the first discriminating factor for part candidacy. Economic feasibility carries no weight in deciding AM part candidacy in this situation. Cost benefit analysis studies should be conducted for obsolete systems to determine whether unsupported parts cost more to manufacture than replacing the system. Inventory, sparing method integration, and priority designation considerations are not areas of concern for unsupported parts that have no demand. The capability of AM manufacturing for unsupported parts is the primary concern. Ultimately, unavailable parts should be screened for AM technical feasibility on an "as needed" basis. If AM program usage is low, unsupported parts of uncomplicated design should be screened for readiness and training purposes to establish policy and procedural protocols for critical AM support requirements.

c. Criticality

Critical part requirements are a function of mission readiness. It follows that the process of readiness-based sparing is the best starting point for suitability analysis. Analysis of criticality is a part of program-level, life-cycle logistics documented within COSAL and WSS files. For the purposes of this report, an ancillary analysis was conducted. C-4 CASREPs on equipment, WSS critically identified parts, and actively managed COSAL items all feed into each weapons system's program office strategy as a part of NSS support. Manually scrubbing one part at a time for criticality, as a redundancy check, adds little value to critical parts validation. This process is adequately handled at the configuration management level of program oversight. A change to the criticality of systems, subsystems, and associated parts is not practical. The only feasible way for a part to become critically essential is for the availability to approach zero.

2. Sample Decision Process

a. The USS Whidbey Island Example for the Decision Process

The USS Whidbey Island sound-powered phone jack boxes, mentioned in Chapters III and IV, will serve as the sample product that will be applied to the Navy demand decision analysis for AM part candidacy.

Frequency is measured for the phone jack boxes in terms of the number of boxes required. Forty boxes of various sizes were required on USS Whidbey Island (Lambeth, 2014). As brass boxes continue to require replacement on other afloat platforms, the total number of boxes required will grow to a number well over 500, just for initial outfitting. New construction ships and vessels undergoing extensive shipyard work will increase these numbers even more. Although frequency is oriented in a short-term direction, the demand will affect inventory requirements, thus necessitating AM candidacy consideration. Technological capability has already been determined, so the next step is economic feasibility. Before proceeding to economic feasibility, however, investigation into the other two approaches of demand analysis must be conducted.

Availability is reviewed to determine if current inventory levels meet the non-brass-jack-box requirement. At present, the Navy does not have an alternative to brass, sound-powered, phone jack boxes, and no contract exists in the supply system to fulfill this requirement either. The lack of availability also flags this part as a candidate for AM. Market research should be conducted to determine if commercial options are available. If commercial items are found to exist, comparing the time required to deliver commercial products and the time spent on AM process will produce a result for urgency and priority decision analysis, if these two factors become salient to this requirement. Finally, criticality in this example is not an issue evidenced by the lack of program office involvement and the lack of a priority or urgency-related directive.

b. *Standards and Specification Requirements*

Using the CDSA USS *Whidbey Island* case study as an example, we are able to identify the material requirements of an AM-produced item for application onboard a U.S. Navy ship. The specific requirements listed in Table 5, derived from the documents in Table 4, highlight the main issues that affect composite materials of this nature and how they function in an austere, at-sea environment. From this table, it is evident that the sound-powered phone jack brackets that were needed onboard the USS *Whidbey Island* would need to meet a wide array of standards, specifications, and requirements to be considered safe for use. Corrosion was the primary concern for the initial modification of the sound-powered phone jacks; however, shock, vibration, temperature, smoke, and solar radiation are additional issues that wreak havoc on any item installed onboard a U.S. Navy ship.

Considering the physical requirements placed on this item, CDSA was able to make a sound decision on which technique would be most appropriate for this application. In this case, FDM proved to be the correct 3-D printing technology that satisfied the requirements of the sound-powered phone adapter. While the mounting brackets for the USS *Whidbey Island* were successfully produced, there is an estimated one-to-two-year approval process to get the required permission needed to integrate these 3-D printed parts into the onboard system (Lambeth, 2014).

c. *Cost Feasibility Analysis of the USS Whidbey Island Case Results*

The material cost results for sound-powered phone jack box 1, SM offset using Formula 1 found in Chapter IV:

Step 1: $C = \frac{V_m \times C_{fm}}{V_{fm}} + \frac{V_s \times C_{fs}}{V_{fs}}$

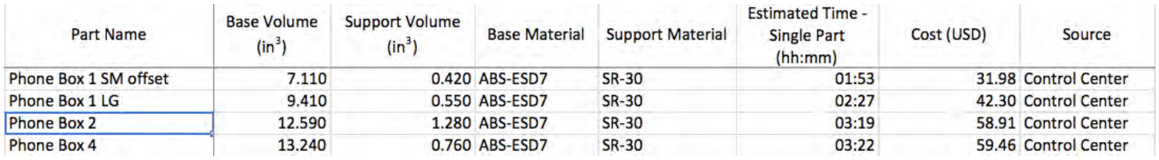
Step 2: $C = \frac{7.11 \times 395}{93} + \frac{.42 \times 360}{93}$

Step 3: $C = \$31.82$ per unit.

The costs of $395 and $360 for model material and support material containers, respectively, were provided by CDSA Dam Neck engineers. CDSA Dam Neck also specified the container capacity of 93 cu.in. The total cost of phone box 1 SM offset was calculated by CDSA Dam Neck software to total $31.98 per unit. It is assumed that the difference in this report's cost and CDSA Dam Neck's calculation is due to not applying the entire 93 cu. in. of material to the AM product. Extracting less than 100% of the contents due to spillage, residual loss, or not fully filled containers are the most probable reasons for the minor discrepancy.

This calculation is applied in the same manner to the phone box 1, large offset, phone box 2, and phone box 4. The CDSA Dam Neck calculation results are:

Table 9. ABS-ESD7 Phone Jack per Unit Cost Totals (from Lambeth, 2014).



Part Name	Base Volume (in^3)	Support Volume (in^3)	Base Material	Support Material	Estimated Time - Single Part (hh:mm)	Cost (USD)	Source
Phone Box 1 SM offset	7.110	0.420	ABS-ESD7	SR-30	01:53	31.98	Control Center
Phone Box 1 LG	9.410	0.550	ABS-ESD7	SR-30	02:27	42.30	Control Center
Phone Box 2	12.590	1.280	ABS-ESD7	SR-30	03:19	58.91	Control Center
Phone Box 4	13.240	0.760	ABS-ESD7	SR-30	03:22	59.46	Control Center

The total of all unit costs, found by totaling the Cost (U.S. Dollars) column of Table 9, equals $192.65. CDSA Dam Neck produced 10 units of each box type, bringing the total cost of all 40 brackets to $1,926.58. This value is also found in the first row of Table 10.

Table 10. Selected Material Cost of Brackets (from Lambeth, 2014).

Material	Technology	Quote Source	Cost	Lead Time
ABS-ESD7	Additive Manufacturing	CDSA Dam Neck	$1,926.58	1-2 weeks
Polycarbonate	Additive Manufacturing	CDSA Dam Neck	$1,891.33	1-2 weeks
ULTEM 9085	Additive Manufacturing	CDSA Dam Neck	$3,279.90	1-2 weeks
Anodized Aluminum	Traditional Manufacturing	NSWC Dahlgren	$1,800.00	9-12 days
Anodized Aluminum	Traditional Manufacturing	CompuCraft	$1,802.70	5 weeks
ULTEM 2300	Traditional Manufacturing	Plastic Machining	$3,267.90	5 weeks

Table 10 illustrates the cost differences and production lead times of the three different material solutions used in CDSA Dam Neck's AM case study. CDSA Dam Neck also researched and provided TM cost and production lead-time data. NSWC Dahlgren conducted the least expensive and quickest production solution, but NSWC Dahlgren does not qualify as a supply sourcing solution due to the nature and scope of the enterprise. NSWC Dahlgren is a laboratory, similar to CDSA Dam Neck, and it does not have the dedicated production capacity and is not chartered as a production facility capable to fulfill this requirement. For the purposes of this report and in all other practical applications of production assessment, NSWC Dahlgren should not be considered as an option for AM item decision making for the Naval supply chain.

The AM solution of ULTEM 9085 and the TM solution of ULTEM 2300 are significantly more expensive than other solutions in Table 10; therefore, they are removed from further decision-making analysis. Compucraft's TM total estimated cost is $1,802.70, but has a lead-time three to four weeks slower than CDSA Dam Neck's AM capabilities. The ABS-ESD7 brackets cost approximately 6.9% more than the ULTEM 2300 brackets, but are produced roughly three times faster. These types of trade-offs are often the crux of individual manufacturing type determinations.

To determine which solution is better in this case, the following questions are proposed for consideration:

> Is the government willing to pay a slight premium for the convenience of insourcing?
>
> Is there a required delivery date that makes insourcing more advantageous than commercial sourcing?
>
> Will this requirement have ongoing demand?

These questions address issues specific to this bracket case; but to address AM part candidacy as a Navy supply chain solution, program-level questions must be posed, assuming the requisite data is available.

d. The USS **Whidbey Island** *Case Shortcomings*

The primary shortcoming of the economic feasibility portion of this study is due to the immaturity of the Navy AM program. The program is in the early stages of development and the experimentation occurring is oriented at production levels of effort. AM machine production statistics are being compiled and success rates of production are being monitored, but man-hours spent on production have not been meticulously tracked. Insourced AM labor hours expended can generally be determined at full time rates if the AM program is robust enough to support continuous production demand. Presently, that is not the case. Comparative cost efforts that capture labor, like commercial sourcing versus Navy AM production, or O-level maintenance versus Navy AM production, cannot be calculated at this time. Without comprehensive cost data, results of this report are limited to theoretical analysis of simple cost comparatives, rather than quantitative analysis.

Other categories of costs not captured are indirect and fixed costs. These costs are not being captured because Navy-sponsored AM production facilities have not been established. Test platforms, like USS *Essex* (LHD-2), USS *Whidbey Island* (LSD-41), and NSWC *Dahlgren*, all conduct AM experiments aimed at establishing part substitutes in real time. Mr. James Lambeth’s stated purpose in AM experimentation is to create a standardized approach. Some traditional costs, such as manufacturing overhead, administrative, and AM machine repairs, are unavailable for analysis. Inventory costs, such as obsolescence, downtime, carrying, ordering, and transportation, are also undisclosed. Too many assumptions must be made in this report to responsibly apply the Figure 5 formulas from the 2014 Aatlo University research.

Referring back to the Aalto University work conducted by Khajavi et al. (2013), while the study contains some assumed costs in the calculation methods used, these methods are sound and could become even more accurate if actual cost data is used in place of some of the assumptions. Additionally, this report asserts that the implementation of AM technologies into the typical spare parts supply chain will likely become more realistic and achievable as the technology becomes less capital-intensive (Khajavi et al., 2013).

Without a robust, enterprise-wide AM program, the collection and analysis of all relevant costs are not practical. The lowest level of cost analysis is captured best on an individual parts basis. Direct comparison of manufacturing methods for economic feasibility determination purposes is the only viable means of analysis at this early stage of Navy AM program development.

C. COMPARING TM AND AM COSTS

Comparing TM and AM production alternatives is ultimately a question of whether to make or buy required parts. On a per unit basis, only known costs of each production method are directly compared. Material expenses, manufacturing time, and labor rates are the most basic and easiest production data elements to compile. The most relevant costs are material input and direct labor. Datar et al. (2012, p. 393) define relevant costs as "expected future costs that differ among the alternative courses of action being considered." Although labor and material are the only costs currently available, their relevance is significant enough to be the basis for economic feasibility decisions.

Formula 3 infers that as the volume and/or cost of model and support material increase, the unit price increases. Therefore, AM material cost relative to TM material cost is a critical factor in economic feasibility comparisons. It can also be generally assumed that AM requires less direct labor due to CAD software automation and minimal setup efforts. Therefore, comparative AM direct costs are less than TM direct costs when technology allows for AM production and material costs are low.

From a program-level prospective, as the Navy identifies individual parts for AM, data collection will capture machine workload information. Analyzing this data will allow others to assess AM versus TM machine cost justifications. This type of analysis will inform supply chain-level economic feasibility and facilitation program-level viability determinations.

D. SUMMARY OF FINDINGS

In this chapter, AM part candidacy is determined by determining frequency, availability, and criticality of part requirements. Sparing methods and priority designation inform inventory requirements that fulfill maintenance demands to meet operational availability objectives. This process is one portion in AM part identification for supply chain inclusion, but it is the only portion that is based on mission requirements and Navy objectives. Frequency of need is the driving factor for AM part candidate selection and will ultimately determine AM program viability as a supply chain solution.

Second, successful application to the findings from previous chapters to show a process in which the technical specifications and standards required by Naval equipment and weapons systems can be used to select an suitable method of AM. Technical capabilities and limitations are very important factors to consider when attempting introducing a new 3-D printed part into the Navy supply chain.

Finally, the make-versus-buy selection criteria are the cornerstone concept of determining the economic feasibility of AM part candidates. The U.S. Navy must make each decision on an individual part basis to determine economic feasibility. At this stage of program maturity and analytical commitment, material and labor costs should drive AM program decisions. The decision-making process will expand to include fixed and indirect costs as the AM program matures and becomes more robust.

VI. CONCLUSIONS

A. OVERVIEW

The primary goal of this research project was to raise the real issues that will influence the success or failure of implementing AM into the Navy’s existing supply chain. Specifically, this project intended to assess the current state of AM and the Navy’s supply system in an effort to determine the influential factors that need to be thought about when considering any particular item to be produced via AM versus TM methods in use. Additionally, this research strived to determine the factors that affect the economic feasibility of introducing AM into the Navy’s current supply chain, and search for any ongoing initiatives to investigate the integration of AM into the Navy.

The first two chapters introduce the research questions and provide background information on how the NSS functions and how the technology of AM achieves a newer, more efficient method of manufacturing. The information in these chapters goes on to introduce some of the applications of AM that is occurring within various industries outside of the DOD.

The exploration of additional information related to AM, the NSS, economic decision criteria, and ongoing AM implementation initiative areas addressed in the literature review chapter. This examination supports the research on economic feasibility and on the Navy’s current investigations into implementing AM as a legitimate manufacturing alternative.

The methodology chapter introduces the relationship of the NSSs maintenance and inventory processes, sparing theory, and priority designation as a means to assign AM parts candidate necessity for each part identified. This chapter goes on to explain the importance of the three approaches to identifying AM parts, and the method of calculating costs and how they will be applied to part candidate determination. Finally, the analysis chapter reviewed the application of determined factors of influence to a real-world example of where AM was used within a Navy supply chain.

B. SUMMARY OF MAIN FINDINGS

The research questions of this project were:

> What are the influential factors to consider when detecting potential AM candidates from within the existing Navy supply chains?
>
> What factors determine the economic feasibility of individual part candidates?
>
> What current initiatives are investigating the integration of AM into the Navy?

After an assessment of the current Navy supply system and the current state of AM, this research project was able to identify three major factors that should be considered when implementing AM into the current supply chain. Those factors are:

> The criticality, availability, and frequency at which a part candidate is demanded within the current system. Specifically addressed is the consideration of demand and readiness as a sparing solution for prospective AM part candidate requirements.
>
> The material standards and specifications of part candidates and the corresponding AM technological availability. The major concern that this factor influences is whether the AM technology can meet established military standards and specifications required by the items that are introduced into any Navy supply chain.
>
> The economic feasibility of introducing AM into the Navy supply chain. Adding value to the Navy supply chain by means of cost and/or time savings, with respect to insourcing versus outsourcing and traditional versus AM methods are the economic feasibility decision alternatives.
>
> The factors that determine economic feasibility of individual part candidates are:
>
> Costs of producing raw material via AM
>
> Labor costs of producing via AM
>
> Operations and Maintenance (O&M) costs of AM
>
> Supply costs of producing via AM
>
> Traditional manufacturing costs (i.e., price paid for replacement parts or price to produce "in-house")
>
> Extended lead time costs

Transportation costs

Inventory holding costs

The research conducted in support of this project revealed one primary organization within the Navy that is leading the investigation of bringing AM to the Navy’s supply chain. The CDSA in Dam Neck, Virginia, is spearheading an additive manufacturing initiate known as “print the fleet.” This is an exploratory endeavor that contributes to advancing technology in an effort to increase productivity, decrease costs, and improve warfighter support. The analyzed example of CDSA Dam Neck’s initiatives is the case of introducing AM as a material solution for sound-powered phone box adapters used onboard USS *Whidbey Island*.

C. RECOMMENDATIONS

While AM is already being experimented with on a limited basis within the Navy, this report recommends that, as more parts are considered for sourcing via AM vice traditional manufacturing methods, the suggested influential factors are considered more thoroughly. Collecting and quantify cost drivers and their comparative outcomes will yield vast insight into the relative cost relationship of each sourcing and manufacturing method. Using the individual part candidate findings to compile more robust system or program-wide analysis is the next logical step in long-term supply chain solution determinations. Knowing where the current technological capabilities are positioned, and how that related to economic feasibility of implementation, is crucial for program success.

These three factors, while simple, could assist in preventing decision makers from implementing this new technology when it may not be the most economically viable supply chain solution. AM has the potential to bring extraordinary capability and flexibility to any supply chain; however, it may not be the right solution to every requirement at this point in time.

D. AREAS FOR FURTHER RESEARCH

As AM applications continue to be developed within DOD, and within the civilian industry, there will be more research conducted on the subject. A few areas for further research that were realized during this project include:

> What are the intellectual property and/or copyright infringement implications of introducing AM into a Navy/DOD supply chain?
>
> What are the true costs of operating an AM process within a Navy/DOD supply chain (i.e., training, maintenance, labor, etc.)?
>
> If introduced, is it more economical to operate AM with military, government civilian, or contracted personnel?

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