NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

MBA PROFESSIONAL REPORT

NAVY ADDITIVE MANUFACTURING: ADDING PARTS, SUBTRACTING STEPS

June 2015

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2015	**3. REPORT TYPE AND DATES COVERED** MBA Professional Report	
4. TITLE AND SUBTITLE NAVY ADDITIVE MANUFACTURING: ADDING PARTS, SUBTRACTING STEPS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Victor Cunningham, Christopher A. Schrader, and James (Trae) Young			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A________.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS additive manufacturing, 3D printing, 3DP			**15. NUMBER OF PAGES** 97
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89)

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Submitted in partial fulfillment of the requirements for the degree of

MASTER OF BUSINESS ADMINISTRATION

from the

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NAVY ADDITIVE MANUFACTURING: ADDING PARTS, SUBTRACTING STEPS

ABSTRACT

This study examines additive manufacturing (AM) and describes its potential impact on the Navy's Supply Chain Management processes. Included in the analysis is the implementation of 3D printing technology and how it could impact the Navy's future procurement processes, specifically based on a conducted analysis of the automotive aerospace industry. Industry research and development has identified multiple dimensions of AM technology, including material variety, cost saving advantages, and lead-time minimizations for manufacturing products. This project is designed to provide the Navy with a recommendation based on an in-depth industry case-study analysis.

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
A&D	aerospace and defense
ACS	Advance Composite Structures
ALM	additive layer manufacturing
AM	additive manufacturing
ASTM	American Society for Testing and Materials
BAAM	big-area additive manufacturing
BAE	British Aerospace Engineering
CAD	computer-aided design
DARPA	Defense Advanced Research Projects Agency
DLA	Defense Logistics Agency
DLP	digital light processing
DLR	depot level repairable
DMLS	direct metal laser sintering
DOD	Department of Defense
DON	Department of Navy
DREAMS	Design, Research, and Education for Additive Manufacturing
EBM	electron beam melting
FDM	fused deposition modeling
FFF	fused filament fabrication
FLC	Fleet Logistics Center
FY	fiscal year
GE	General Electric
GM	General Motors
JHSV	joint high-speed vessel
LEAP	Leading Edge Aviation Propulsion
LMD	laser metal deposition
LOM	laminated object manufacturing
MJM	multi-jet modeling

MRE	meals ready-to-eat
MSC	Military Sealift Command
NASA	National Aeronautics and Space Administration
ORNL	Oak Ridge National Laboratory
PBIH	powder bed and inkjet head
PJP	plastic jet printing
PP	plaster-based 3D printing
PTFE	polytetrafluoroethylene
R&D	research and development
SHS	selective heat sintering
SLA	sterolithography
SLM	selective laser melting
SLS	selective laser sintering
TARP	troubled asset recovery program
UC	ultrasonic consolidation
UV	ultraviolet
VTOL	vertical takeoff and landing

ACKNOWLEDGMENTS

To our thesis advisors, Professors Bryan Hudgens and Douglas Brinkley, thank you for wisdom, support, and, above all, patience during this process. Your thoughts, ideas, and feedback were instrumental in this entire process.

I am forever thankful to my wife, Beth, for believing in me when I did not believe in myself, especially during my tenure as a naval officer. She has not only stood by me during the highlights, but also during the challenging times when I needed her most. She saw the potential in me that I did not see in myself from my undergraduate days at Worcester State College up to and including my days at NPS. I want to publicly thank her for believing in me and loving me the only way she knows how. I can only hope to return the love, devotion, and patience that she have shown over the last decade, especially during my graduate education. To my two sons, Taylon and Caiden, thank you for your loving support, and I can only hope that I can live up to your expectations.

Finally, to my MBA project partners, Vic and Trae, without your hard work and dedication, this project may not have been possible. Thank you for your candid feedback. It has been a distinct pleasure to work with both of you.

—LT Christopher A. Schrader

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I. INTRODUCTION

A. OVERVIEW

The U.S. Department of Defense (DOD) operates and maintains the most equipment-intensive military force in the world. In FY2012, the total obligation authority was more than $650 billon and, of that, the operation and maintenance (O&M) money accounted for 42 percent of total resource allocation—about $263.9 billion (Department of Defense, 2011). The breakdown of just how many systems are supported by the DOD maintenance organizations is:

- 346,000 tactical vehicles
- 40,600 combat vehicles
- 14,800 aircraft
- 256 ships
- 896 strategic missiles
  (Department of Defense, 2011)

The Defense Logistics Agency (DLA) is the DOD's logistics provider, ensuring proper stocking and storage for many repair components. This equipment is critical to the sustainability and readiness of combat forces. Figure 1 represents DLA's massive scope of operations and overall responsibility for supporting DOD's logistical requirements.

THE DEFENSE LOGISTICS AGENCY QUICK FACTS

The Defense Logistics Agency provides the Army, Navy, Air Force, Marine Corps, and other federal agencies as well as several allied military forces with a full range of logistics, acquisition, and technical services. Some of the DLA's quick facts:

- In 2014, DLA generated more than $38 billion in sales and revenue.
- If ranked in Fortune 500, DLA would rank at #79.
- Supplies nearly 90 percent of military's spare parts.
- Manages nine supply chains and nearly 5.3 million line items.
- Employs 25,000 civilians and military.
- Supports 2,430 weapon systems.
- Processes 100,000 requisitions and awards 10,000 contract lines each day.
- Manages 24 distribution centers worldwide.
- Operates in 48 states and 28 countries.
- Supports 110 nations with $2 billion of support items annually through Foreign Military Sales program.

* This data was extracted from Defense Logistics Agency "At a Glance"

Figure 1. DLA quick facts (after DLA, n.d.).

Maintaining complex weapon systems within designed specifications requires extensive routine and preventative maintenance as well as expeditious repairs when failures occur. These repairs are sometimes complex and often unpredictable in both peace and wartime environments. To keep these weapon systems operating within optimal operating parameters, the DOD maintenance capabilities span three major levels of maintenance. The DOD refers to these as organizational, intermediate, and depot levels. According to the DOD Depot Maintenance Strategy Plan (DOD, 2004, p. I-1), the three levels are:

- Organizational maintenance: Consists of the on-equipment tasks necessary for day-to-day operation, including inspection, service, and remove-and-replace operations for failed components (includes line-replaceable units or weapon-replaceable items).
- Intermediate maintenance: Consists of off-equipment repair capabilities possessed by operating units and in-theater sustainment organizations. These capabilities can be quite extensive and include remove-and-replace operations for subcomponents of line-replaceable units.
- Depot-level maintenance: Consists of all repairs beyond the capabilities of the operating units, including rebuild, overhaul, and extensive modification of equipment platforms, systems, and sub-systems. The depot level is the ultimate source of repair.

The maintenance organization’s capabilities are critical for readiness because they provide the right part—at the right time and in the right quantity—to complete the repair. Providing these maintenance entities with repair parts, components, systems, and sub-systems is a daunting task. In response, the DOD established the DLA, which consolidates the parts management functions for four military services.

As the logistics support agency to the armed forces, DLA provides nearly 90 percent of the military’s spare parts, manages nearly 5.3 million line items, and supports over 2,430 weapon systems (DLA, n.d.). DLA also supports several other federal agencies, state and local governments, as well as foreign militaries via the Foreign Military Sales program. With 24 distribution centers worldwide material can be prepositioned closer to the warfighter. This improves material readiness, reduces customer wait times, and reduces overall costs (DLA, n.d.). Supplying these spare parts to the services and other government organizations requires quick turnaround times, which can be challenging in a fiscally constrained environment. Currently, DLA responds to customer requirements by increasing or decreasing the amount of parts they purchase for stocking based on historical demand for parts. Customer demand ordering, as it is referred to, has been a long-standing issue for the military. When customer demand ordering for an item unpredictably increases, this increases the possibility that a stock-out can occur, resulting in degraded readiness. Likewise, when a part has an unanticipated decline in demand, excess inventory occurs, which increases DLA's holding costs. This is a problem that DLA and the DOD battle on a consistent basis.

The solution is not a simple one, but rather one of high complexity that cannot just be adopted from a big-box store such as Walmart, Target, Costco, or BJs. Military parts are unique and, in most cases, produced in low volume with demand predictability challenges and tight timelines. For this reason, many commercial manufactures have difficulties meeting product demand and often deem the defense market as non-lucrative. With these constraints in mind, some suppliers are making it difficult for smaller companies to produce parts for the military. Furthermore, the consequences of failing to meet tight military deadlines and the resultant implications are far greater than those encountered by most commercial vendors. Similar concerns include lower than optimal operational readiness, higher transportation costs, long lead-times, and excess inventory.

The DOD is continually exploring new and innovative ways to combat this problem. It has more recently realized that the largest industrial transformations of our time—additive manufacturing (AM)—could have prodigious implications. This may be best said in statements made by the U.S. Navy's Deputy Chief of Naval Operations for Fleet Readiness and Logistics, Vice Admiral Philip Cullom, in an interview with National Defense Magazine:

> It is my strong belief that 3D printing and advanced manufacturing are break-through technologies for our maintenance and logistics functions in the future. We can gain new capabilities to make rapid repairs, print tools and parts where and when we need them, carry fewer spares and ultimately transform our maritime maintenance and logistics supply chain. (Tadjdeh, 2014, para. 5)

The aerospace and automotive industries have also invested heavily in this technology. Aravind Melligeri, Chairman and CEO of Aequs—an emerging global player in the aerospace and automotive industries whose customers include Airbus, UTAS, Eaton, and Baker Hughes—believes that AM offers a potential that could drastically change the supply chain landscape. He states:

> As cutting-edge manufacturing technology, Additive Layer Manufacturing offers tremendous potential for creating new manufacturing capabilities and economies of scale and scope. ALM provides a means for creating complex, high-mix, and low-volume parts that would be impossible or cost prohibitive using traditional subtractive manufacturing techniques, such as machining….Both traditional subtractive manufacturing and ALM offer distinct advantages and disadvantages in manufacturing speed, scope, scale, capital intensity, and cost. By adding ALM to our already broad value chain capabilities—engineering, machining, forging, fabrication, surface treatment and assembly—we create greater manufacturing flexibility and cost effectiveness to serve the particular needs of each of our A&D [aerospace and defense] customers. (Millsaps, 2015, para. 4–5)

How the DOD responds to this technology may have long-lasting positive impacts on the most equipment-intensive military force in the world, or may negatively impact the greatest military of our time and its ability to project power around the world.

B. REPORT ORGANIZATION

This project report is organized as follows. Chapter II, the literature review, provides a brief history of how additive manufacturing has evolved and introduces the reader to some of the specifics of the technology. It is important to introduce, or in some cases re-introduce, some of the specifics of the technology because of the speed at which this technology has evolved, the advancements it has made, and changes it continues to make. This review also discusses how the American Society for Testing and Materials (ASTM International), a recognized international leader in the development of international standards, formed a committee to standardize AM terminology. The discussion then describes AM technology process names, the ASTM International definition, an example of a technology within the category and who patented that technology, and a graphical representation of the process specified. Continuing with some principle AM benefits and uses, the review then transitions into some of the many challenges, issues, and concerns that the technology faces. The literature review concludes with industry applications that are currently printing various end-use items.

Chapter III, the case-study analysis, discusses a fact-finding research project that examines the aerospace and automotive industries, since these industries closely parallel the DOD due to the magnitude of equipment it owns. For the military to fully adopt this technology and the many advantages it has to offer, exploring the automotive and aerospace industries will provide the necessary information the DOD needs to make a fully informed decision whether or not to invest in this technology.

Chapter IV, on implementation, discusses several implementation strategies that the DOD can utilize to best diffuse this technology into the military. Some of the challenges that the DOD will ultimately face implementing this technology include material integrity, intellectual property infringement, part testing and certification, and operator or personnel issues.

As AM continues to grow and mature in the commercial realm, the DOD must address some challenges. Based on analysis of corporate manufacturers' successes in using AM, this study can further identify the lessons learned and utilize them to effectively and efficiently implement AM as a core process.

II. LITERATURE REVIEW

This review provides a general introduction to the AM technique, also known as 3D printing. This type of manufacturing is setting trends in industry, and its rapid evolution is changing the dynamics of the business world. The research on 3D printing for this project provides a conceptual framework to understand the complexity of the processes that enable the technology, facilitating a clear understanding of the 3D printing process. Following a brief history and overview on the topic, this chapter discusses industry standard terminology to provide clarification. Next, the chapter reviews AM processes and methods to further examine potential advantages and disadvantages impacting industry. Lastly, the chapter discusses current industry and military applications to demonstrate the impact AM has on federal and corporate markets. Providing application examples validates the significance of 3D printing within industry and defense arenas alike.

A. ADDITIVE MANUFACTURING HISTORY

Dating back to 1892, although antiquated by today's standards, J. E. Blanther created a layer-by-layer approach to form topographical maps (Blanther, U.S. Patent Office 473901). According to Bourell, Beaman, Leu, and Rosen (2009):

> His patent suggested a layered method for making a mold for topographical relief maps. The method consisted of impressing topographical contour lines on a series of wax plates and cutting these wax plates on these lines. After stacking and smoothing these wax sections, one obtains both a positive and negative three-dimensional surface that corresponds to the terrain indicated by the contour lines. After suitable backing of these surfaces, a paper map is then pressed between the positive and negative forms to create a raised relief map. (p. 1)

After outlining this process, the authors discuss in further detail the first three-dimensional replicas called photosculptures. Photosculptures originated in the 19th century and created precise three-dimensional replicas of objects, including humans, as shown in Figure 2 (Bourell et al., 2009).

> One somewhat successful realization of this technology was designed by Frenchman François Willème in 1860 [as shown in Figure 2]….A subject or object was placed in a circular room and simultaneously photographed by 24 cameras placed equally about the circumference of the room. An artisan then carved a 1/24th cylindrical portion of the figure using a silhouette of each photograph. (Bourell et al., 2009, p. 7)

Figure 2. Human photosculpture in Willème's studio (from Bourell et al., 2009).

The late 1980s saw the process of AM come at the speed of light—literally—with the development of stereolithography. The recent *Wohlers 2011 Report* references this invention as the catalyst for 3D printing capabilities, stating "additive manufacturing first emerged in 1987 with stereolithography (SLA) from 3D systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser" (Wohlers, 2011, para. 2). The emergence of SLA spawned the theory of 3D use in the manufacturing processes.

Additive manufacturing technology was originally designed solely for prototyping; however, in recent years AM and its techniques have proven to be successful in a variety of applications. The AM overview highlights the technology itself and how its functions are evolving in a standard manufacturing process.

B. ADDITIVE MANUFACTURING OVERVIEW

The knowledge of technique and processes in rapid manufacturing, most notably AM, is making significant strides within the international manufacturing base. Research and development (R&D) into AM is extending into multiple fields of study to include health care, aerospace and defense (A&D), automotive, repair/replacement parts, and food production. AM, commonly referred to as rapid prototyping or 3D printing, has one of the biggest public endorsements for technology in decades and undoubtedly will soon become an everyday household name. Fifteen minutes into his 2013 State of the Union Address, President Barack Obama promoted AM into what quite possibly could be the next industrial revolution by claiming that "additive manufacturing has the potential to revolutionize the way we make almost everything."

So what exactly is 3D printing? ASTM International defines AM as, "a process of joining materials to make an object's 3D model data, usually layer upon layer as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing and freeform fabrication" (Wohlers, 2011, "Glossary of Terms"). Since additive manufacturing and 3D printing are used interchangeably, some try to differentiate the two terms by classifying 3D printing as being used for "home printers" and additive manufacturing as being used for industry, but there is essentially no difference. 3D printing and additive manufacturing are substitutable terms.

The process of AM is an alternative to subtractive manufacturing, which is currently the preferred manufacturing process (see Figure 3). AM manufacturing techniques create 3D objects by adding material layer-by-layer; whereas traditional manufacturing uses molds, dyes, and/or the cutting and shaping of raw materials from a solid piece of material. As Figure 3 illustrates, AM is completed in various stages taking computer-aided designs, cutting the design data into segmented or layered graphical data, and then sending to an AM machine.

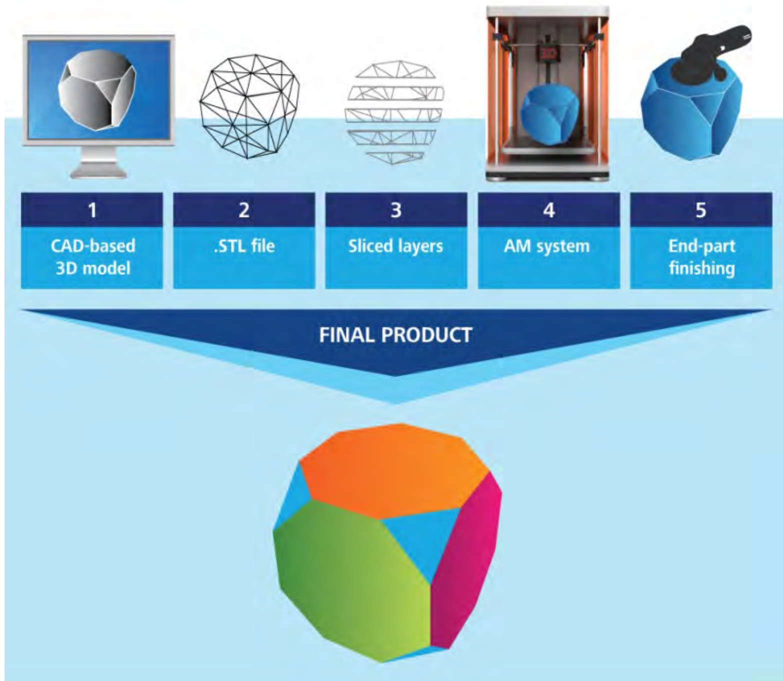

Figure 3. AM process flow (from Cotteleer, Holdowsky, & Mahto, 2014, p. 5).

The layer-by-layer process begins and, after each layer is added, a binding process begins. Whether each layer is bonded chemically or heat-induced, every layer is sequentially added and the process continues until the design criteria has been met. This process allows for complex geometric shapes that are not possible with traditional manufacturing techniques (Wohlers, 2011).

AM has the potential to change fundamental societal standards in economic and corporate operations, such as conventional engineering and production. Not only is AM a new process to the business world, but alternative terminology is also closely associated with it, primarily "disruptive technology." In his research, Christensen (1997, p. 3) describes disruptive technology as, "a new technology that unexpectedly displaces an established one." Essentially, this means "work smarter, not harder." If one thinks of the steam engine in the age of sail or the Ford Model T in the days of horse and carriage, these progressions forever changed their respective transportation arenas. It is conceivable that AM has these characteristics and its disruption in current industry standards is not limited to manufacturing, supply chain, and business, but has the ability to change how we live our daily lives. For example, food production, medical procedures, homebuilding, and space exploration are at the forefront of a new industrial revolution.

As previously explained, additive manufacturing applies to a variety of processes that use almost identical methods. For example (referenced further in next section), Stratasys, a manufacturer of 3D printers, defines AM as Fused Deposition Modeling (FDM), whereas the RepRap Project calls it Fused Filament Fabrication (FFF), and 3D Systems uses the term Plastic Jet Printing (PJP). This may be for several reasons, one being legal protection. Various companies claim to have developed the process, and in turn have seeked copyright. This can be troublesome to users, so the ASTM International committee formed a sub-committee to standardize AM terminology and "to eliminate duplication of effort while maximizing resource allocation within the additive manufacturing industry" (ASTM International, 2012, para. 3). The sub-committee approved a list of terms called Standard Terminology for Additive Manufacturing Technologies (Wohlers & Caffrey, 2013) that reduced the processes into seven categories: Vat Photo Polymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, and Directed Energy Deposition.

C. ADDITIVE MANUFACTURING PROCESSES AND METHODS

Early AM machines used only plastic or polymer materials, but advancing technology required more complex machines and materials, increasing efficiency. Currently, AM printers can employ materials such as metals, metal alloys and powders, ceramics, acrylic, sand, and a variety of composites. The following section discusses 1) AM technology process names, 2) the ASTM International definition, 3) the industry definition, 4) an example of a technology within the category, and 5) a graphical representation of the process specified. Figure 4 compares current available technologies by listing advantages, disadvantages, and typical materials for each.

Technology	AM process	Typical materials	Advantages	Disadvantages
Stereolithography	Vat polymerization	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing required; requires support structures
Digital light processing	Vat polymerization	Liquid photopolymer	Allows concurrent production; complex shapes and sizes; high precision	Limited product thickness; limited range of materials
Multi-jet modeling (MJM)	Material jetting	Photopolymers, wax	Good accuracy and surface finish; may use multiple materials (also with color); hands-free removal of support material	Range of wax-like materials is limited; relatively slow build process
Fused deposition modeling	Material extrusion	Thermoplastics	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Titanium powder, cobalt chrome	Speed; less distortion of parts; less material wastage	Needs finishing; difficult to clean the machine; caution required when dealing with X-rays
Selective laser sintering	Powder bed fusion	Paper, plastic, metal, glass, ceramic, composites	Requires no support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures required; quick turnaround	New technology with limited track record
Direct metal laser sintering	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Dense components; intricate geometries	Needs finishing; not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	Full-color models; inexpensive; fast to build	Limited accuracy; poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster, plaster composites	Lower price; enables color printing; high speed; excess powder can be reused	Limited choice of materials; fragile parts
Laminated object manufacturing	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate; non-homogenous parts
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally non-toxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM processes; need for post-processing
Laser metal deposition	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively higher cost of systems; support structures are required; need for post-processing activities to obtain smooth finish

Figure 4. Current AM technologies, materials, advantages, and disadvantages (from Cotteleer, Holdowsky, & Mahto, 2014, p. 9).

Using the standardized processes chart shown in Figure 5, which associates the various technologies with applicable materials, the Navy can identify which method of 3D printing it could adopt and what materials are available with the corresponding method. Since each processing method is similar yet different, corporations and the Navy alike can match target goals with the method required to produce that part.

Technology	Polymers	Metals	Ceramics	Composites
Stereolithography	●			●
Digital light processing	●			
Multi-jet modeling (MJM)	●			●
Fused deposition modeling	●			
Electron beam melting		●		
Selective laser sintering	●	●	●	●
Selective heat sintering	●			
Direct metal laser sintering		●		
Powder bed and inkjet head printing[13]	●	●	●	●
Plaster-based 3D printing			●	●
Laminated object manufacturing[14]	●	●	●	●
Ultrasonic consolidation		●		
Laser metal deposition		●		●

Figure 5. AM technologies and their material compatibility (from Cotteleer et al., 2014, p. 10).

The following ASTM International approved terminologies are alphabetically listed.

1. Binder Jetting

ASTM International (2012, "Definition") defines Binder Jetting as "an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials." An example of the Binder Jetting process is shown in Figure 6. The organization, Design, Research, and Education for Additive Manufacturing (DREAMS) states:

> Binder Jetting…creates artifacts through the deposition of binder into a powder bed of raw material. Once a layer has been printed, the powder feed piston raises, the build piston lowers, and a counter-rotating roller spreads a new layer of powder on top of the previous layer. The subsequent layer is then printed and is stitched to the previous layer by the jetted binder. (DREAMS, n.d., "Binder Jetting")

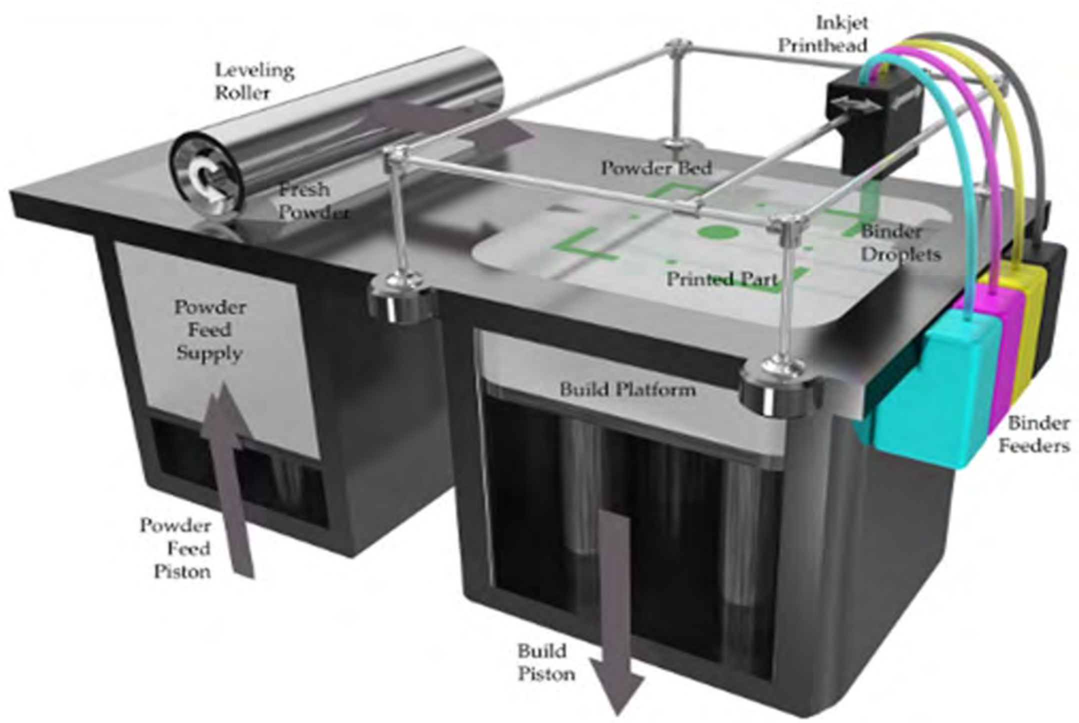

Figure 6. Binder Jetting (from DREAMS, n.d., "Binder Jetting").

One example of Binder Jetting is Plaster-based 3D Printing (3DP)—a technology patented in 1993 by Ely Sachs and Mike Cima of the Massachusetts Institute of Technology (MIT) (Lou & Grosvenor, 2012, Appendix A).

2. Directed Energy Deposition

ASTM International (2012, “Definition”) defines Directed Energy Deposition as “an additive manufacturing process in which focused thermal energy is used to fuse materials by melting into place as they are being deposited.” A form of Directed Energy Deposition—Laser Engineered Net Shaping (LENS)—can be seen in Figure 7. According to the Oxford 3D Printing Society:

> This process is a welding-based process which uses a laser beam to form a melt pool on a metallic substrate, into which metal powder is fed. The powder melts to form a deposit that is fusion bonded to the substrate. The required geometry is built up layer by layer. Both the laser and nozzle from which the powder is delivered are manipulated using a gantry system or robotic arm. (Oxford 3D Printing Society, n.d., para. 1)

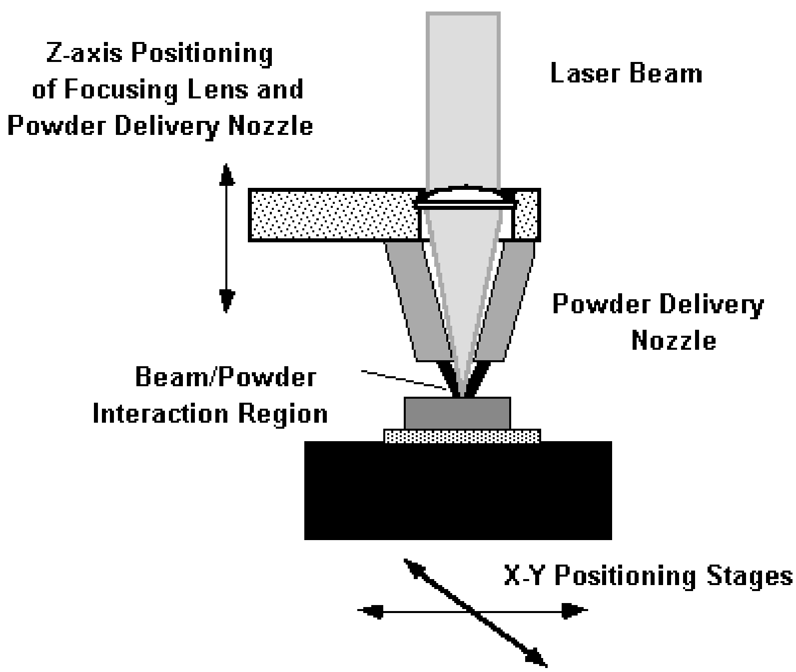

Figure 7. Laser Engineered Net Shaping (NUS Engineering, n.d., para. 3).

3. Material Extrusion

ASTM International (2012, “Definition”) defines Material Extrusion as “an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.” An example of Material Extrusion is Fused Deposition Modeling

(FDM), shown in Figure 8. FDM is a technology developed by Scott Crump of Stratasys in 1988 (ASTM International, 2012). According to Oberdas:

> FDM can easily be understood as drawing with a very precise hot glue gun. FDM (rebranded by the open source community as Fused Filament Fabrication, FFF) works by extruding material through a nozzle to print one cross section of an object, then moving up vertically to repeat the process for a new layer. The printer nozzle contains resistive heaters that melt the plastic as it flows through the tip and forms the layers. The extruded plastic then hardens immediately as it bonds to the layer below it. Repeating this process builds up the object one layer at a time. The quality of prints using this technology depends largely on layer height; the thinner the cross sections, the less noticeable they are, and the smoother the printed objects are. The cross section's resolution typically ranges between 75 microns (slightly thinner than a sheet of copy paper) and 300 microns. (Oberdas, n.d., "FDM Printing")

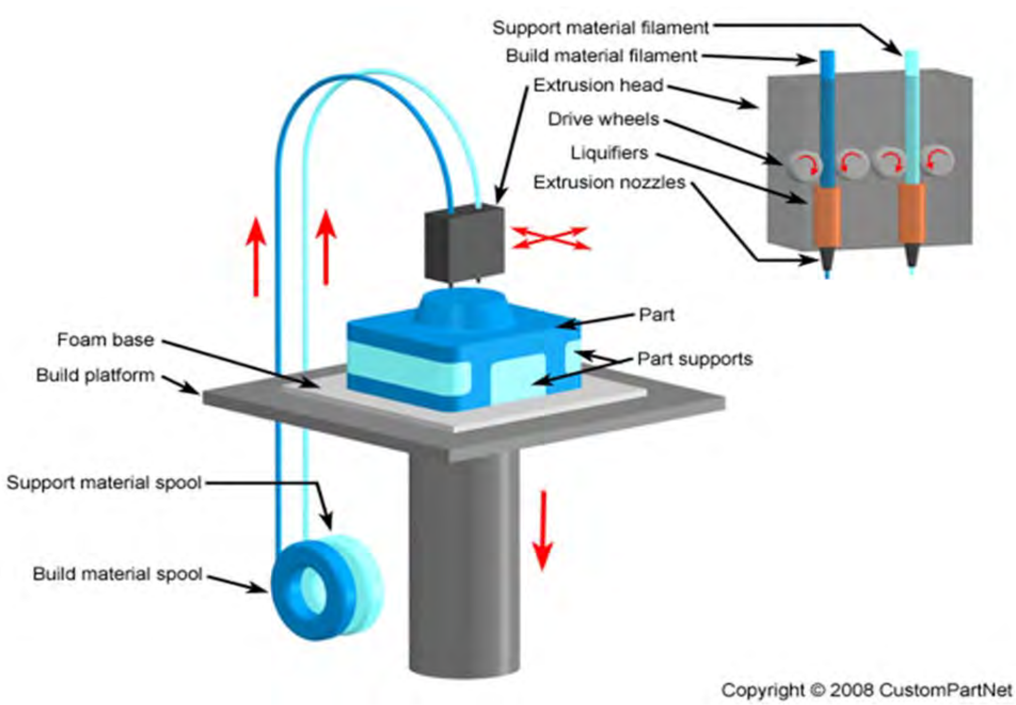

Figure 8. Fused Deposition Modeling (from Custompart.net, n.d., "Fused Deposition Modeling").

4. Material Jetting

ASTM International (2012, “Definition”) defines Material Jetting as “an additive manufacturing process in which droplets of build material are selectively deposited.” Illustrated in Figure 9 is the Jetted Photopolymer process, which is an example of Material Jetting. DREAMS (n.d., “Material Jetting”) explains:

> Material jetting is similar to inkjet document printing, but instead of jetting drops of ink onto paper, PolyJet 3D printers jet drops of liquid photopolymer onto the build tray. Multiple print heads jet material simultaneously to create each layer and UV light is then used to cure the layers. These layers build up one at a time in an additive process to create a 3D model. Fully cured models can be handled and used immediately without additional post-curing. Along with the selected model materials, a gel-like support material facilitates successful printing of complicated geometries. Support material can be removed by hand or by a high-powered water jet station….material jetting is the only additive manufacturing technology that can combine different print materials within the same 3D printed model in the same print job. Additionally, the multi-material printing process is capable of constructing functional assemblies, which reduces the need for multiple builds.

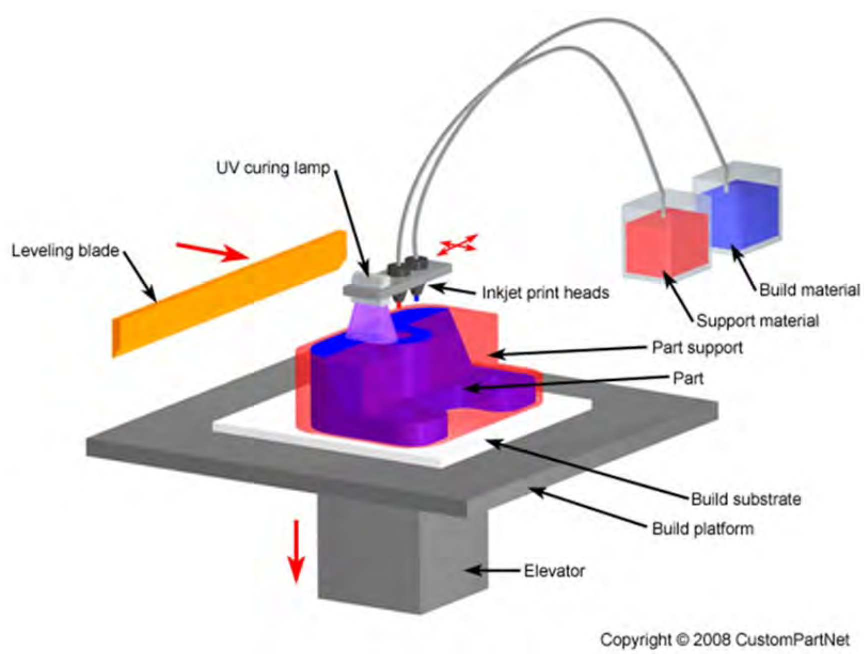

Figure 9. Jetted Photopolymer (from Custompart.net, n.d., “Jetted Photopolymer”).

5. Powder Bed Fusion

ASTM International (2012, "Definition") defines Powder Bed Fusion as "an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed." Selective Laser Sintering (SLS) is an example of Powder Bed Fusion, as shown in Figure 10. DREAMS describe this technology as:

> [a] technique which uses lasers as its power source to sinter powdered material into a mass that has a desired three-dimensional shape. The laser selectively fuses powdered material by scanning cross-sections generated from a 3D model of the part on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed. (DREAMS, n.d., "Laser Sintering")

Examples of this process include:

- Selective Laser Sintering (SLS): Powder-based technology was invented in 1986 by Carl Deckard and Joe Beaman (Lou & Grosvenor, 2012, "The Early Years 1981–1986").
- Selective Laser Melting (SLM): Current market leader in SLM technology is the German company EOS (Lou & Grosvenor, 2012, "Sold and Sold Again: 1997-Present").
- Electron Beam Melting (EBM): EBM was invented by the Swedish corporation Arcam. Unlike other Powder Bed Techniques, "EBM uses an electron beam rather than a laser and builds parts in a vacuum, which allows the use of highly oxygen reactive metals (usually titanium), a common aerospace material" (Lou & Grosvenor, 2012, "Direction of the Industry").

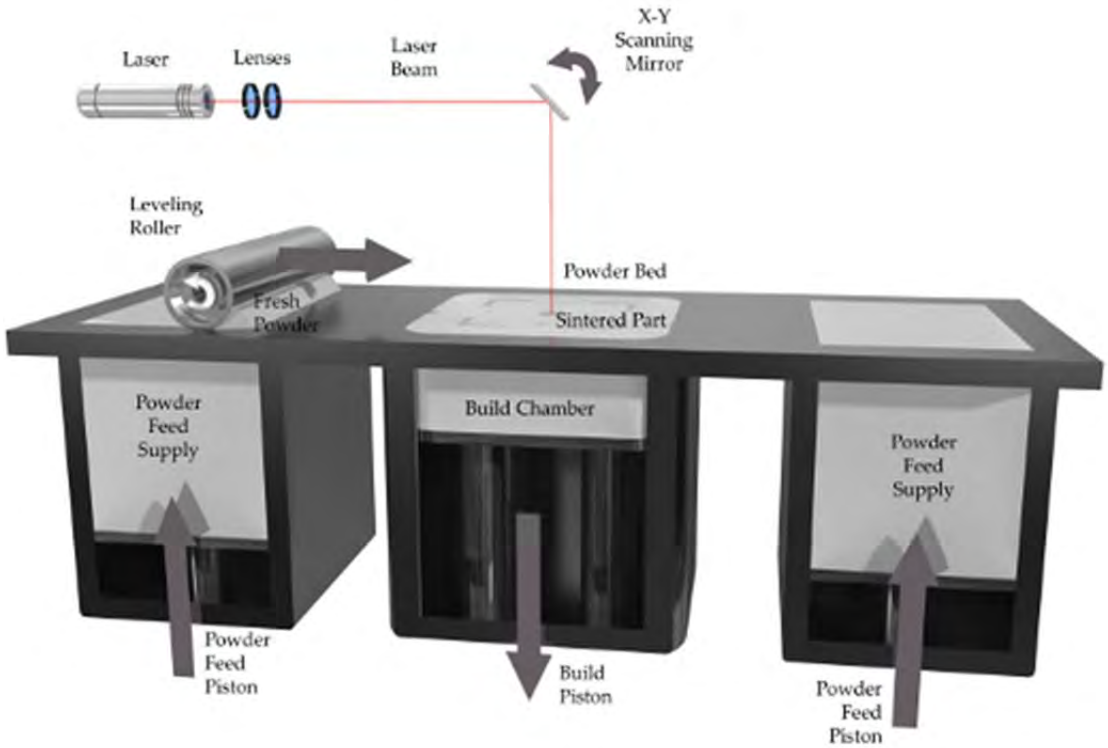

Figure 10. Selective Laser Sintering (from DREAMS, n.d., “Laser Sintering”).

6. Sheet Lamination

ASTM International (2012, “Definition”) defines Sheet Lamination as “an additive manufacturing process in which sheets of material are bonded to form an object.” Figure 11 illustrates Limited Object Manufacturing, which is one example of the Sheet Lamination process. Custompart.net describes this process as:

> The main components of the system are a feed mechanism that advances a sheet over a build platform, a heated roller to apply pressure to bond the sheet to the layer below, and a laser to cut the outline of the part in each sheet layer. Parts are produced by stacking, bonding, and cutting layers of adhesive-coated sheet material on top of the previous one. A laser cuts the outline of the part into each layer. After each cut is completed, the platform lowers by a depth equal to the sheet thickness (typically 0.002–0.020 in), and another sheet is advanced on top of the previously deposited layers. The platform then rises slightly and the heated roller applies pressure to bond the new layer. The laser cuts the outline and the process is repeated until the part is completed. After a layer is cut, the extra material remains in place to support the part during build. (Custompart.net, n.d., “Laminated Object Manufacturing”)

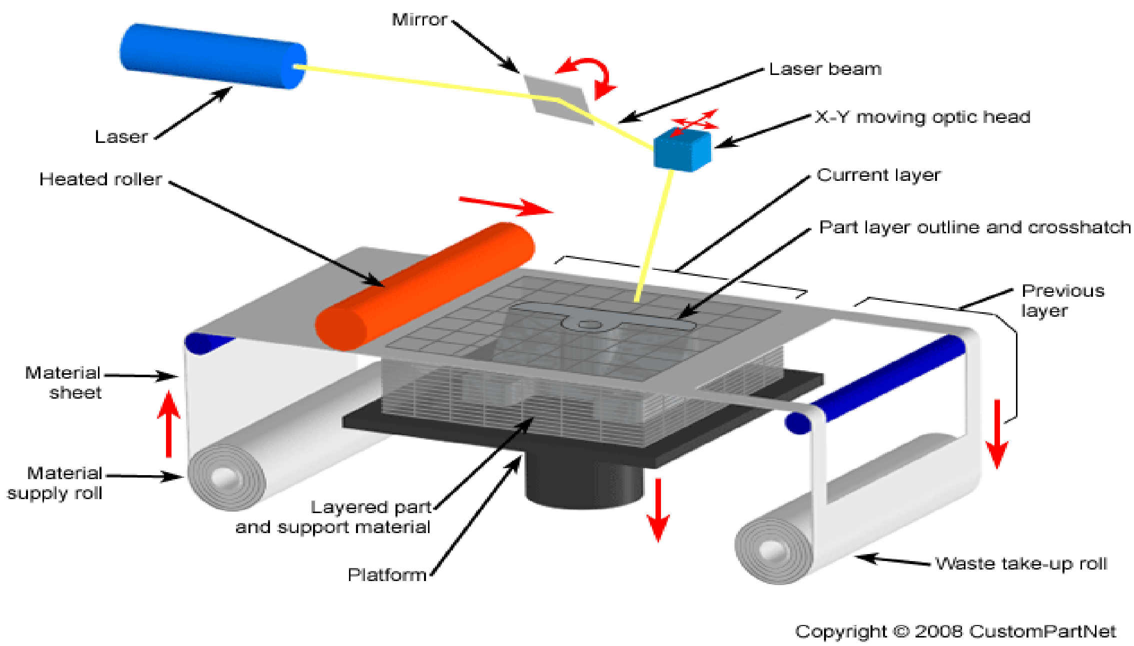

Figure 11. Laminated Object Manufacturing (from Custompart.net, n.d., "Laminated Object Manufacturing").

Examples of this process include:

- Laminated Object Manufacturing (LOM): This was developed by Helisys of Torrance, California, and the first system shipped in 1991 (Custompart.net, n.d., para. 1).
- Ultrasonic Consolidation (UC): The UC process was invented and patented by Dawn White, and in 1999 she founded Solidica Inc. (White, 2003, para. 1).

7. Vat Photopolymerization

ASTM International (2012, "Definition") defines Vat Photopolymerization as "an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization." Figure 12 shows the process of Stereolithography (SLA), which is one example of Vat Photopolymerization. DREAMS describe this process as:

> A machine uses a broad spectrum light source to cure photopolymers by projecting 2D images using a Digital Micromirror Device. This machine was developed by students in the lab, and unlike commercially available machines, the hardware and operating software of this process can be

completely customized for more specialized applications. The constrained surface design cures photopolymer layers between a glass plate and the previous layers. The newest layer is peeled from the glass, which is coated in oxygen inhibiting PTFE Teflon to reduce adhesion. This allows for an economically advantageous process that requires less photopolymer and has a vertical build rate greater than other projection stereolithography systems. The peeling process performed in the constrained surface technique, however, limits the achievable minimum feature size. (DREAMS, n.d., “Mask Projection Stereolithography”)

Examples of this process are:

- Stereolithography (SLA): This was developed by Charles Hull of 3D Systems in 1984 (Hull, 1986, para. 1).
- Digital Light Processing (DLP): This was developed in 1987 by Dr. Larry Hornbeck of Texas Instruments (Texas Instruments, n.d., para. 2).

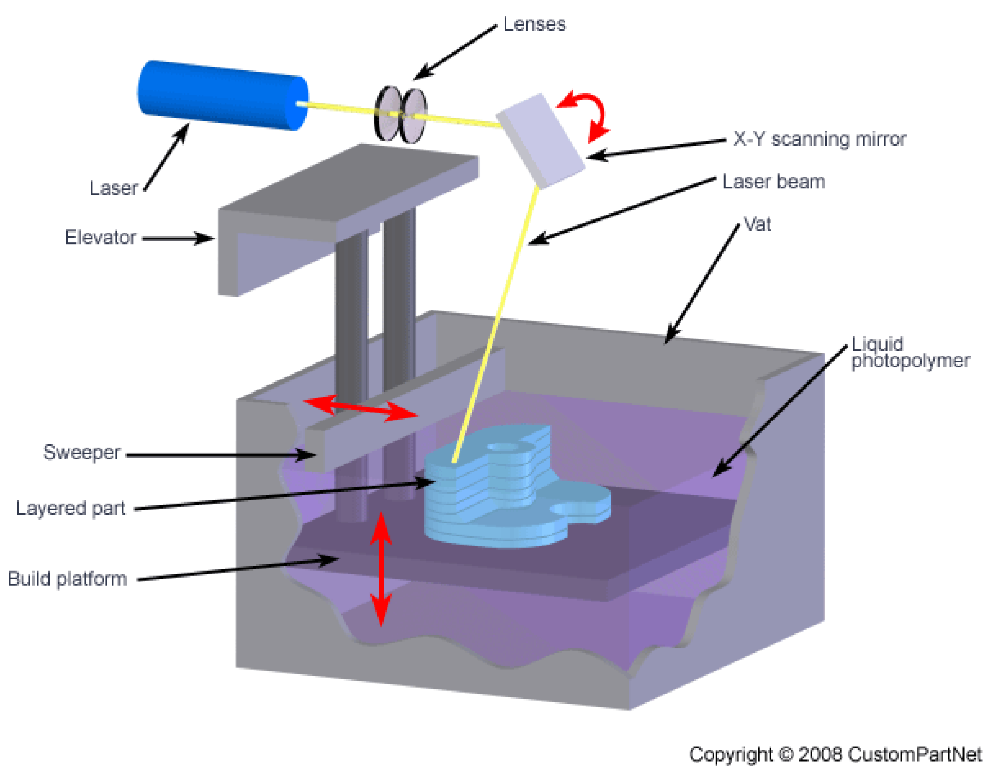

Figure 12. Stereolithography (from Custompart.net, n.d., “Stereolighography”).

D. ADDITIVE MANUFACTURING USES AND BENEFITS

Since the inception of AM, its capabilities have matured and evolved and even though it is a new technology, global business is already recognizing its benefits. The following are some of the principal benefits AM can provide:

(1) Reduced Time to Market

AM has the ability to quickly manufacture prototypes with the complexity and precise dimensions necessary for proper fit and functionality. Likewise, it permits companies to harness an item’s intricate specifications to quickly build prototypes thereby accelerating design progressions and reducing time to market. A 2014 Deloitte report shows “that when Aerospace and Defense (A&D) companies switch from traditional manufacturing to AM, they could benefit from time savings in prototyping ranging from 43% to 75% depending on the conventional techniques used” (Coykendall, Cotteleer, Holdowsky, & Mahto, 2014, p. 8). Boeing provides an intriguing example: “…when the Defense Advanced Research Projects Agency (DARPA) asked for proposals to improve the design of vertical takeoff and landing (VTOL) aircraft in 2013, Boeing additively manufactured a prototype, whose construction would have otherwise taken several months—in less than 30 days” (Coykendall et al., 2014, p. 8).

(2) Flexibility of Design Iterations

Coykendall et al. (2014, p. 8) suggest “AM offers the flexibility to design and test products as many times as required, helping A&D companies reduce risks and uncertainties, improving product functionality at lower costs.” Having the ability to make design changes without expensive retooling has huge cost advantages, as proven by National Aeronautical and Space Administration (NASA) during its Mars rover prototype which utilized AM technology to redesign several system components (Crandall, 2013).

(3) Complex-Design Tools

AM has the ability to create complex designs that are impossible for traditional machining techniques. An article in the Australian Journal of Multi-disciplinary Engineering Journal states “traditional machining can create cooling channels only in straight lines, thus making it difficult to optimize fluid flow in corners. “AM can create cooling channels that conform to the curvature of a part, a feature that is especially important for engine parts” (Bobby & Singamneni, 2013, p. 155).

(4) One-Off Production

AM enables companies to quickly design tools that are needed for a specific job, that may only be needed once, or to create an obsolete part. Traditional manufacturing may take hours. In a 2014 interview, the president of Advanced Composite Structures (ACS), a repair company servicing fixed and rotary-wing aircraft, said that FDM “produces the majority of its tools using AM, leading to overall cost savings of 79 percent and lead-time reduction of 96 percent compared with traditional tooling” (Coykendall et al., 2014, p. 9). Furthermore, tooling using AM is particularly relevant for one-off applications especially in the A&D industries, as described next by Bruce Anning, president of ACS:

> For the repairs and short-volume production work that we specialize in, tooling often constitutes a major portion of the overall cost. Moving from traditional methods to producing composite tooling with fused deposition modeling has helped us substantially improve our competitive position. (Hiemenz, 2013, p. 3)

(5) Mass Customization

AM technology allows the “possibility to create complex geometric designs without the use of molds or extra tooling” (Appleton, 2014, p. 10). Examples include dentures and Invisalign Braces. Another example is “making precisely fitted orthotics by 3D-scanning the user’s foot and then printing a completely unique insert, the cost being no greater than an “off-the-shelf” orthotic insert” (Appleton, 2014, p. 10).

(6) Stronger/Lighter Products

Using additive manufacturing eliminates design constraints, making it is possible to produce items that are stronger and lighter. “Furthermore, because of the near elimination of waste, residue materials can be quickly recycled; reducing costs even further” (Appleton, 2014, p. 10).

E. ADDITIVE MANUFACTURING CHALLENGES, ISSUES, AND CONCERNS

AM's ability to "manage small volumes, create complex designs, and fabricate lightweight but strong structures makes it a natural fit for the A&D industry" (Coykendall et al., 2014, p. 16). The technology does face some challenges however, including physical size limitations, uncertain scalability, high material costs, limited range of materials, limited multi-material printing capability, and consistency of quality (Coykendall et al., 2014). "Continuing advances in AM technology and materials science are likely to address these limitations and are expected to drive wider adoptions of AM in the A&D industry" (Coykendall et al., 2014, p. 16).

(1) Size Limitations

Large components are a current downfall of AM. "AM providers are focusing their R&D efforts on addressing the size limitations of existing AM systems" (Coykendall et al., 2014, p. 16). For example, "Lockheed Martin is working with Oak Ridge National Laboratory (ORNL) on a big-area additive manufacturing (BAAM) system in which multiple deposition heads work in coordination to build large parts in an open environment, unconstrained by the typical envelope size" (Coykendall et al., 2014, p. 16). BAE Systems in collaboration with Cranfield University in the United Kingdom has reported developing a 1.2-meter titanium wing spar in December 2013 which would be one of the largest 3D-printed metal parts to date, taking just 37 hours (3ders, 2013).

(2) Production Scalability Limitations

AM's ability to print-on-demand is one of AM's biggest advantages, but it is also one of its weaknesses. Traditionally companies stock large inventories, the majority of which remain stagnant to meet the demand of a product. Currently AM's print-on-demand capabilities would not be able to scale up production when required. To maximize the potential, A&D companies would need several different types of printers, a risk some may not invest in due to the infancy of the technology.

(3) High Material Cost

To manufacture A&D parts, additive manufacturing primarily uses a narrow range of material, ranging from polymers to metal powders. Currently the costs of AM materials are substantially higher than the ones used in traditional manufacturing methods. During a recent AM symposium, Cotteleer briefed that "Thermoplastics and photopolymers are $175–$250 per kg, while those used in injection-based molding cost just $2–3 per kg" (Cotteleer & Joyce, 2014, p. 10). Similarly, "the stainless steel used in AM costs about $8 per square centimeter, which is more than 100 times the commercial-grade stainless steel used in traditional manufacturing methods" (Cotteleer & Joyce, 2014, p. 10). Over the next few years, advances in AM compatible materials are likely to expand the scope of printing capabilities as well as drive down costs. According to one AM expert (Coykendall et al., 2014):

> Traditionally, hardware capabilities have driven materials science developments. But we are going through a change now where material developments will start to lead hardware developments ... In the intermediate to long term, it should not be surprising to see AM companies getting into materials science in a pervasive symbiotic relationship—the marriage of technical science with materials science. (Coykendall et al., 2014, p. 17)

(4) Limited Multi-Material Printing Capability

AM systems currently have the ability to print using multi-material printing which provides flexibility in design; however, only a few of these machines exist. Further advances are needed to allow increased flexibility and utilization of varying materials. For example, in the aerospace industry, one section of an aircraft may be manufactured using a lightweight material, while other sections can be made of material with flame-retardant properties.

F. NAVY PROCUREMENT PROCESS

The Navy's procurement process begins when a maintenance person onboard a ship, in an aircraft squadron, or submarine squadron requires a part. That part is then removed from local or onboard stock and given to the maintenance person. "The individual work center in a standard vessel conducts maintenance or troubleshoots a broken system; then requisitions the necessary part to complete the maintenance or repairs" (Kenny, 2013, p. 5). Supply department either provides a new part or submits an electronic requisition to the Navy's stock system (Department of the Navy, 2008). If the part is no longer available within the Navy's stock system, DLA contacts the item's manufacturer and procures the part through a contract. Best-case scenario the company still has the part in stock, but if the company discontinued stocking the part, the process is at a standstill. If the part is obsolete, no longer produced, or the parent company is no longer in business, then DLA has to proceed with finding vendors from the private sector to re-manufacture the item (Department of the Navy, 2008). This contracting process may take weeks, months, or even years, and it can be a significant problem given the age of the Navy's existing assets (Department of the Navy, 2008). Likewise, depending on the part size and composition, this long-lead process can severely impact operational readiness. There are few instances when the Navy can lean on its own maintenance activity or depot-level repair facility to have the repair part made.

The Navy does have in place a Depot Level Repairable (DLR) program, which was designed as a means to contend with increasing cost of repair parts, especially advanced weapon systems and extremely high dollar items (Department of the Navy, 2008). Through the DLR program, selected components are specially identified for repair or refurbishment, which is conducted at the depot level or at the original manufacturer such as Lockheed Martin or Raytheon. By repairing or refurbishing equipment and components, the Navy can save a significant amount of money compared with the acquisition of replacement components (Department of the Navy, 2008). This assumes, however, that the original manufacture or the depot level can repair the item, halt an assembly line in order to repair, and provide parts for the repair. Again, this causes lead-times to vary and may ultimately negatively impact readiness levels.

G. SUMMARY

The purpose of the literature review was to introduce AM, provide a basic foundation and terminologies, and discuss the potential of AM in industry. Next, this study discussed the different classifications, technologies, and processes of AM to learn how these technologies could be used in diverse applications. Additionally, the review explored the advancement of AM technology and its associated benefits. Finally, it briefly explained the Navy's traditional process for acquisition of parts and the challenges that can hinder the Navy's entire state of readiness.

In the next chapter, there will be a discussion on this study's methodology and analytical process utilized to determine the probable impact AM will have on the future of military readiness, supply, and combat operations. It will be beneficial to utilize a case-study analysis to appreciate how AM can aid the future performance, growth, and innovation of the military and, also, discuss how to convince leaders that this technology will best suit readiness goals.

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III. METHODOLOGY

This chapter introduces the case-study methodology on which the findings of the main study are based. Chapter IV contains the case-study analysis itself. Following Chapter IV, possible implementation initiatives and options available to the U.S. Navy are targeted as well as how the Navy could diffuse AM technology into the Navy and eventually the entire DOD.

A. MULTIPLE CASE-STUDY ANALYSIS

The findings of this project are based upon a multiple case-study analysis. The multiple case-study approach uses repetition or replication of a process to illustrate results that can be applied to like applications. Yin (1984, p. 23) defines the case-study research method as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used." Utilizing the case-study research is an important tool when research seeks to understand complex technology or applications such as AM. This multiple case-study research is designed to add strength to previous research and emphasize contextual analysis to further AM knowledge to aid the DOD in future decision making. Although select A&D companies have conducted some research studies, their results are not always available to the public domain.

The objective of this case study was to analyze two industries, General Motors (GM) and Boeing Corporation, which have similar characteristics to military supply chain and part demand, and that have successfully implemented AM technology into their businesses. Principally, a company with quality measurability, along with the ability to assess business practices and their effectiveness, makes a company's success a case to be analyzed.

Understanding the knowledge gained from a multiple case-study analysis, the authors were able to properly process and analyze the knowledge value added and produce implementation strategy that decision and policy makers alike can use to make informed decisions.

B. IMPLEMENTATION

Understanding how these companies implemented AM technology and the documented lessons learned played a crucial role in formulating the implementation suggestions in Chapter V. The information collected from the authors' case studies were used to formulate an implementation strategy that uses the lessons learned taken from the successful implementation of AM into GM's and Boeing's manufacturing processes. Utilizing these lessons learned, this study's authors were able to suggest a possible implementation scenario while avoiding the many pitfalls GM and Boeing encountered. Within this analysis, the authors looked at how the U.S. Navy would actually implement the new AM technology, both procedurally and doctrinally. It was discovered that multiple options are available to the Navy using a tiered implementation approach, merging lessons learned in the areas of manpower maximization, software & hardware, and operating environment to devise a 3D printing execution strategy.

C. SUMMARY

The purpose of this chapter was to introduce the reader to the multiple case-study analysis and illustrate how utilizing the findings to discern whether the inclusion of AM technologies into the U.S. Navy will increase overall benefit. In Chapter IV, the authors conduct case-study analysis and discuss the findings. In Chapter V, it is demonstrated how important case-study analysis is by extracting the lessons learned and incorporating an implementation plan that can be used by the U.S. Navy. Finally, in Chapter VI, research project is concluded with a brief summary of findings and recommended items for further research.

IV. CASE ANALYSIS

A. BIG INDUSTRY: ADDITIVE MANUFACTURING IN AVIATION AND AUTOMOTIVE MANUFACTURING

AM has become the most explosive technology over the last decade. Incorporating this technology into major industry continues to expand as its capabilities mature and evolve. The adaptations of various forms of AM such as inkjets, SLA, EBM, and SLS rely heavily on advancing the capabilities of each method. Companies such as ProtoLabs, Stratasys, and ExOne—the three leading publicly exchanged corporations—have expanded into the larger industry sectors with automotive, aviation, space, and U.S. Defense. Stratasys launched a collaborative venture with Airbus to provide 3D-printed flight parts for its A350 XWB Aircraft (Masterson, 2015). Two major manufacturing industries to implement additive manufacturing technologies are the automotive and aerospace industries. This case analysis delves into General Motors (GM) and Boeing Aviation Corporation and their applications of AM in product design, component production, and tooling.

1. Automotive Industry

a. General Motors Financial Troubles

In June of 2009, GM filed bankruptcy with $254.8 billion in assets and liabilities, with June sales hitting a low point of 9.545 million vehicles (Isidore, 2009). This was largely due to vehicle sales declining by 41% from 2007 to 2008, equaling almost 400,000 fewer vehicles (Isidore, 2009). GM, along with Chrysler and Ford, whose sales also declined by 47 percent and 30 percent, respectively, applied for the Troubled Asset Recovery Program (TARP), in which Congress approved the bailout of the Big 3 car manufacturers totaling an estimated $34 billion (Isidore, 2009). In the declining economy of 2008, GM had a focused emphasis on manufacturing trucks and SUVs. When gas prices began to rise rapidly in early summer 2008, many consumers shifted buying preferences to vehicles that had higher gas mileage. Figure 13 depicts declining sales for GM, Ford, and Chrysler from 2004 to 2008.

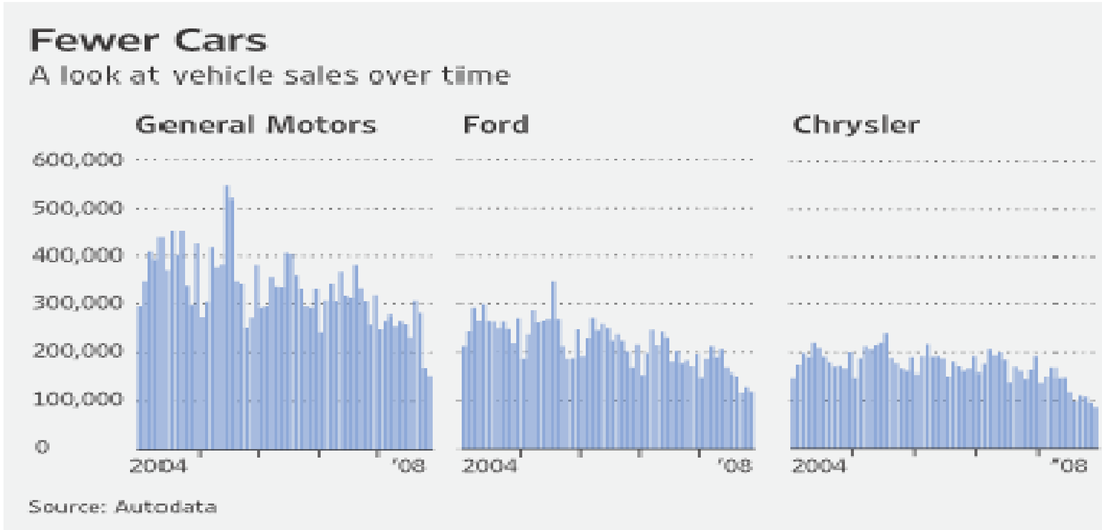


Figure 13. Vehicle sales 2004–2008 (from Stoll, Dolan, McCracken, & Mitchell, 2008, p. 4).

The CEOs of GM, Ford, and Chrysler ultimately found their companies unable to produce higher mileage cars that would appeal to the middle-class buyers. The recovery of the industry approved through Congress required all U.S. automotive manufacturers to reorganize and restructure operations to become competitive in the world market. GM sold and discontinued multiple brands and models including Hummer, Pontiac, Saab, and Saturn. These brands were considered costly and underperforming in the competitive market. Since the bailout, all three major automotive companies have reported financial stability and repaid all government-sponsored debts associated with the bailout proceedings and agreements. Following the repayments, additional stipulations were placed upon the manufacturers to include development of higher fuel-efficiency vehicles in alignment with increased EPA regulations. Figure 14 summarizes these automakers' efforts to recover.

Figure 14. U.S. auto industry CEOs (from Associated Press, n.d.).

b. Costs

In the automotive industry, as with all major manufacturing industries, there are numerous costs incurred when producing goods. One of the main costs is setup cost, which is the cost of labor, time, and resources expended in the setup of machines for a manufacturing assembly line, most commonly known as "tooling." Tooling costs are expenses incurred by a manufacturer in fabrication of the tooling requirements for the performance of a production line. The designing of a product is a continuous cycle of integrating new technologies and features to meet market demand, as can be seen in Figure 15.

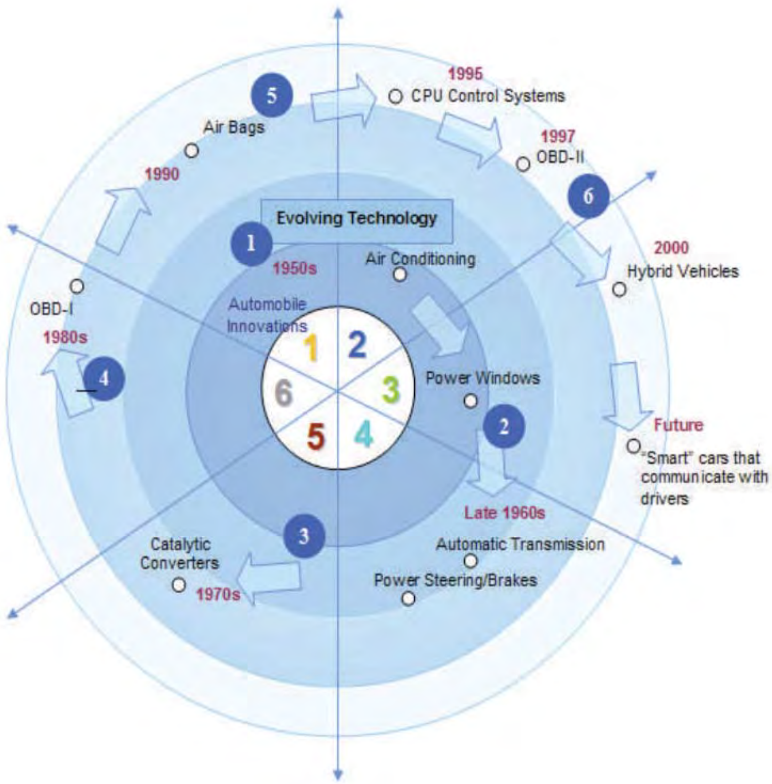


Figure 15. Evolving technology (from SupplyPro, n.d., p. 4).

Once a specific design for a model is finalized, the tooling process begins. Each tooling machine is setup for producing a designated part; modern machines are computerized and are programmed to produce a specific item or part used in the assembly of a product. For each separate piece or part there is a setup cost associated with it; the more parts produced between required setups reduces these costs to a minimum. Company engineers organize and construct the final assembly, or tooling, line to begin the manufacturing of end products. Once the final tooling is completed and initial tests are conducted, any required changes are evaluated by risk analysis based on costs for reconfiguring the line. Most often changes made are minor in nature to prevent excess costs and schedule changes. When major changes are required, however, they are almost never made due to the cost of time to reset the line and the cost of delayed production schedule. Many of the issues for changes are completed post-production, the majority being in the form of vehicle recalls. Figure 16 shows the high number of automobiles recalled by the various automakers during 2013.

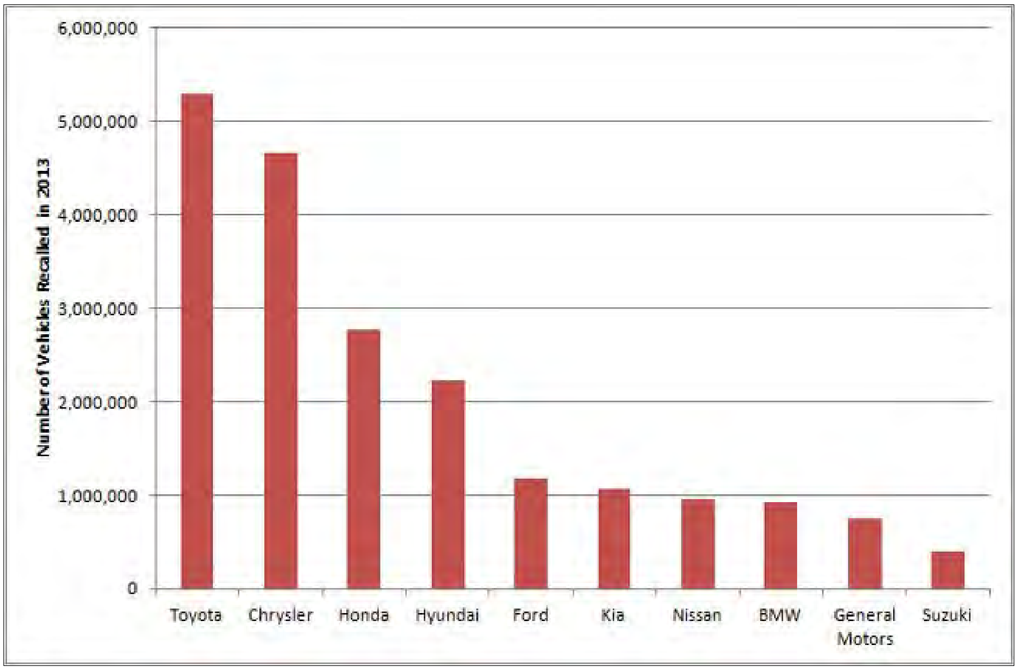


Figure 16. Vehicle recall for 2013 (from Kurtzleben, 2014, para. 2).

In the 1980s, Ford made history with the largest recall by an automotive manufacturer when they recalled 21 million cars due to a transmission system safety defect which caused over 6,000 accidents, 1,700 injuries, and 98 deaths (DeMeter, 2012). The recall resulted from a safety catch, which automobiles would randomly allow the vehicles to shift out of "Park" to "Reverse" (DeMeter, 2012). The resulting recall cost Ford an estimated $1.7 billion in lawsuits, damages, parts, and labor (DeMeter, 2012). Toyota leads the most costly recall in history when they recalled close to 9 million vehicles for models between 2004–2010 (Avalon, Camry, Corolla, Matrix, Highlander, Prius, RAV4, Tundra, Tacoma and various Lexus models) (DeMeter, 2012). The cause was manufacturing flaws, and "in some cases the floor mats became lodged under the accelerator, jamming it down. In others the gas pedal would simply stick" (DeMeter, 2012, p. 2). In reports of over 60 cases of runaway vehicles, half resulted in at least one death; thus, "Toyota issued two separate recalls in 2009 and 2010 to 'reconfigure' the accelerator setup" (DeMeter, 2012, p. 2). Company officials have estimated the cost of $5 billion after lawsuits, parts, labor, and damages, making it the costliest recall ever recorded (DeMeter, 2012, p. 2).

c. Additive Manufacturing in Tooling Process

Over the recent years as profit margins decrease, many manufacturers have been scrutinizing tooling costs. Understanding the costs of tooling requires more effective cost estimations that are both consistent and time efficient. So the question remains: What does AM have to do with this?

The evolving use of additive manufacturing has flowed into the tooling process to help industry design more effective parts and components while reducing costs of production. Tooling design processes and production can often be very expensive and time-consuming. Companies will forgo new design updates on products due to the investment costs of new tooling. New AM technologies, however, can now assist in custom fabrication and improvement of product performance. Additionally, AM technology reduces the lead-time associated with prototype development and tooling redesigns. Tooling redesigns can take advantage of 3D printer’s ability to create complex geometries (Cotteleer, Neier, & Crane, 2014). “GM engineers use it to reduce tooling costs and to understand designs prior to final” assembly line configurations (3D Printing Support, 2014, para. 4).

d. Application in Production of Parts

According to research conducted through the Deloitte University, AM will have the greatest impact on two major areas. The first is a source of product innovation. 3D printers can print components with less design restrictions that constrain traditional subtractive manufacturing. The second is supply chain transformation. By eliminating the need for new tooling, intermediate 3D printers can produce the final products, reducing lead-times while improving market responsiveness (Louis, Seymour, & Joyce, 2014).

GM has invested heavily into the AM world to drive changes and cost reductions across various fields. One of these fields lies within parts production. “SLS and SLA techniques allow designers to quickly and inexpensively go from computer models to one-off parts for wind-tunnel testing so more iterations can be tested in less time” (Rapid Prototyping, n.d., para 3). According to Aerodynamic Development Engineer Suzanne Cody, “long before a full-size model or vehicle is built, rapid prototyping helps to improve the accuracy of the one-third scale models that are used for early aerodynamic testing" (Rapid Prototyping, n.d., para 5).

Along with providing higher quality prototypes, GM has been able to reduce the number of individual components required for a part assembly (known as part count reduction). Engineers analyze each assembly and part to evaluate whether elimination of the part or if multiple parts could be manufactured into one. AM has allowed designers and engineers to accomplish part-count reduction. Reduction in required parts translates into financial savings through reductions in lead-time and overall inventory. "GM Aerodynamicists adapt the technology to speed solutions that increase fuel economy and reduce drag—and quick iteration for scale and full size model testing" (3D Printing Support, 2014, para. 8). "Key components that impact airflow like side mirrors, rocker and rear quarter panels, and front fascias can be quickly changed and tested" (3D Printing Support, 2014, para. 8).

In 2014, GM adopted AM technology for the Chevrolet Malibu (see Figure 17), designing a new front fascia allowing for faster design testing in their wind-tunnel facility. Additionally, GM used the rapid prototyping for interior design as well, manufacturing the floor center console using lighter materials and less production time (see Figure 18).

Figure 17. 2014 Chevrolet Malibu (from GM Authority, 2013, "2014 Chevrolet Malibu").

Figure 18. 2014 Malibu rapid prototyping (from GM Authority, 2013, para. 1).

GM continues to develop AM technology. “This technology allows very quick iteration of parts with no tooling right from the math and facilitates exponential gains in creativity, flexibility, speed and accuracy with dramatic efficiency” (3D Printing Support, 2014, para. 10). “The return on investment can be very attractive. It reduces product development time and gives each end-user more options. Moreover, the reduction in tooling cost, tooling change costs, and piece cost is attractive for the right type of parts” (3D Printing Support, 2014, para. 11).

AM is one of “several technologies keeping GM at the forefront of innovation in the automotive industry and the Rapid Prototype Laboratory is helping to pave the way” (3D Printing Support, 2014, para. 12). Continued advances in technology and new applications for developing designs and producing parts will allow more cost savings in lead-times, leading to faster delivery of final products and reducing the potential for vehicle recalls through improved designs.

2. Aerospace Industry

The aerospace industry is currently “engaged in the research, development, and manufacture of flight vehicles, including unpowered gliders and sailplanes, lighter-than-air craft (balloons and airships), heavier-than-air craft (includes fixed-wing aircraft and rotary-wing), missiles, space launch vehicles, and spacecraft (manned and unmanned)” (see Figures 19–20) (Weiss, n.d., “Aerospace Industry”). “In addition, the industry is engaged in the fabrication of non-aerospace products and systems that make use of aerospace technology” (Weiss, n.d., “Aerospace Industry”).

Figure 19. Lockheed Martin Airship (from Lockheed Martin, n.d.).

Figure 20. Bell/Boeing V-22 Osprey (from Boeing Company, n.d.).

Over the last few years, the aerospace industry reported improving sales in both civilian and military aircraft. U.S. Aerospace Industries Association (AIA) estimates the 2015 projected sales of various aircraft systems at $240 billion dollars, a 5.3% increase from 2014 sales (Yeo, 2014). The majority of increase is in civil aircraft sales to meet the growing demand from passengers along with advancements and production of next generation fuel-efficiency aircraft (Yeo, 2014).

One of the newest technologies the aerospace industry is investing in is the use of AM and 3D printing. Industry giants like Boeing, Lockheed Martin, Honeywell, and GE—the leading manufacturer of aircraft engines—are incorporating additive-manufactured components into their designs (Flanagan, 2014).

3. Boeing Aviation Corporation

Boeing is one of the world's leading aircraft manufacturers with an estimated 10,000 active commercial aircraft in service and another 5,500 on order. Defense aircraft include the F/A-18E/F Super Hornet, AH-64 Apache, V-22 Osprey, P-8 Poseidon, and the KC-46A tanker. The supply chain to support the Boeing's global neighborhood is in itself its own entity: Over 5,000 factories and an estimated half-million personnel produce components, parts, and systems to support existing aircraft preventative and corrective maintenance requirements. Figure 21 summarizes Boeing's current global supply chain. Boeing has even expanded its support to the Air Force in support of the Fairchild Republic by developing aircraft such as the A-10 Thunderbolt II (Warthog). U.S. Air Force recently awarded Boeing the approved contract to produce 173 sets of replacement wings for the weapon systems (Orndorff, 2012).

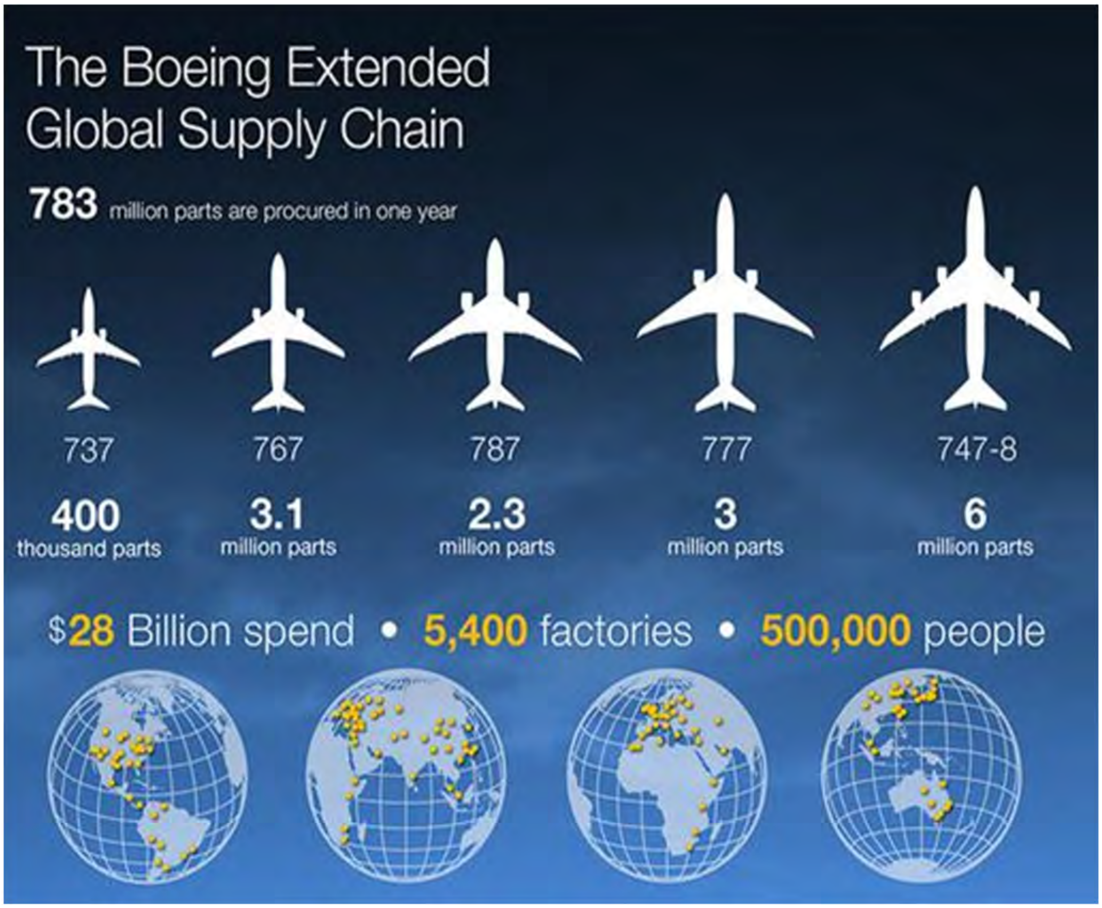


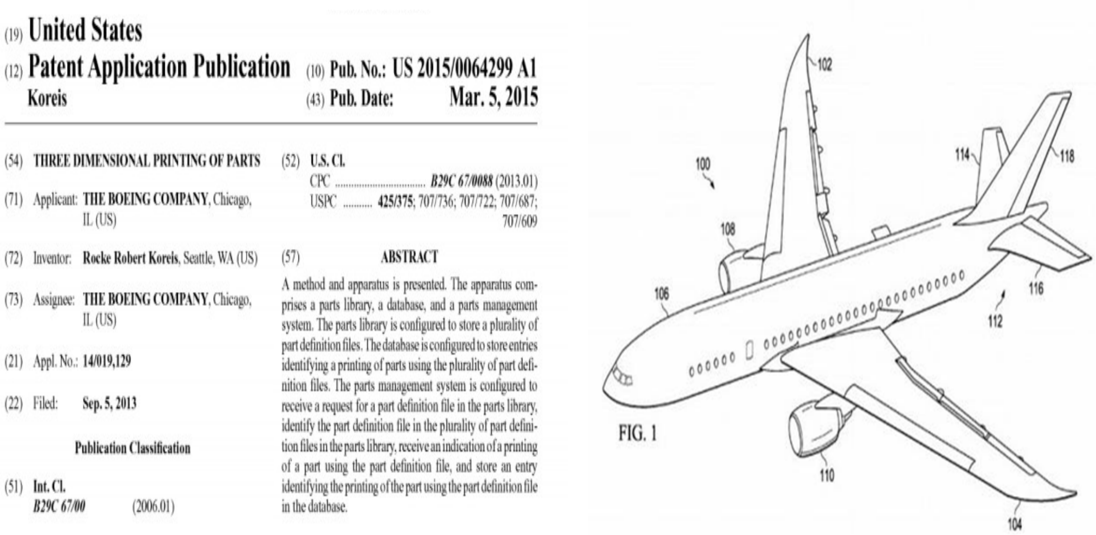
Figure 21. Boeing’s extended global supply chain (from World Class Supplier Quality, n.d., para. 3).

4. Additive Manufacturing Developments

Boeing has grown into the leading manufacturer utilizing AM for their aircraft and systems. In early 2015, Boeing filed for a patent that would permit the manufacturing of aircraft parts using 3D printer technology, as shown in Figure 22. The application describes the methodology for 3D-printing an object from a CAD design through a central database management system that Boeing and its customers can use to fulfill spare part orders. The patent application cited a major challenge facing aircraft operators today:

> During the lifetime of an aircraft, parts may be replaced. In order to meet demand for replacement parts, aircraft manufacturers may keep an inventory of parts on hand. A client may request parts from the aircraft manufacturer when a replacement part is desired. However, receiving

> requested parts from the aircraft manufacturer may take an undesirable amount of time for a client. Some clients may keep an inventory of parts on hand to avoid waiting an undesirable amount of time. However, storing an inventory of extra parts either at an aircraft manufacturer or at a client may use an undesirable amount of resources. (Boeing Company, 2015, p. 1)



(19) United States
(12) Patent Application Publication
Koreis
(10) Pub. No.: US 2015/0064299 A1
(43) Pub. Date: Mar. 5, 2015

(54) THREE DIMENSIONAL PRINTING OF PARTS

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(21) Appl. No.: 14/019,129

(22) Filed: Sep. 5, 2013

Publication Classification

(51) Int. Cl.
B29C 67/00 (2006.01)

(52) U.S. Cl.
CPC B29C 67/0088 (2013.01)
USPC 425/375; 707/736; 707/722; 707/687; 707/609

(57) ABSTRACT

A method and apparatus is presented. The apparatus comprises a parts library, a database, and a parts management system. The parts library is configured to store a plurality of part definition files. The database is configured to store entries identifying a printing of parts using the plurality of part definition files. The parts management system is configured to receive a request for a part definition file in the parts library, identify the part definition file in the plurality of part definition files in the parts library, receive an indication of a printing of a part using the part definition file, and store an entry identifying the printing of the part using the part definition file in the database.

Figure 22. Boeing patents application (from Boeing Company, 2015, p. 1).

Boeing currently uses AM to produce approximately 300 non-metallic parts across 10 different aircraft platforms, estimating more than 20,000 3D-printed parts in active aircraft. This includes the Navy's F/A-18 E/F Super Hornet (see Figure 23), which uses roughly 150 parts within its fuselage area. The greatest advantage is in the ability to place a 3D printer anywhere in the world, even onboard a Navy vessel at sea, and with the hit of a button the machine will print the replacement part. Lead-time reduction for the Navy could amount to days or weeks depending on the current location of the ship. Additionally, the current extremely costly transportation costs for shipping a priority part out to a ship could be greatly reduced.

Figure 23. Boeing F/A-18F Super Hornet (from Boeing F/A-18 Super hornet, n.d.).

Boeing launched a collaborative pilot program with the Department of Energy's Manufacturing Facility at the Oak Ridge National Laboratory (ORNL) to explore additive manufacturing. Boeing technical experts conducted a weeklong training program focused towards hands-on specialized technical training on additive manufacturing. At the same time, Boeing experts provide ORNL with valuable knowledge and insights into current industry needs and challenges to advance technologies and revolutionize how products are designed and built (Oak Ridge, 2014).

Another major collaborative venture incorporates supporting General Electric (GE) Aviation in applying AM into their engine designs. GE Aviation developed a new housing for the compressor temperature sensor (Figure 24), which "recently became the first 3D-printed part approved by the U.S. Federal Aviation Administration (FAA) to fly within a commercial jet" (GE Reports Staff, 2015, para. 2). The Boeing/GE venture will "retrofit more than 400 GE90-94B jet engines—some of the world's largest and most powerful—with the 3D printed part" (GE Reports Staff, 2015, para. 3).

Figure 24. GE’s first 3D printed temperature sensor (from GE Reports Staff, 2015, p. 1).

Additional research from GE helped them develop new 3D woven carbon fiber fan blades and shroud for the GEnx-1B and GE90 engines, which shed hundreds of pounds of weight from the engine without losing power or durability. The carbon fiber material makes the blades more corrosive resistant, while the new design allows more FOD resistance. GEnx-1B engine is designed to power Boeing’s 787 Dreamliner and the Air Force’s pair of new 747s to replace the current Air Force One aircraft. Additional engine advancements follow with GE’s new LEAP engine, seen in Figure 25, which uses 19 3D-printed fuel nozzles per engine (GE Reports Staff, 2015, para. 4). “The engine is being developed by CFM International, a 50–50 joint venture between GE and France’s Snecma (Safran)” (GE Reports Staff, 2015, para. 4). “GE Aviation is investing $70 million in an Auburn, Alabama factory to make 3D printed fuel nozzles for its LEAP jet engine” (Flanagan, 2014, para. 1). Utilizing the printing capabilities, GE places emphasis on part count reduction: whereas fuel nozzles used to require 20 separate components welded together, they now only require printing just one.

Given these examples, it is no surprise that of the global market share "AM now represents a small $3 billion slice of overall manufacturing output" (Flanagan, 2014, para. 4).

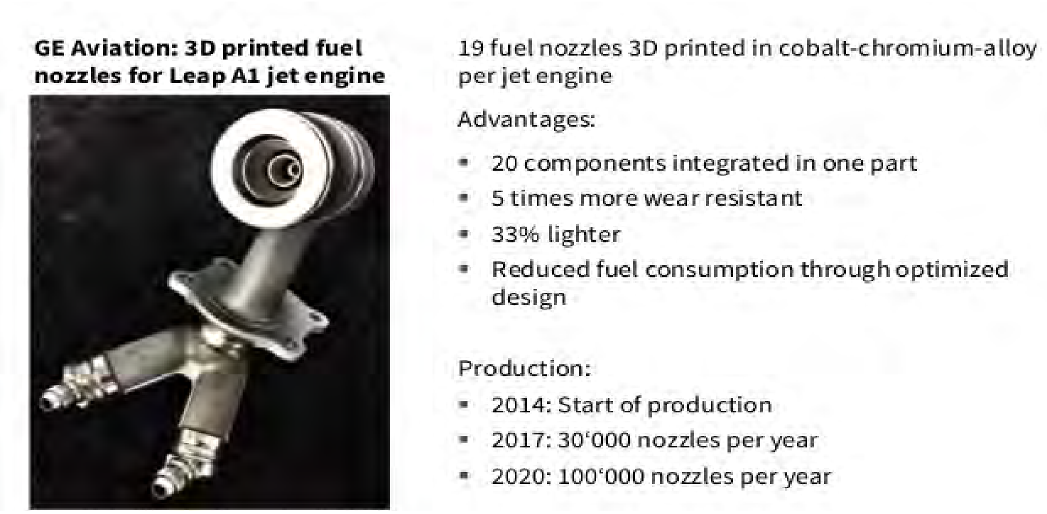

Figure 25. 3D printed fuel nozzle (from GE Reports Staff, 2014, para. 5).

B. CONCLUSIONS

AM has secured a concrete hold in the manufacturing world and continues to shape major industries. With major corporations making large investments into the various forms of additive manufacturing technologies, the advancements of machine capabilities will spawn more innovative thinking. They will move past the age-old mantra of "design-by-manufacture" towards "manufacture-to-design," removing restrictions set by the limitations of modern subtractive manufacturing.

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V. IMPLEMENTATION

A. INDUSTRY APPLICATIONS

Hundreds of companies use 3D printing to fabricate end-use items. Specifically, the large, more well-known corporations are investing heavily in 3D printed parts, even fabricating items larger than most would think imaginable. Many of these companies fall into the aviation category, which the military finds particularly of interest. Most engineering concepts originate in large aerospace firms who invest heavily in research and development. This project will highlight a few of these and elaborate on the successes they are enjoying using 3D printing production.

(1) Boeing

Several major companies are already taking advantage of this growing technology and on a much larger scale than most would believe. Seattle-based aerospace giant Boeing has been investing in 3D technologies over the last several years, setting new industry standards and records with not only the vast quantity of printed parts used, but also the variety of aircraft using these parts. According to Davidson (2012, "Advantages and Tradeoffs"), "In recent years, Boeing has dramatically increased the number of distinct parts it prints to about 300, and the technology has cranked out a total 22,000 pieces across 10 types of military and commercial aircraft." Boeing's new generation of airliner, the 787 "Dreamliner" as seen in Figure 26, is expected to set records with its incredible range and fuel efficiency, including the ability to "hold 280 passengers, travel over 8000 nautical miles, and [use] 20% less fuel than most similar-sized aircrafts" (Phillips, 2014, "A Near Vertical Takeoff"). The Dreamliner has roughly 30 3D-printed parts (Phillips, 2014). Boeing continues to explore the use of 3D printing to create lightweight metallic parts, but eventually it expects "to use 3D printing to make an entire unmanned air vehicle and possibly even a commercial airliner, or at least a wing" (Davidson, 2012, "Advantages and Tradeoffs").

Figure 26. Boeing Dreamliner 787 (from Boeing 787, n.d.).

(2) General Electric

Another company harnessing the new capability is GE. GE is searching for a way to produce some 85,000 fuel nozzles for its newest jet engine—the LEAP engine (see Figure 27). Instead of assembling the nozzles from over 20 different parts, it plans to create the units in one single piece with the help of 3D printers (Worstall, 2013). Catts (2013, para. 3) observes, “To do so, GE plans to spend tens of millions of dollars to help get machines ready for its purposes, triple the aviation business’s 70-person 3D printing staff and expand the factory floor fourfold in the coming years. The push would bolster a 3D industry that consultant Wohlers Associates estimates is poised to almost triple to about $6 billion annually by 2017.” GE’s “embrace of 3D printing for critical components throws the weight of the world’s largest jet-engine maker” behind the new process, paving the way for other leading global industries (Catts, 2013, para. 5). The aerospace market alone for 3D printers may triple to $1 billion, and it is projected to climb to $10 billion over time (Catts, 2013). Reflective of this investment is GE’s new combined research and manufacturing facility dubbed a “micro factory” near its aviation headquarters in Cincinnati (Catts, 2013). This facility is specifically designed to train workers and to let engineers test new advanced composite materials and further applications with 3D printing (Catts, 2013).

Figure 27. GE’s LEAP engine (from GE Joint Venture, 2012, “Leap Engine”).

(3) Rolls-Royce

Rolls-Royce, another leading engine manufacturer, is also planning to exploit 3D printing to manufacture fuel nozzles and other components for their engines. Rolls-Royce’s head of technology, Dr. Henner Wapenhans, claims that the use of 3D printing would enable Rolls-Royce to “slash lead-times, as well as gain an ‘inventory advantage’ with less need to store parts” (Vasagar, 2013, para. 11). Dr. Henner Wapenhans emphasizes that “one of the great advantages in the aerospace world is that some of these parts that we make have very long lead-times, because of the tooling process that’s got to [happen], and then it takes potentially 18 months to get the first part after placing an order—versus printing it, which could be done quite rapidly” (Vasagar, 2013, para. 12).

B. MILITARY APPLICATIONS

When industry develops new ideas, technology, equipment, or scientific breakthroughs, the military always has one eye open. Although the DOD is plagued with budget cuts and dwindling financial backing, and Research and Development (R&D) funds are often limited, the military is always keen to explore the latest innovations. Whether in aeronautics, engineering, bio-technology, or other beneficial novelties, the military is constantly searching for ways to get the latest and greatest to harness the combat advantage. Where technology ripens, they are not far behind. Although they promote innovation, they are rarely in the forefront of design and concept. With 3D printing, however, the U.S. military, specifically the Army and Navy, and even NASA are venturing far into the unknown, and they are spearheading multiple new ways of thinking and new methodologies of approaching 3D applications.

(1) U.S. Army

The potential for 3D applications in the military is mind-boggling. Currently numerous projects are underway, primarily with the U.S. Army testing the envelope of 3D printing capabilities. The Army's future vision of 3D printing systems exists in the form of mobile battlefield printing, shown in this artist's depiction in Figure 28. The Army's partnerships with private enterprise, as well as federally funded technology initiatives, have put the organization at the cutting-edge of digital manufacturing (Boren, 2014). Army scientists are designing and printing items such as "parts for protective masks, holders for improvised explosive device detectors, medical prosthetics, batteries, antennas, fuse elements, and wings for unmanned aircraft" (Insinna, 2014, para. 4). They have also tested 3D printers in the austere environment and combat conditions of Afghanistan, where two printers are deployed to provide soldiers with small parts on demand (Insinna, 2014). According to General Dennis Via, Commander of Army Materiel Command, "printers could one day be embedded with squads, so that troops can manufacture weapons, tools or repair parts while they are in the field" (Insinna, 2014, para. 20).

Figure 28. Future depiction of 3D printing in the battlefield (from Louis et al., 2014, p. 1).

The Army is anticipating the capability of printing food on the battlefield. Food scientists at the U.S. Army Natick Solider Research, Development and Engineering Center are "investigating the 3D applications of food processing and how the technology will eventually allow not only for a more varied menu for soldiers, but will also be able to provide particular nutrients for those who require it" (Boren, 2014, "Food"). A "soldier who is worn out from battle and needs carbohydrates or protein could print out protein- and carbohydrate-rich food, while another soldier who is vitamin D-deficient could print out a meal rich in vitamin D" (Docksai, 2014, para. 4). With food printing capability, the immense logistics tail of meals ready-to-eat (MREs) would be alleviated. This does not mitigate the requirement for food-printed materials, however. As MREs currently subsidize soldiers' meals and nutrition, these could soon be replaced with food that is nutritiously specifically tailored to a given combat situation or mission (Docksai, 2014).

3D applications offer some medical benefits, too. Dr. Thomas Russel, Director of the Army Research Lab, stated that “many of the injuries soldiers receive in the field are not traditional. A lot of the medical community sees this as a new approach to medicine. We can 3D-scan injuries” (Boren, 2014, “Medicine”). Specifically, Dr. Russel is examining skin repair as a very real possibility: “The scars that soldiers develop as a result of burns constrict movement and disfigure them permanently. The initiative to restore skin that is elastic and complete with sweat glands, appropriate pigmentation and hair follicles is incredibly important” (Boren, 2014, “Medicine”).

(2) U.S. Navy

The Navy is also expanding its use of 3D printers to Navy warships at sea. In 2013, the Navy installed a 3D printer on a joint high speed vessel (JHSV) to test its durability and productivity. In early 2014, the service outfitted the USS Essex, an amphibious assault ship, with a 3D printer to “employ the same testing methodology used on the JHSV to collect data that will inform the service on how the motion of a ship affects 3D printers” (Insinna, 2014, para. 27). According to the Navy, “the goal isn’t to create printed items that would replace existing product lines, but to provide short-term solutions when parts break onboard a ship. Having a printer will also give sailors the opportunity to ‘play with the new technology’ and come up with ways it can be useful” (Insinna, 2014, para. 25).

(3) NASA

NASA is another key organization that is not only interested in 3D printing objects in space, but has actually completed its first real print test on the International Space Station using its space-compatible 3D printer (see Figure 29). In combined efforts with Made In Space, Inc., the organization that collaborated on this space station technology, NASA has successfully printed several items in this zero-gravity environment, paving the way for future innovations in 3D printing technology (Loff & Dunbar 2015). Since spacecraft are uniquely designed with specific weight and space restrictions, when something breaks there is little room for spare parts. With 3D printing now a reality in space, NASA engineers can look towards planning for long-term space expeditions. "This capability may decrease cost and risk on the station, which will be critical when space explorers venture far from Earth and will create an on-demand supply chain for needed tools and parts," much like a "machine-shop" in space (Loff & Dunbar 2015, para. 3). Much like the Army, NASA is also experimenting with 3D-printed food. This would also allow deeper and longer space missions and provide astronauts with a sustainable and nutritious food supply. Further tests will be conducted by NASA on food and parts alike to ensure the printing process is as effective in a microgravity environment as it is on Earth.

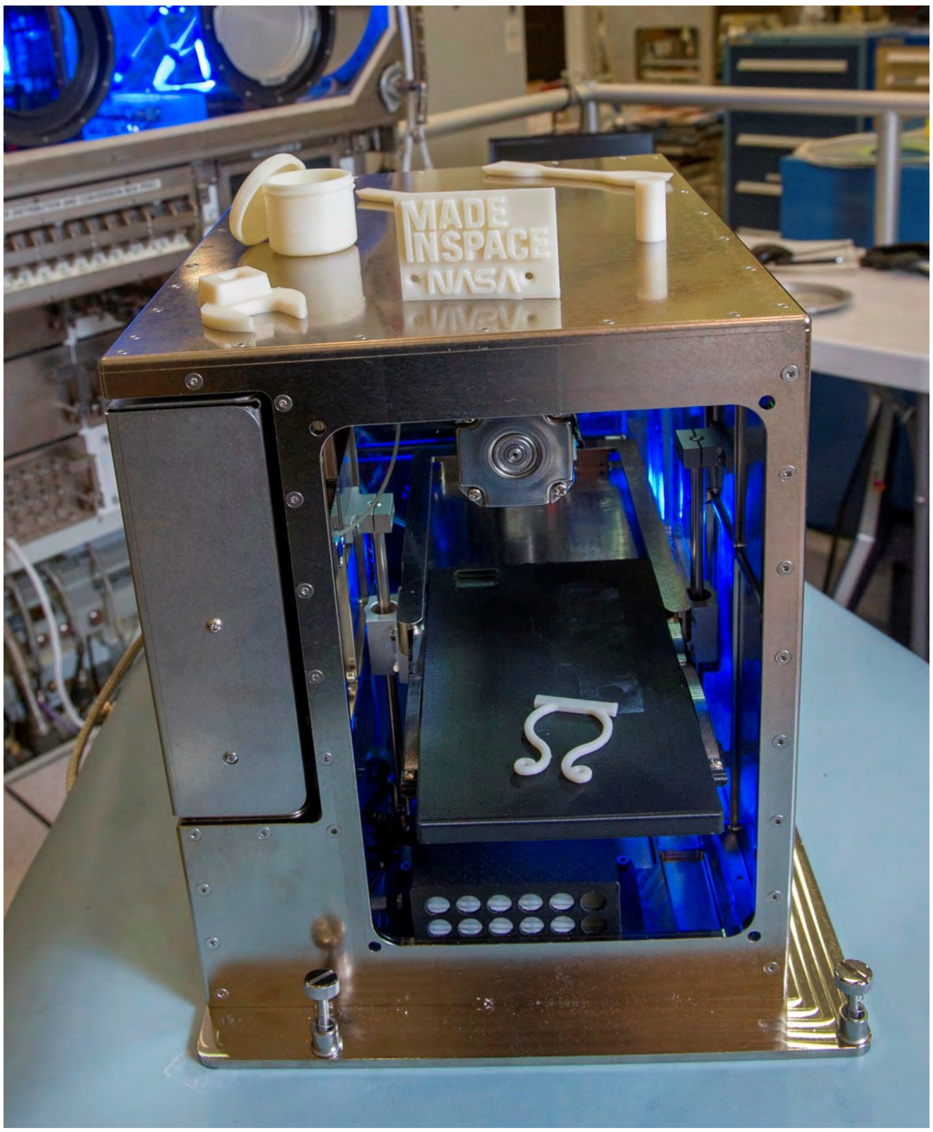

Figure 29. NASA's 3D printer (from NASA, 2015, para. 1).

C. IMPLEMENTATION PROCESS AND CRITERIA

Making the decision to utilize AM in the military is not an easy process, but a pilot project approach can weigh the costs and benefits to measure a part or systems compatibility with AM. As Deloitte illustrates in Figure 30, the process of implementation of AM begins with identifying exactly what parts or systems can be replaced with AM items. Next, the organization can conduct comparative testing of parts that are produced under traditional subtracting methods and those using additive manufacturing methods (Louis et al., 2014). In this phase, material criteria are analyzed by engineering properties such as tensile strength, ductility, thermal conductivity, flammability, and corrosive properties (Louis et al., 2014). Once establishing material criteria, performance testing can identify various failures and their acceptable limits (Louis et al., 2014).

In the business case phase, the testing is analyzed to answer such questions as: Did the additive manufactured part performed better or not? Did the AM part reduce the number of piece parts required to traditionally produce or assemble a part (Louis et al., 2014)? What is the differential in cost between the two processes? Using quantifying data, a cost-benefit analysis can determine the life cycle costs assuming the AM part performs superior.

Lastly, the pilot project becomes a reality as the physical supply chain is realized and implemented. Taking into effect operational limitations and tempo, those applications with lower risk and higher impact should be chosen for pilot tests, keeping close track of key performance indicators (KPIs) (Louis et al., 2014). Once the military organization implements several pilot programs, it can gain more experience and invest that knowledge in future manufacturing and operating strategies.

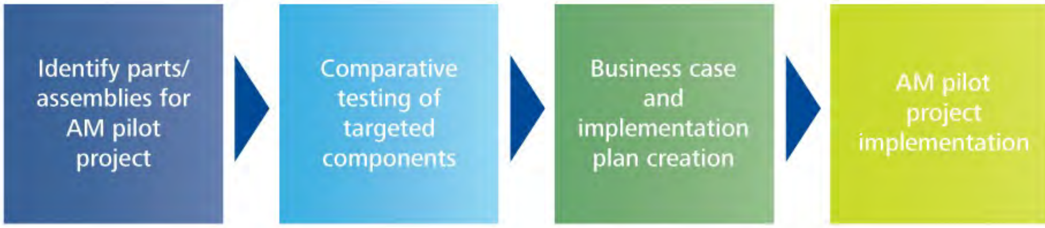

Figure 30. AM pilot project approach (from Louis et al., 2014, p. 14).

D. MILITARY ISSUES WITH AM

Additive manufacturing as seen in the case-study analysis is an extremely effective manufacturing process for certain parts and system assemblies. In military applications, there are real efficiencies gained by utilizing such processes, and there is much money to be saved once the process is realized in scope. As the advantages of additive manufacturing become internationally recognized, their effect on many industries is predicted to revolutionize corporate business structures and their associated supply chains (Economist, 2011). Driving this interest is the ability to produce complex parts with unique design attributes (e.g., reduction in weight, fewer parts, fewer hydraulic leaks point, part consolidation, reduced press loss) for “one-off” or short production runs, mass-customization, prototyping, and critical applications at a fraction of the time and money of traditional manufacturing techniques. There are many issues when implementing such digital supply chains, however, and the military must recognize and validate a multitude of concerns prior to using AM in full spectrum.

1. Parts Testing and Certification

Part testing methods and, also, certification standards are critical aspects of AM utilization, and they remain two of the biggest hurdles to overcome before AM technology is widely accepted in defense applications. Due to the wide range of requirements and many different pieces of equipment, a proper quality assessment and control procedure would have to be successfully established. When dealing with metal components, each part for an assembly on an aircraft, for example, is meticulously tested for durability under anticipated exposure specifications. Some parts will be under extreme pressure, and some parts will be subjected to extreme temperatures over extended periods of time. Recently, there have been part failures recorded on the new Dreamliner, and although those parts are not AM produced parts, they point to the importance of testing, especially in the aerospace environment (Goodin, 2015). These parts are built to aerospace specifications and requirements. How then can the military safely produce parts using AM technology for possible remote environments while staying within the proper regulations and specifications designed for said component?

The defense industry, much like the aerospace industry, places stringent requirements to ensure parts can achieve mandated performance levels. The defense and aerospace industries either use standards promulgated by established organizational or by internal standards based on minimal allowable performance standards. These requirements established for traditional manufacturing methods often require a long list of complex requirements to meet certain performance levels necessary to ensure safe air, land, sea, and undersea operations. Some of these factors include smoke and toxicity levels, material strength, flammability characteristics, fatigue resistance, survival temperature, and radiation and chemical sensitivity. These requirements are needed for even the most simplistic parts used by the aerospace and military industries. Not only are the qualities of parts imperative, but the standardization of those parts are equally important factors. Examining and understanding these rules and regulations are imperative to implementing AM into the DOD.

In the defense industry, the Defense Standardization Program (DSP) is the governing body that ensures that the Secretary of Defense maintains a unified standardization program. Per the DOD 4120.24-M (2014, p. 15), this program provides:

- Standardizing like products and technologies
- Using a common set of specifications and standards
- Cooperating with industry in the development of standards
- Assigning standardization responsibilities in the DOD
- Resolving disputes between the military departments and defense agencies
- Making final decisions on all DSP-related matters

According to the DOD 4120.24-M (2014, p. 15) this standardization affords the warfighter with “equipment that is interoperable, reliable, technologically superior, and affordable.” Some of those key capabilities discussed in the DOD 4120.24-M (2014, p. 15) that require standardization to be successful include:

- Interoperability with multi-national partners and among the military departments, which requires standardization of physical, electronic, and functional interfaces and performance requirements;
- Information superiority, which demands standardized data and equipment interfaces and performance requirements to permit information to be shared among systems and personnel;
- Rapid new technology insertion, which requires standard interfaces and performance requirements. Since the DOD must retain existing systems for decades beyond their planned life, affordable technology refreshments will depend in part on the department’s ability to define standard solutions across systems based on performance and interface requirements.

For the defense arena, the Defense Standard (MIL-STD), Defense Specification (MIL-SPEC), Defense Handbook (MIL-HDBK), Performance Specification (MIL-PRF), and Detail Specification (MIL-DTL) established by DSP policies and procedures are the governing doctrines that are used to achieve U.S. Department of Defense standardization objectives. These terms tend to be used interchangeably but subsequently have subtle differences that must be maintained throughout the part certification process. Table 1 lists these terms and definitions extracted from the DOD 4120.24-M, *Defense Standardization Program (DSP) Policies and Procedures*, March 2000, Acquisition, Technology and Logistics (OUSD).

Table 1. Defense Standardization Program Definitions (after DOD 4120.24-M, 2014, p. 34).

Acronym	Type	Definition
MIL-HDBK	Defense Handbook	Guidance containing standard procedural, technical, engineering, or design information about the material, processes, and practices
MIL-SPEC	Defense Specification	Document describing the essential technical requirements for purchased material that is military-unique or substantially modified commercial items
MIL-STD	Defense Standard	Document establishing 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, design criteria, manufacturing process, standard practices, and test method standards
MIL-PRF	Performance Specification	Document stating 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	Document 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

Despite the subtle differences among them, all of these definitions go by the standard rubric of “military standard” and will be referred to as such throughout the rest of the certification portion of this project.

In order for the DOD to take full advantage of all the AM benefits discussed throughout this project, a certification process must be established including: general AM doctrine, proper procedures, certification, standards, design rules, and specification policy. If the certification process remains status quo and does not adopt AM technology, however, the DOD would certainly never see the benefits of this technology. Part certification will unnecessarily become the bottleneck in AM implementation unless there is drastic reform of the certification and qualification of parts to create acceptable "military standard" parts. This could be completed in two ways: "in-process" certification or "platform" certification.

During the AM process, the ultimate goal in certification should be "in-process," "self-certified," or "on-machine acceptance and qualification" (Das, Wang, & White, 2013). For this to happen, Das et al. suggest much work is needed to be done, including:

- Validate and verify a wide range of different processes, processing conditions, and materials
- Quantify uncertainties associated with materials
- Develop new certification methods based on, for instance, "similarity" of material, process, or part geometry
- Augment physical experimentations with powerful computational models, data, and tools to shorten the time to market

This "in-process" certification will need to be able to provide a high level of confidence to prevent parts with defects to enter the military's supply system. This process will need to be able to identify defects such as lack of fusion, porosity, cracking, and vaporization. Ultimately the "in-process" needs assure the quality of the part. In February 2013, Sigma Labs, Inc. filed a provisional patent that will enable real-time, on-machine measurements to meet very strict guidelines that will provide rapid qualification and certification of parts. According to Mark Cola, President and CEO of Sigma Labs, "The ability to offer rapid qualification and certification capability will favorably impact our current and future customers as they bring new products to market" (Sigma Labs, 2013, para. 1).

Secondly, "platform" certification is an option for end-use part certification. "Platform" certification means that repeatability, part quality, dimensional accuracy, heat distribution, part performance, and financial benefits meet strict quality standards (Woodcock, 2014). Bell Helicopter has partnered with its supplier, Harvest Technologies, to produce flight-certified parts using a laser-sintering AM machine from EOS, a maker or AM systems. Elliot Schulte, an engineer at Bell Helicopter, said, "We characterized the mechanical properties of each additively manufactured build so that we could confirm that the EOS system met specification requirements and produced the same quality product each time” (Woodcock, 2014, para. 4). He continued: “The system was done with a number of different materials and across a series of individual build to establish that EOS technology was robust and highly repeatable” (Woodcock, 2014, para. 5).

For the DOD, certification of an AM process is potentially the largest challenge for building and using end-use parts. The following tasks could accelerate the AM maturation process and transition from the laboratory to maintenance shops and eventually to the battlefield (NIST, 2013):

Government Tasks:

- Encourage AM adoption through rewarding suppliers taking risks to implement AM technologies by offering ancillary benefits
- Facilitate collaboration between designers and consumers
- Develop doctrine and publicize standards to assist in certification process
- Inspire research and development through greater funding opportunities

Industry Tasks:

- Foster key relationships with identical firms for development in strategic AM technologies
- Help develop AM standards
- Publish and communicate AM benefits
- Invest in AM research and development

Academia Tasks:

- Develop certification processes to conduct modeling and process optimization simulation
- Publish process optimization techniques
- Share new processes that improve quality verifiability and speed
- Educate next generation users

Overcoming the certification hurdle will take the partnership of several entities. Now that AM technology is continually evolving and growing at a rapid pace, it is now time for the DOD to have a vested interest. Having the ability to additively manufacture a part, and realizing and capitalizing on the benefits that the technology offers will only increase the readiness of our military.

Although the Army and Navy specifically are putting AM manufactured parts to the test for certain items, there is great hesitancy to proceed in producing such critical parts for sophisticated equipment. Many challenges still loom regarding how exactly the DOD will conduct its integrity certifications on AM parts. Would separate test equipment need to accompany 3D printers themselves? Will the DOD require every part to be screened by a qualified individual or company? The requirement to test each item that is additively manufactured for tensile strength, conductivity, heat resistance, and other scientific qualities is paramount. The DOD is not in the business of forfeiting reliability for costs. As Deloitte highlights, the success of these certification efforts may well become the tipping point in the adoption of AM technologies (Louis et al., 2014).

2. Information Security

With the realization of AM in the battlefield, the use of 3D printing there has recently been challenged: Is blueprint data secure from possible cyber-attacks? Since sensitive information and data can flow electronically, there is always the risk of that data being intercepted or blocked. Cyber-attacks on 3D printing software could potentially negate the system entirely, rendering it useless and potentially placing lives at risk. Enemy forces have the potential of obstructing or jamming the 3D printing digital supply chain. Recognizing this danger, in 2014 President Obama fostered the Digital Manufacturing and Design Innovation Institute (DMDII). Based on a public-private partnership, the goal of the DMDII was to study, test, and develop advanced analytics in a secure cyber system to counter potential cyber threats (Louis et al., 2014).

3. Intellectual Property Infringement

Intellectual property (IP) can be defined as “property that results from mental labor” (Harris, Pritchard, Rabins, James, & Englehardt, 2009, chapter 5 section 8). Lambeth (2015, p. 7) outlines several methods used to protect IP, including:

- Trade secrets: Pieces of information, such as formulas, procedures, or devices, are kept secret by keeping them out of the public domain by the owner.
- Patents: The federal government gives exclusive use of a new, useful, and non-obvious invention to the recipient of the patent for 20 years.

- Trademarks: Government protection is given to words, phrases, symbols, sounds, or designs.
- Copyrights: Protection is given to the unique expression of an idea, such as in art (e.g., books, moves, sculptures, or music) or computer programs.

Since AM technology makes is easier for outside sources to replicate parts, it makes protecting IP extremely difficult. AM users have the potential to modify computer-aided design (CAD) models, allowing them to design and produce parts with minor modifications to an original, patent protected part (Lambeth, 2015). When individual users are able to create and post a digital model of a repair to a common household item, the model can be printed by anyone that has a 3D printer, which can highly impact a company's revenue stream. These patent infringements can also be broken down into direct and indirect infringement. Direct infringement refers to the entities that make, sell, or use a patented product (Doherty, 2012). For the 3D printing of a patented part, the maker and the user of the part could be held liable for direct infringement; however, some companies, such as Shapeways, include terms and conditions that would place all infringement costs on the purchaser of that part (Lambeth, 2015). Indirect infringement refers to those who actively induce patent infringement or offer to sell a component of a patented part to use in a patented process (Doherty, 2012). It may be difficult to hold either liable, however, due to the fact that it is difficult to prove that either the 3D printing company or the model designer intended to cause patent infringement (Lambeth, 2015).

In the commercial business of 3D printing, several such infringement accusations have already taken place, and as 3D printing becomes more prevalent and users become more experienced, many more IP infringements are certainly on the horizon.

Current DOD acquisition practices allow the purchase of parts outright directly from the original manufactures, avoiding issues with manufacturer's property rights. When using AM parts, essentially the suppliers are losing out on thousands—even millions—of dollars. The DOD must come up with a way to pay for the legal rights associated with the printed parts (i.e., paying for the electronic part like they would a physical part). There are a variety of ways that this can be done: one of them is to write this in the contract prior to the electronic or digital exchange. Since the DOD purchases the CAD file and it can also print an infinite number of parts from that file, it must develop a licensing strategy associated with that file. If this licensing exchange is included in an overarching contract for the part files, then the DOD would be paying essentially a fee/charge for every part that is printed using the company's provided CAD file. Many experts, due to inconsistencies and ambiguity of certain parts of the law regarding AM, recommend legislators improve the legal framework for IP rights. Since the DOD will soon be printing on a massive scale, they will have to be intimately familiar with current legal guidance and control measures when initiating contracts and acquisition strategies.

4. Personnel Training and Skill Set Development

Since AM is still a relatively new technology, the DOD has not and cannot initiate force-wide assimilation without a competent workforce capable of operating the 3D printers and associated CAD files. Current industries are still gaining knowledge and experience, and the DOD must start initially by drawing on industry practices to pioneer its own training pipeline. While the DOD has been experimenting with AM applications for years, it has not integrated the process into military and civilian occupations (Louis et al., 2014).

AM is simply more than pressing a "print" button on a machine. AM requires an understanding of CAD design manipulation, raw material preparation and management, product finishing, and limited certification methods. As noted in the civilian sector, these skills require increased experience levels to be fully qualified in the AM spectrum (Louis et al., 2014). As congruent with most military applications—combat systems and equipment—civilian contractors are typically utilized during the initial implementation phases. New aircraft, for example, often require some level of contractor oversight of maintenance functions before handing the functions over to military personnel. AM could probably work much in the same way, while simultaneously training their personnel. The military also faces the challenge as to who will be responsible for 3D printing internally. Will the Navy, for example, form a specific rate of sailors with an engineering background to operate the AM process? Will the Navy include this responsibility in a rate with similar experience and fundamental knowledge?

E. ADDITIVE MANUFACTURING PROCESSES DEPLOYED

The DOD has many options regarding the most optimal 3D printing implementation plan. Technology maturation will likely drive DOD AM processes towards full deployment, but there are several ways in which the DOD can begin this strategy. Currently, the DOD is targeting non-critical and non-essential parts to be 3D print-tested first, such as common consumables. In this sense, if there is a material error or faulty process, then no expensive equipment is significantly damaged nor personnel injured. Although all materials are being prototyped, materials such as plastics are being heavily tested as they are more affordable. In studying the DOD potential laydown plans and roadmap strategy for 3D printing employment, one can use the U.S. Navy force structure as an example.

For the U.S. Navy, having the ability to 3D print onboard its ocean-going vessels is paramount and is key to their immense investment in the technology. The Navy has several options that can and probably will eventually be executed, but for this project discussions for that potential are in the present. Next is a suggested list of potential 3D printing implementation options that the Navy could utilize to establish its processes, based on a tiered approach to readiness, along with associated advantages and disadvantages.

(1) 3D print parts solely from DLA Distribution Depots: Placing a 3D printer in all DLA Distribution Depots around the world

Advantages: By utilizing DLA’s vast budget and space allocations, DLA could be responsible for producing all such parts not only for the Navy, but for all services. Having print capabilities at 24 strategically located parts’ hubs could provide valuable control mechanisms as well as provide consolidated quality control, inspection, certification, and qualification of all printed parts (Defense Logistics Agency, n.d.). Additionally, this would allow the Navy to harness the experience gained by DLA’s employment of 3D printers.

Disadvantages: By centralizing all printing capabilities within the DLA, it provides too much oversight and control by one agency and undermines the Navy's ultimate strategy of ship-born printing capabilities. This takes the flexibility away from the Navy, and it does not remove the anticipated distribution and transportation costs savings associated with AM.

(2) 3D print parts using DLA and Fleet Logistics Center (FLC): Utilizing DLA's vast civilian and contractor support, the Navy's FLCs can mimic the successes and efficiencies gained by DLA's operating experience to fabricate and test some of its own high-demand parts.

Advantages: Having 3D printers located at DLA hubs and specific, fleet-concentrated FLC locations will provide a greater range of flexibility to the Navy's part management. The Navy's assets will deep-order, based on their own demand management, the parts to be stocked on board fleet assets. FLCs can then utilize printers for high-priority and/or low-demand assets. FLCs can also concentrate on providing and managing CASREP (casualty reports) parts and they can have access to a shore-based quality control program prior to releasing the part to the Navy asset.

Disadvantages: With many printers being operated to fulfill parts for like Navy assets, there could be confusion on defining ordering parameters, and priorities.

(3) 3D print parts using Combat Logistics Force (CLF)/ Military Sealift Command (MSC) assets only: Operate MSC assets as floating part fabrication hubs.

Advantages: MSC assets offer the U.S. Navy a unique, mobile, and expeditionary method for supplies replenishment while at sea. Similar to the way that MSC ships deliver food, mail, ammo, and fuel, MSC could also not only deliver but fabricate essential parts using onboard 3D printers. MSC ships are more spacious than combatants, and they can offer the ability to utilize larger printers than on other ships. This offers the Navy an extremely reliable and quick turnaround on parts, alleviating the long lead-times and shipping times associated with the current parts-ordering process.

Disadvantages: This new printing environment will also have its challenges. A pitching and rolling ship is a harsh environment for any system or piece of machinery, and it would be mandatory for printers to be thoroughly tested to be deemed certified. According to the MSC ship inventory of 2015, MSC has 30 replenishment ships covering five world-wide regions (Military Sealift Command, 2015). These ships would require retrofitting of 3D printing gear, and the question remains: Would there be enough replenishment ships to cover the entire fleet? Additionally, who and how would the part qualification process be applied? The ships would most likely require specially trained personnel or contractors onboard these ships to certify the printed parts.

(4) 3D print parts using all CLF/MSC and combatant assets: This plan would see the implementation of 3D printers on all Navy assets, regardless of size.

Advantages: This plan would provide the Navy the supreme capability of having a part fabrication process on every asset, allowing maximum flexibility and operational readiness. Without the reliance of shore-based replenishment, all ships would be able to internally provide the majority of part-related maintenance and CASREP support.

Disadvantages: Providing every ship in the fleet with 3D printing capability would be extremely costly. Almost every ship would require refurbishment to house the printer itself, and it would also most likely require bolster manning to allocate for a part certification person(s). The Navy would also face the issue of technical support, such when a printer goes down. There would be no technical representative available to provide an immediate fix. The ship would then have to rely on shore support for part replenishment.

VI. CONCLUSION

AM technology is rapidly maturing, and its capabilities are expanding almost daily. Universities, scientists, and DOD officials alike are continuing to test new materials and push the limits of the AM realm. The DOD is posturing itself to be a leader in this technology, and it continues to discover new uses for AM in a variety of ways within a variety of environments.

A. SUMMARY

This study has analyzed how the evolution of AM is leading to even more innovation within both corporate and military applications alike, and it continues to press to the forefront of modern science. The study has examined the various types of AM technology available, and it has explored the science behind the 3D printing process. Although many challenges still exist, the technology is demonstrating true cost savings and efficiencies with select parts. Customers of AM parts are already experiencing huge savings in transportation, holding costs, and variable overhead costs associated with 3D-printed parts and assemblies.

The case-study analysis shows how companies such as Boeing and GM are harnessing AM with great efficiency. The case analysis shows that great economies of scale can be achieved through AM and, thus, can have lasting effects on corporate supply chains.

This study also illustrates the variety of options that the U.S. Navy has for implementation of the AM process. It explores the methodology behind the implementation process. This process, which has been studied and developed through the Wohler's group, has provided guidelines that can be adopted and practiced by the military to create smooth employment of the technology. With an implementation process laid out by Louis, Seymour, and Joyce, the Navy can emulate this practice as they implement its 3D printing technology into the fleet. Through a tiered approach, the Navy can utilize shore facility capacity to gain experience using the technology and with further research can implement those technologies onboard U.S. ships.

B. FURTHER RESEARCH

Further research can explore a variety of AM functions such as contracting concerns with 3D printing companies, material optimization, compatibility of AM printers in the ocean environment, as well as the intellectual rights and part certification processes that will challenge the Navy in the future. Additional research can also provide a deeper look into the strategic value of AM within the supply chain. As the technology matures within the Navy, the lessons learned and hard data acquired by testing will provide a crucial foundation for standardized use throughout the fleet. As data is compounded, it will drive decisions and demonstrate how AM will decrease the supply chain, minimize transportation and holding costs, and create new ways for the Navy to analyze part replenishment. A comprehensive cost-benefit analysis would be immensely rewarding, and it will be crucial in Navy leadership's ability to make AM fielding decisions within the fleet. Cost-analysis figures will provide the hard data necessary for congressional and financial support essential for fleet-wide implementation. As further tests on U.S. ships are conducted, the Navy will gain a better picture on how 3D printing can be applied to sea-going vessels and what processes are required for such unforgiving environments. Lastly, further research can target manning and man-hours in concluding exactly what manning requirements exist for 3D printing processes both at shore and at sea. As DOD-wide manning levels continue to be a shortfall, research could shed light on how the Navy would implement this expertise into its rating system and precisely how many sailors would be needed to operate the machinery and computer software.

The topic of 3D printing in the DOD, specifically the Navy, has only begun to be explored, and it will open the door for many follow-on and future research projects. The future projects can include a more in-depth analysis on recommendations driven by AM part data, which can be then be implemented and tested on different levels. Part certification and intellectual rights are likely to remain the Navy's largest challenges. As AM corporations and Navy standards evolve, bold ideas will be realized in order to properly, securely, and safely utilize AM parts in military environments. One recommendation to solve the intellectual rights issue would be to implement a token system, whereby the Navy could purchase a quantity of tokens which resemble the actual data rights, CAD schematics, or electronic part details. Every time the Navy asset desires to print a part, the AM machine operator must input the proper code. This code would translate the actual part being printed into an account transfer method, essentially paying for every part printed. Part certification will require more in-depth analysis depending on the part's use and implementation environment.

There is still much to be learned from 3D printing, but one thing is sure: The technology is well on its way to setting the true standard in part manufacturing. Further, shrinking the supply chain through AM will provide huge cost savings both in the corporate world and in the military.

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