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ADDITIVE MANUFACTURING IN THE MARINE CORPS

by

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June 2015

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As the Marine Corps continues to conduct small-unit distributed operations, the strain on its logistics intensifies. The Marine Corps must search for a solution to increase the efficiency and responsiveness of its logistics. One solution is using additive manufacturing, commonly referred to as 3D printing.

This thesis answers the question of how additive manufacturing can improve the effectiveness of Marine Corps logistics. In order to answer the question, beneficial process(es), application(s), and level of integration are determined through a comparative analysis of current and future 3D-printing processes, examination of several civilian and military examples, and examination of the impact across current doctrine, organization, training, material, leadership, personnel, and facilities.

Several issues should be addressed prior to the Marine Corps fully integrating 3D printers, such as the lack of certification and qualification standards, unreliable end product results, and determining ownership of intellectual property. When these issues are properly mitigated, the Marine Corps should procure printers for the purpose of manufacturing repair parts, tools, and other support aids. Marine Expeditionary Units should be the first units to receive the printers. If the printers are integrated properly, they could assist logisticians in supporting Marines conducting distributed operations throughout the battlefield.

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ADDITIVE MANUFACTURING IN THE MARINE CORPS

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
2D	two-dimensional
AFIRM	Armed Forces Institute for Regenerative Medicine
AFRL	Air Force Research Laboratory
AM	additive manufacturing
AMF	Additive Manufacturing Format
ARDEC	Armament Research, Development, and Engineering Center
BAAM	big area additive manufacturing
CAD	computer aided design
CE	command element
CNC	computer numerical control
DOD	Department of Defense
DOTMLPF	doctrine, organization, training, material, leadership, personnel, facilities
EBM	electron beam melting
FDM	fused deposition modeling
FRCE	Fleet Readiness Center East
GE	General Electric
IP	intellectual property
KPP	key performance parameter
KSA	key system attribute
LCE	logistics combat element
MEB	Marine Expeditionary Brigade
MEF	Marine Expeditionary Force
MEU	Marine Expeditionary Unit
MLG	Marine Logistics Group
MPS	maritime prepositioning ship
MPSRON	maritime prepositioning squadron
MRAP	mine resistant ambush protected

MTT	mobile training team
NIST	National Institute of Standards and Technology
NSDREC	Natick Soldier Research, Development, and Engineering Center
OEM	original equipment manufacturer
OJT	on the job training
ORNL	Oak Ridge National Laboratory
REF	Rapid Equipping Force
ROMO	range of military operations
SAW	squad automatic weapon
SIS	selective inhibition sintering
SME	subject matter expert
STL	STereoLithography
TRHS	tray ration heating system
TRL	technology readiness level
UBR	unitized B-ration
UGR-H&S	unitized group rations-heat and serve
UGV	unmanned ground vehicle
UV	ultraviolet
WFIRM	Wake Forest Institute for Regenerative Medicine

I. INTRODUCTION

A. BACKGROUND

Logistics is neither glamorous nor exciting, but it is absolutely critical to the success of the military. General Dwight D. Eisenhower is quoted as saying, "You will not find it difficult to prove that battles, campaigns, and even wars have been won or lost primarily because of logistics."[1] Despite technological advances since World War II, logistics is still a source of friction as evident during the latest sustained combat operations of Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF). The RAND Corporation conducted research on OIF logistics and published its work called "Sustainment of Army Forces in Operation Iraqi Freedom: Battlefield Logistics and Effect on Operations." The study highlighted several logistics related deficiencies on the battlefield. Some of the deficiencies stemmed from the execution of a relatively new method of sustainment called distribution based logistics. Distribution based logistics consists of limited inventory as opposed to establishing large forward stockpiles, which was the previous method of sustainment.[2] This new method of sustainment is essential to supporting units that are spread throughout the battlefield. Although the article focused on U.S. Army operations, Marine Corps logistics uses the same model.

In his article "Expeditionary Logistics for the 21st Century: Tactical and operational efficiency," Lieutenant General Faulkner, Marine Corps, states that logisticians must "become more adaptable, imaginative, and creative to solve logistics challenges inherent in our crisis response mission and other operational requirements across the ROMO [range of military operations]."[3] He claims that the historical method

[1] Bradford K. Nelson, "Defeat the Threat to Sustainment Operations," *Army Logistician*, 40, no. 2 (April 2008): 1, http://www.alu.army.mil/alog/issues/MarApr08/defeatthreat_susop.html#top.

[2] Eric Peltz, John Halliday, Marc Robbiens, and Kenneth J. Girandini. Sustainment of Army Forces in Operation Iraqi Freedom: Battlefield Logistics and Effects on Operations. Santa Monica, CA: RAND Corporation, 2005, xi.

[3] William M. Faulkner, "Expeditionary Logistics for the 21st Century: Tactical and operational efficiency," *Marine Corps Gazette*, 98, no. 10 (October 2014), 11.

of "pushing"[4] logistics forward to build large supply points ashore are not compatible with how the Marine Corps fights. He argues that logistics units must maintain a smaller footprint to better support the smaller-sized maneuver units that are conducting distributed operations. Faulkner states that logisticians should only take what is absolutely necessary ashore and leave everything else on the ship at the sea base to remain quick and responsive.[5] As the Marine Corps continues to conduct distributed operations, it must improve the self-reliance and performance of its forward-deployed units. The existing supply chain model has inherent limitations related to the challenges associated with inventory management and is often unresponsive and unable to effectively support units distributed throughout the battlefield.

Like all identified gaps in the military, the first attempt to correct the issue is to identify a solution that does not require developing and/or acquiring a new system. The solution may involve changing current doctrine, organization, training, material, leadership, personnel, or facilities (DOTMLPF). While it is highly important, this thesis will forego that process in favor of evaluating a new system that may fill the identified gaps. The DOTMLPF process is used in chapter IV, however, to determine the impact of integrating the new system. The chosen system is the rapidly evolving technology of additive manufacturing (AM), commonly referred to as 3D printing. U.S. Marine Corps Forces, Pacific (MARFORPAC) recognizes the potential of this technology and submitted a request to the Naval Postgraduate School via the Thesis Research Working Group (TRWG) to determine the greatest advantage to the Marine Corps. This thesis will provide insight and recommendations regarding the request from MARFORPAC.

[4] Pushing logistics refers to sending sustainment forward to a location to build a stockpile based on planning estimates without requiring requests from the supported unit. The opposite method of sustainment is called the pull method where the supported unit requests sustainment from the supporting unit. (U.S. Marine Corps, *Tactical-Level* Logistics, MCWP 4–11 (Washington, D.C.: Government Printing Office, 2000), 3–7).

[5] Faulkner, "Expeditionary Logistics," 12.

B. PURPOSE

Additive manufacturing has the potential to partially fill the identified gaps by reducing a unit's reliance on current supply chains. It has the potential to enhance organic logistics capabilities without increasing the overall size and footprint of the unit. Responsiveness may also increase depending on where additive manufacturing technology is implemented. The Marine Corps will maintain the ability to operate in expeditionary environments while limiting the effects of unresponsive logistics. Depending on the application, AM has the capability to increase responsiveness in various environments and scenarios such as training exercises as well as operations ashore in austere environments and operations at sea. The purpose of this thesis is to analyze how AM might affects Marine Corps logistics with the ultimate goal of improving its responsiveness and ability to support units distributed throughout the battlefield.

C. RESEARCH QUESTION

The specific question this thesis answers is the following:

- How can current and future additive manufacturing technologies improve Marine Corps logistics?

To fully answer the question, three related questions will be answered in conjunction with the main research question.

- Which additive manufacturing process(es) should the Marine Corps consider for use?
- What application(s) could the Marine Corps use the 3D printers for?
- Where might the 3D printers be integrated?

By answering the three subsidiary questions, the answer to the actual thesis question will be more apparent. By the end of the thesis, recommendations will be made as to how the U.S. Marine Corps could benefit from the emerging technology of additive manufacturing.

D. METHODOLOGY AND ORGANIZATION

This thesis answers the research question by addressing the three related questions in subsequent chapters. The next chapter describes the myriad different AM processes. It examines each of the relevant processes that are currently in use as of 2015. The advantages and disadvantages of the processes are discussed. A comparative analysis of the most prevalent additive manufacturing processes further highlights the benefits of certain processes over others. Factors such as speed and end product attributes are used for the analysis. The cost of the printers, however, is not analyzed. The focus of this thesis is solely on making Marine Corps logistics more efficient and responsive. The recommendations at the end of the thesis may or may not be cost effective. It is recommended that further research develop the business case for additive manufacturing. The third chapter shifts towards identifying applications that are recommended for the Marine Corps. As identified earlier, the initial purpose of AM technology was for prototyping. It is still used heavily for prototyping, but the technology is now used for numerous additional applications. This thesis studies several examples of each of the types of applications from both the civilian industry as well as examples from several military services. It identifies those cases that have transferability to a Marine Corps application. Chapter IV is an analysis of the impact across DOTMLPF as a result of integrating 3D printers at several different levels within the Marine Corps. The chapter further breaks the analysis down to the impact due to the actual application to further determine which application might benefit the Marine Corps. The final chapter summarizes the results of the previous three chapters. It provides several recommendations regarding the type of process to use, what applications to use the 3D printers for, and where they might be incorporated.

E. HISTORY OF ADDITIVE MANUFACTURING

Additive manufacturing is a relatively new term for a technology that dates to the late 1980s. When it was first introduced, AM was referred to as Rapid Prototyping. This term is still widely used in many publications.[6] The technology was also referred to as Rapid Manufacturing.[7] In an attempt to simplify the numerous terms surrounding the technology, a Technical Committee within ASTM International coined the term additive manufacturing.[8] Additive manufacturing refers to the production of parts by adding material in layers according to input from a three-dimensional computer-aided design (CAD) file. There are numerous types of AM processes; many of which are described in Chapter II. The different processes vary in the materials they use, the method of creating the layers, as well as how the layers are bonded to each other.

Chuck Hull is considered the founder of AM. He invented and patented the first process and machine in 1986 called Stereolithography. The company 3D Systems was founded based on the new technology.[9] The company produced and sold the first 3D printer in 1988.[10] After the release of Chuck Hull's printer, numerous other companies such as Statasys, EOS, DTM, Quadrax, and Cubital designed and released their own AM processes and printers. While some of the products were similar to stereolithography, many of them were completely different processes.[11] Most of these companies only produced and sold one printer. It was not until 1993 that companies started to merge and produce several different variants.[12] The technology continued to accelerate at an average rate of 57% per year from 1988 to 1997.[13] By 2004, AM was nearly a billion-dollar industry.[14] As evident in Chapter II, the technology continues to advance at a rapid

[6] Ian Gibson, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (New York: Springer Science+Business Media, 2010), 1.

[7] Neil Hopkinson, Phil Dickens, and Richard Hague, eds., *Rapid Manufacturing; An Industrial Revolution for the Digital Age* (Chichester: John Wiley & Sons, Ltd, 2006), 1.

[8] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies,* 1.

[9] Todd Grimm, *User's Guide to Rapid Prototyping* (Dearborn: Society of Manufacturing Engineers, 2004), 15.

[10] Ibid., 16.

[11] Ibid., 17.

[12] Ibid., 19.

[13] Ibid., 21.

[14] Ibid., 22.

pace and includes even more types of processes. Many of the limitations of current systems including precision and repeatability are likely to be mitigated in the near future.

F. ADDITIVE MANUFACTURING BASIC PROCEDURES

Additive manufacturing refers to a large group of processes that vary greatly. While each process is unique, they all follow the same generic eight steps or sequence of tasks. Each step is slightly different for each type of AM process and some include one or more sub steps. The eight steps from beginning to end are:

- conceptualization and Computer-Aided Design (CAD)
- conversion to STereoLithography (STL)/ Additive Manufacturing Format (AMF)
- transfer and manipulation of STL file on AM machine
- machine setup
- build product
- part removal and cleanup
- post-processing of part
- application of printed part

1. Step 1: Conceptualization and CAD

The first step in any of the AM processes is determining the product that is needed. The idea for a printed product can come from any number of sources such as a broken repair part, a specifically sized wrench, a drill jig for a new job, or a required modification to a piece of equipment. The end user will determine the requirements of the product such as the look, dimensions, and functionality. The desired product must have the ability to be converted into a three-dimensional model. This model is designed using Computer Aided Design (CAD) software installed on a computer. A user trained in CAD will input the specific parameters of the design and let the software create a solid computer model. The user may alter the design of the product by changing its dimensions, angles, thickness, etc., until it meets the exact requirements of the desired product.[15] There are several types of 3D CAD: wireframe, surfaced wireframe, and solids. To create a viable model for 3D printers, only surfaced wireframe and solid models can be used. Wireframe models only detail the surface of the design and not the

[15] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 442.

interior, which makes it unsuitable for 3D printing.[16] While this is the basic process of conceptualization and developing the CAD model, there are other methods of developing a CAD model such as 3D scanning that will be discussed in the next chapter.

2. Step 2: Conversion to STL/AMF

The next step in the process is converting the CAD file created in the first step into a file format that is recognizable by a 3D printer. Most older 3D printers recognize and use a file format called STL. STL was developed in the 1990s and became the standard format for 3D printers. It converts the three-dimensional model into a series of very small triangular facets to approximate the various surfaces of the model.[17] The STL file is a large list of the coordinates of the vertices of each of the triangles in the mesh combined with a surface normal that dictates the orientation of the model.[18] The size of the triangles is usually specified and determines the accuracy and surface quality of the part.[19] Most CAD software can automatically convert the data into the STL format. There are times, however, when errors occur during the conversion process such as small unintentional gaps in the surface. Users cannot always detect the flaws; therefore, software in addition to the CAD software is needed to detect and correct the errors of the STL file. In some situations, the error correcting software may not be able to automatically correct the problem and will alert the user of the issue to manually correct the problem.[20] In some scenarios, the error is too significant to correct in the STL format and must be exported back to CAD to correct the deficiency. According to Grimm, there are two basic rules that should be followed to limit the errors of the STL file. The first rule is that adjacent triangles in the mesh must share two vertices. The second rule is that surface normals that dictate the orientation must be pointed away from the volume of the part.[21] While still prominent, the STL file format is slowly being

[16] Grimm, *Rapid Prototyping*, 53.

[17] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 44.

[18] Grimm, *Rapid Prototyping*, 56.

[19] Ibid., 57.

[20] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 44.

[21] Grimm, *Rapid Prototyping*, 59.

replaced by a newer file format called AMF. Two professors at Cornell University developed AMF in 2011. Both ASTM and International Organization for Standardization (ISO) adopted AMF as a standard for converting CAD files to a format readable by a 3D printer, similar to STL. AMF is an XML[22] format that was designed to overcome some of the challenges experienced with STL. It allows the use of multiple materials and colors as well as the use of more complex structures. Unlike STL, AMF converts the file to curved triangles vice flat triangles. The curved triangles improve precision compared to STL. Additionally, the compressed size of an AMF file is approximately 50% smaller than the compressed size of an STL. Despite its many improvements and acceptance as a standard, it has not become mainstream for two reasons. First, many 3D printers are not designed to accept AMF. Second, most of the more prominent CAD software does not utilize AMF. The reason printer manufacturers are not designing their hardware to accept AMF is because the software companies are not utilizing it; however, the reason software companies do not use AMF is because the printers are not able to accept the new format.[23] This paradox is starting to fade as successful CAD software companies like Cimatron begin to adopt AMF.[24]

3. Step 3: Transfer to AM Machine and STL/AMF Manipulation

After the printer readable file is created (either STL or AMF), it is then transferred to the actual printing device. It is transferred in any number of ways such as through cabling or an external media device like USB drives. Most printers have the capability to view and manipulate the part. At this step in the process, the user determines the exact orientation to build the product. The orientation of the part in the printer will partially determine how much clean up is required after it is built. As the product is built, the printer will automatically add support structures. These support structures attach the

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[22] XML is an abbreviation for Extensible Markup Language. It is a computer language that is both human and machine readable.

[23] Todd Grimm, "New AMF File Format to Unleash the Potential of 3D Printing," Stratasys Blog, September 19, 2012, http://blog.stratasys.com/2012/09/19/new-amf-file-format-to-unleash-the-potential-of-3d-printing/.

[24] Shane Taylor, "AMF Format for 3D Printing Goes Wider – Now Supported by CimatronE," 3D Printing Industry, January 27, 2014. http://3dprintingindustry.com/2014/01/27/amf-format-3d-printing-goes-wider-now-supported-cimatrone/.

product to the build platform. They also give the product rigidity as it is built, especially in weak spots such as overhangs. The orientation of the product will determine the total number of support structures that are required.[25] The orientation also affects the machine time of the build. Parts that are oriented with the largest dimension in the vertical direction (or height) will take longer to build than if they are oriented with their largest dimension in the horizontal direction since most printers build from the bottom up.[26] Another significant consideration for the orientation of the build is the quality of the end product. As the printer builds the product layer by layer it creates a stair stepping effect in the vertical direction that is dependent on the thickness of each layer. The amount of stair stepping will determine the smoothness of the end product. The appropriate orientation must be selected to achieve maximum smoothness and minimum build time.[27] Similar to orientation, the placement of the part can be altered. The placement will also affect the build time and build quality of the part. Part placement is a significant factor in some processes to include stereolithography and laser sintering. If a part is placed correctly, it will also allow for the construction of multiple parts at the same time. Machines can build multiple copies of the same part or several different parts as long as they are all able to fit within the build space of the printer. Some printers can even build parts on top of other parts during the construction step.[28] In addition to the orientation and part placement, the size of the part can be changed at this point. It can either be enlarged or shrunk depending on the desired outcome. This feature is useful when taking in consideration any follow on treatments that may increase the overall dimensions of the part. One such example is coating a plastic product with metal to increase its rigidity. The thickness of the metal coating may not have been considered when developing the file, but it can be accounted for by appropriately scaling the part using the printer's size functionality. Some printers are able to add embossed text to the part itself. This feature is useful to identify parts by putting a unique part number on them. The part numbers could reference the same part

[25] Grimm, *Rapid Prototyping*, 63–67.

[26] Ibid., 59.

[27] Grimm, *Rapid Prototyping*, 62.

[28] Ibid., 68.

number as an original equipment manufacturer (OEM) part that it was designed to replace. Though most of the features listed are basic functionality of most printers, they vary with each printer manufacturer and model.[29]

4. Step 4: Machine Setup

During this step, the user will fine-tune the settings of the machine to enhance the final quality of the part. These settings vary with each type of process and printer. One of the most significant factors that will require adjustment to the machine's settings is the type of raw material used. For printers that are only able to accept one type of material this is not a concern. However, most printers are able to accept multiple types of raw material. In this case, the machine's settings must be optimized for the type of build material. Most modern printers have pre-configured settings for each type of material that are accepted by the printer. Another setting that is usually adjustable is the resolution of the printer. If speed is more important than the finish quality of the part, the user can decrease the resolution. On the other hand, if quality is more important than speed, then the user can increase the resolution of the printer.[30] The actual features available depend on the type of printer, but often include features such as speeds, dwells, path widths and depths, path overlap, and fill types, which are collectively known as the build style.[31]

5. Step 5: Build

The fifth step of the process is significantly different than the previous four steps in that it requires minimal user input. Once the file is loaded and the machine is adjusted properly, the machine constructs the part. The method of construction varies with each process, but the basic premise is the part is built layer by layer by adding and combining raw material to create a 3D product. The printer will continue to automatically build the part without user interaction until it is finished or in the event that it runs out of raw

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[29] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 45.

[30] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 45.

[31] Grimm, *Rapid Prototyping*, 73.

material, similar in nature to a 2D printer.[32] The processes vary greatly and are examined thoroughly in the next chapter.

6. Step 6: Removal and Cleanup

Once the part is completely built, it is removed from the printer. This step is rarely automated and is done manually by the user. The machine usually has safety precautions integrated to ensure the part's temperature is safe and that there are no moving parts.[33] The part is either connected to a build platform or laying in excess build material. In either case, the user must separate and remove the product. At this point, it resembles the final product, but it may need additional preparation to meet the intended specifications. Most notable is the removal of support structures that were mentioned in step three. The type and number of support structures varies greatly depending on the process used and the part that was built.[34] Specific cleaning methods may include processes such as post-curing, chemical stripping, bed blasting, or water jetting.[35] The type of cleaning methods required for each process is discussed in the next chapter. Some manufacturers design their printers for minimal removal and cleanup, but the removal and cleanup step is still a significant portion of the process.[36]

7. Step 7: Post-process

The next step in the AM process focuses on preparing the part for its application specific purpose. During this step, the user prepares the surface of the part. The part will most likely need sanding or polishing at this stage. In some cases, the part is coated with another material such as metal. The amount of finishing required is largely dependent on the application of the part. If the part is designed to be a rough prototype, the time and effort required during this step is minimal, whereas, if the part is designed for installation in a larger component or is part of an aviation platform, this step consumes a considerable

[32] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies,* 46.

[33] Ibid., 5.

[34] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 46.

[35] Grimm, *Rapid Prototyping*, 77.

[36] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies,* 46.

amount of time and effort.[37] Regardless of the application, this step requires significant human interaction and can often require certain skill sets to ensure the product is finished correctly.[38]

8. Step 8: Application

The final step in the AM process is the actual application of the printed part. Similar to the previous step, the time and effort required during this step varies significantly depending on the application. If the part is a model or prototype, it is ready for use. If the printed part is a piece of a larger system, then it must be installed. In some applications the part is inspected and analyzed prior to installation.[39]

These are the basic procedures for how most Am processes work. Each AM process is different, but the overall process and end results are similar. The next chapter explains the differences between some of the more prevalent types of AM processes.

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[37] Ibid., 47.

[38] Grimm, *Rapid Prototyping*, 79.

[39] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 47.

II. ADDITIVE MANUFACTURING TECHNOLOGY

A. CURRENT TECHNOLOGY

1. Blueprint Development

Of the eight steps in the AM process, the first step, conceptualization and CAD, has the potential to be very knowledge and skill intensive. This step requires the user to have an in-depth knowledge of CAD software as well as some structural engineering background to create a file from scratch. In certain applications like prototyping this is unavoidable; however, in applications like repair part reproduction, this step can be streamlined and made more automated. To achieve this, users can utilize three different methods: outsourcing, using files from a database, or creating files using a 3D scanner. The first method, outsourcing, is where the user relies on a third party organization/ company to create the CAD file based on the user's requirements. This process is potentially costly, but may make sense financially if it is expensive to hire an individual with the requisite skills needed to create the CAD file. Organizations with low volume 3D production may favor this alternative. The second method is to access CAD files from a database. This is becoming increasingly more viable with many companies offering thousands of designs. Companies like Thingiverse, CG Trader, GrabCAD, 3D Content Central, and Cubify offer free designs to the public.[40] Even government institutes are starting to create online exchanges of 3D printer files. The National Institutes of Health (NIH) of the U.S. Department of Health and Human Services recently established a 3D print exchange that allows a user to upload and download biomedical 3D print files, modeling tutorials, and educational material.[41] Additionally, there are even companies that are striving to provide this service for tailored markets. For example, the consulting firm Deloitte partnered with 3D Systems (3DS) and Information Systems Worldwide (iSW) to produce a parts-on-demand capability via a secure cloud environment that will

[40] Ellysa Kroski, "5 Great Sites for 30,000+ Free 3D Printing Models," OEDb, May 30, 2014, http://oedb.org/ilibrarian/5-great-sites-downloading-30000-free-3d-printing-models/.

[41] Ashley Wichman, "The Future Will Be Printed – In 3D," DigitalGov, January 15, 2015, http://www.digitalgov.gov/2015/01/15/the-future-will-be-printed-in-3d/.

house weapon system part designs. Although not in production as of yet, Amazon partnered with 3 DLT to develop the capability to download files directly to a personal home based printer.[42] This method is only viable if the user is printing a part that is fairly common. It would not work for prototyping applications where numerous changes are made during the design phase. However, as evident by the numerous third party vendors, it is quickly becoming a more feasible option. The third method is to use a 3D scanner to scan an existing part. The scanner will create a 3D image of the part and convert it to a 3D CAD model. This process was used during a training exercise called ExLog VIII that is discussed further in the next chapter. The scanner allows the user to operate independently and not rely on third party suppliers.[43] Through the use of any of the three methods, the required skill level for the first step is greatly reduced.

2. Types of Processes

AM refers to a broad array of technologies that vary greatly in their processes and capabilities. There is no industry standard for categorizing the different types of processes. For purposes of organization, the types of processes are separated into three categories based on the type of raw material used. The categories are (1) liquid-based systems, (2) powder-based systems, and (3) solid-based systems. Only processes that are used in industry are discussed in this section.

a. Liquid-Based Systems

These systems use photosensitive liquid polymers that are cured to create a solid material. Liquid-based systems account for some of the earliest AM products produced.[44] The products produced using liquid-based systems are similar in appearance to injection-molded parts. One distinct disadvantage is that the end products are sensitive to

[42] Jim Joyce, "3D Printing Supply Chain Overview," (lecture, Additive Manufacturing for Government Conference, Washington, DC, December 9, 2014).

[43] Neil Orringer, "Manufacturing the Future," (lecture, Additive Manufacturing for Government Conference, Washington, DC, December 8, 2014).

[44] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 58.

environmental conditions. Sunlight and humidity can affect the properties of liquid-based system produced products.[45]

(1) Stereolithography

This process is considered the first AM process. Chuck Hull invented the process in the late 1980s and it led to the first commercial machine. It uses an ultraviolet (UV) laser that is maneuvered according to the CAD file to cure portions of photocurable resin on a platform.[46] The laser, which is usually solid-state powered, is directed by scanning mirrors to specific locations for curing. The first layer that is created is the support base for the product to be built and forms a mechanical bond with the build platform.[47] The platform with the cured resin is dropped a depth equal to one layer and liquid resin is deposited on top. A blade is swept over the surface to ensure that the resin is level.[48] The UV laser cures more of the liquid resin, this time bonding it to the first layer. This process is repeated over and over, layer-by-layer to create a 3D product.[49] In addition to the product itself, the stereolithography printer will build structures to support the product as it is being built. These structures must be removed once the product is built and removed from the printer. Once the product is removed from the printer and the supports are disconnected, the part is placed in an oven to cure any resin that was not cured by the UV laser. Parts produced using stereolithography may also undergo a chemical stripping process to remove uncured resin.[50] The stereolithography process is considered to have a good balance between speed, quality, range of materials, and throughput.[51] See Figure 1 for a schematic of the stereolithography process.

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45 Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 59.

46 Ibid., 59.

47 Grimm, *Rapid Prototyping*, 164.

48 Ibid., 175.

49 Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,*59.

50 Grimm, *Rapid Prototyping*, 70.

51 Ibid., 94.

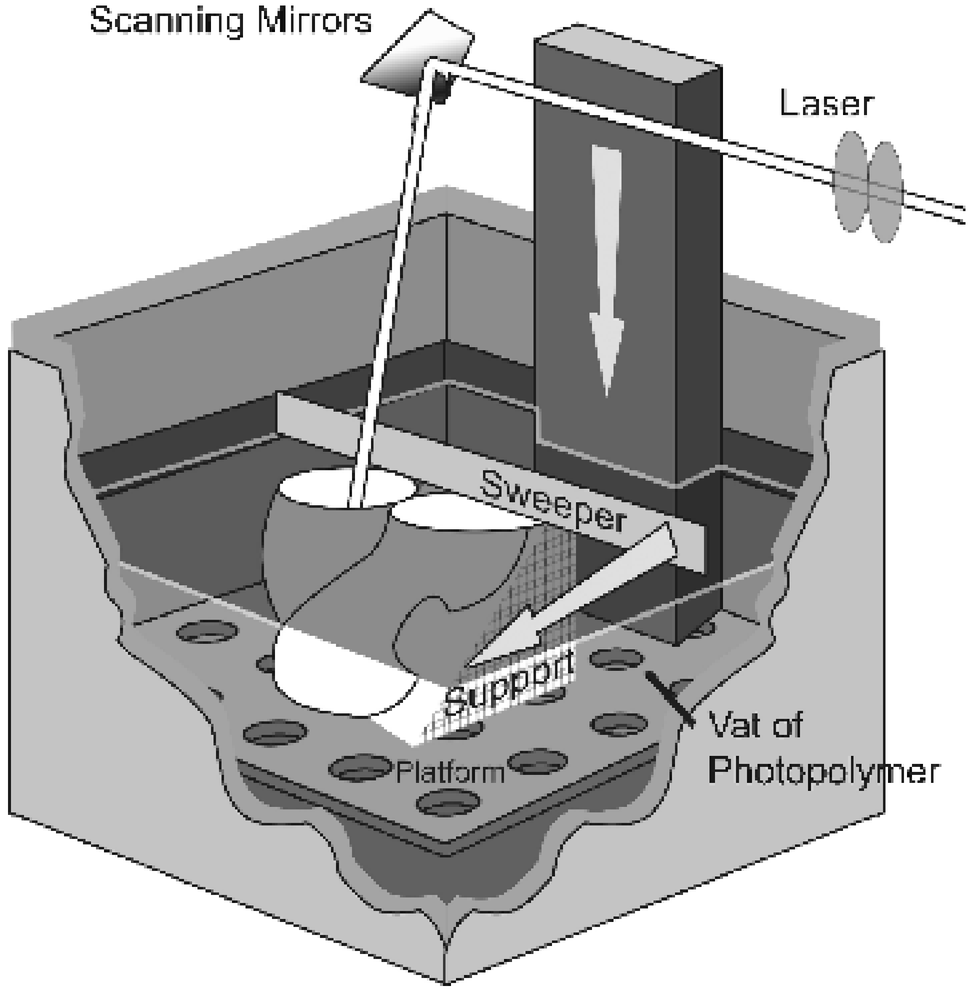

Figure 1. Schematic of stereolithography process (from Hopkinson, Dickens, and Hague, 2006, 59)

(2) Jetting Systems

As the name suggests, jetting systems use multiple printing heads similar to an ink jet printer. They create parts using photocurable resins like stereolithography, but the resin is deposited by an array of printing heads. After the resin is deposited, a UV lamp passes over to cure it. Once the UV lamp cures the resin, the process is repeated, creating multiple layers. Separate printing heads deposit a second material simultaneously to create the support structures. There are two main trademarked machines that use this process, the InVision by 3D Systems and the PolyJet by Objet of Israel.[52] The main difference between the two systems is the material deposited for the support structures. The InVision system uses a wax resin, whereas the PolyJet system uses a gel substance. Both types of support structures most be removed during step six of the AM process. Another difference is that the InVision system allows the use of colored resins.[53]

(3) Direct Light Processing Technologies

This process is similar to jetting systems, but instead of using a UV lamp to pass over the resin it makes use of digital mirror devices (DMDs)[54] to selectively cure the resin. As a result, this process is quicker than either of the jetting systems, but it does not offer as high resolution. Another key distinguishing factor is that it builds products downward vice upward. EnvisionTec commercialized this process in 2003 with is Perfactory machine.[55]

b. Powder-Based Systems

This group of processes all use raw materials that are in the form of powder. The powdered materials include polymers, metals, and ceramics.[56]

(1) Selective Laser Sintering (Polymers)

This process is comparable to stereolithography except that the raw material is a powder and is sintered (melted) by a laser instead of cured by the laser. The laser scans the entire powder bed, sintering the portions together to form the first layer of the product. A second layer of powder is added directly on top of the first layer and the laser again scans the surface and sinters selected portions of the powder, bonding it to the first layer to create the second layer. The Selective Laser Sintering process uses the un-melted

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[52] Objet merged with Statasys in 2012 to form the company Stratasys Ltd. (Nathan, Hurst, "3-D Printing Giants Stratasys and Objet Merge to Create $3 Billion Firm," Wired, December 5, 2012, http://www.wired.com/2012/12/stratasys-objet-merger/.)

[53] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 60.

[54] Digital mirror devices (DMDs) refer to a technology that selectively turn mirrors on and off to reflect UV light from the source to a specific location.

[55] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 61.

[56] Ibid., 64.

powder to serve the same purpose as the printed support structures in the liquid-based processes. Because the supporting material is not physically attached to the product, step five of the AM process is not as labor intensive nor time consuming as the liquid-based processes described in the previous section.[57] Instead of removing the support structures, the excess powder is brushed away from the product and is removed from any internal compartment of the part.[58] To reduce thermal gradients between the sintered and non-sintered powder and to reduce the energy required for the laser to sinter the powder, infrared heaters heat the entire powder bed. This process produces products that are high strength.[59]

(2) Selective Laser Sintering (Ceramics and Metals)

Selective Laser Sintering for ceramics and metals uses the same basic principles as described above. To create ceramic products, sand particles coated with a polymer binder replace the polymer powder of the previous process. Likewise, metal powders are coated in a polymer binder to produce metal 3D products. The metal products must undergo an additional finishing process and are placed in a furnace to burn the polymer binder away. The remaining material is sintered and the porous parts are filled with a secondary metal such as bronze.[60] This process is best suited for tooling purposes.[61] It is also used to print parts for the aerospace industry.[62] The selective laser sintering process is depicted in Figure 2.

[57] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 64.

[58] Grimm, *Rapid Prototyping,* 77.

[59] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 65.

[60] Ibid., 65–66.

[61] Grimm, *Rapid Prototyping,* 97.

[62] Ibid., 98.

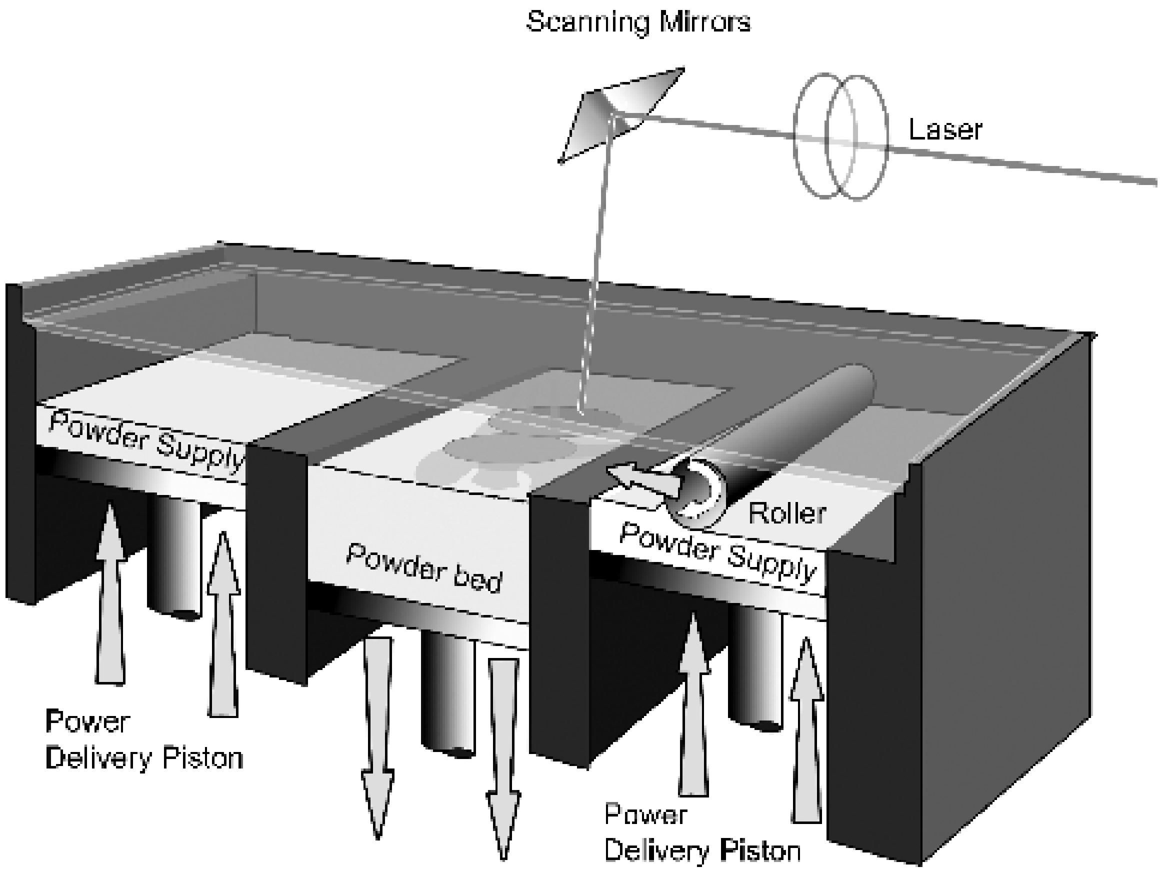

Figure 2. Schematic of selective laser sintering process (from Hopkinson, Dickens, and Hague, 2006, 65)

(3) Direct Metal Laser Sintering

Developed during the 1990s, this process is very similar to the process described above except that it does not need the polymer binder coating. The process, however, is limited to a specific metal powder that consists of several components with different melting points. The main advantage of this type of metal laser sintering is that it does not require the extra finishing steps as the previous process describes.[63]

(4) Powder-binder Printing

This process was developed at the Massachusetts Institute of Technology (MIT) and was later licensed by commercial entities.[64] It was originally licensed with the

[63] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing*, 66.

[64] Grimm, *Rapid Prototyping*, 163.

generic name of three-dimensional printing and was designed for tooling applications.[65] Powder-binder printing uses jetting technology to spread a binder on top of a thin layer of powder. The binder solidifies, creating the first layer of the part. The process is repeated for each subsequent layer until the part is completed. Similar to selective laser sintering, it uses the excess powder to act as the support structure.[66] The process is shown in Figure 3. Surface quality is below par and often requires some sort of machining to ensure the quality is improved enough to be used for tooling purposes.[67] It also requires the removal of excess powder from its surfaces and from any internal cavities.[68]

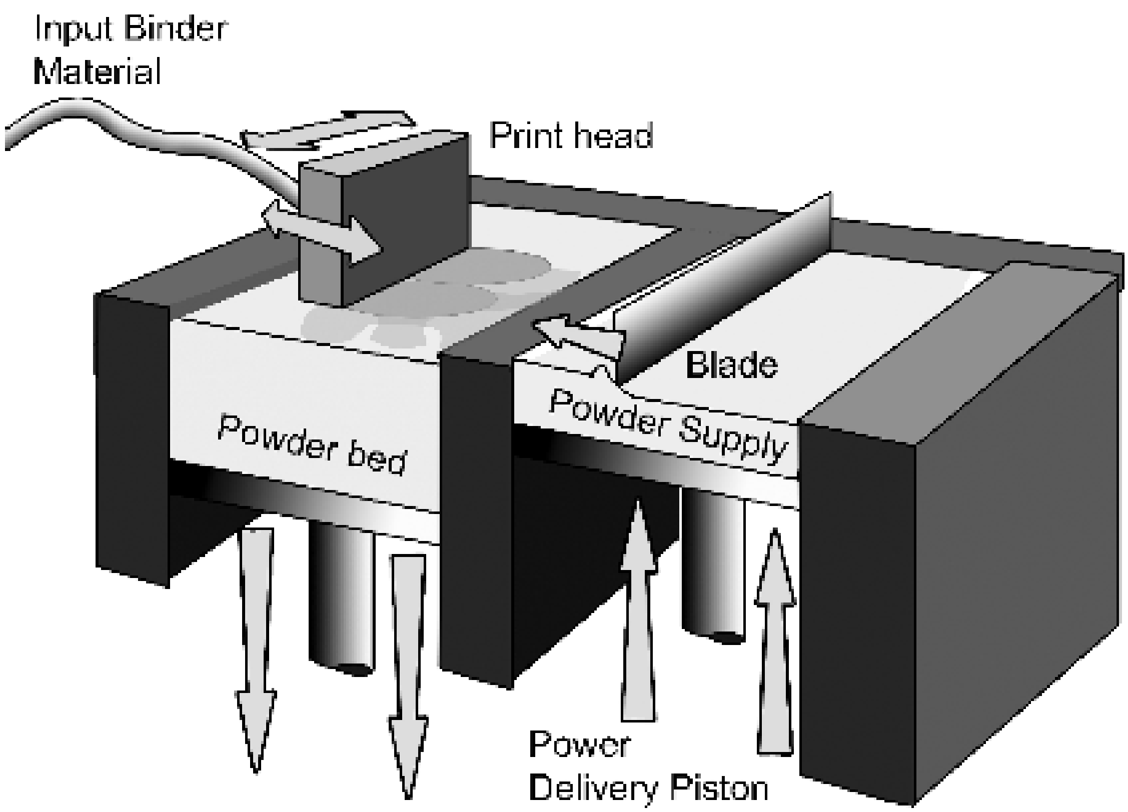

Figure 3. Schematic of powder-binder printing (from Hopkinson, Dickens, and Hague, 2006, 66)

[65] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing*, 66.

[66] Grimm, *Rapid Prototyping*, 170.

[67] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing*, 67.

[68] Grimm, *Rapid Prototyping*, 77.

(5) Fused Metal Deposition Systems

In this process, metal powders are blown onto a melt pool to sinter. A laser is still the primary tool for sintering except in this process it is used to create the melt pool.[69] Compared to other processes, fused metal deposition systems are relatively slow and the products produced have poor surface quality. Its biggest advantage, however, is its ability to build products out of materials with high melting points such as titanium. Another significant advantage is the unique ability to add material to existing products. This capability would allow the user to repair a broken part by adding metal to the area that was broken.[70]

(6) Electron Beam Melting

Electron Beam Melting (EBM) is similar to selective laser sintering except that it uses an electron beam instead of a laser to sinter the material. This scanning process is significantly quicker than processes that use a laser. Another advantage of this process is that the electron beam produces significantly more power than a laser and is therefore able to melt a wider range of metals, including titanium in a short period of time. Additionally, this process does not require that it be placed in a furnace to finish the sintering process, which means its postproduction time is decreased compared to other processes. Its two disadvantages are that it is limited to conductive materials and it requires a substantial amount of finishing to improve its surface quality to a satisfactory level.[71]

(7) Selective Laser Melting

This process is almost identical to laser sintering except that it completely melts the material vice merely sintering or fusing the material together. This process is used to make products out of pure steel. Because this process completely melts the metal, it produces parts that are very strong compared to other processes. The strength is comparable to traditional cast molding manufacturing techniques. The process also

[69] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 67.

[70] Ibid., 68.

[71] Ibid., 69.

allows for the production of relatively small components, even ones with complex lattice structures.[72]

(8) Selective Masking Sintering

Unlike the previous processes, selective masking sintering does not use a laser or a beam to sinter the material together. Instead it relies on a mask of infrared radiation reflecting material on a glass sheet. The mask is then placed on top of the powder bed. An infrared heater is placed over top of the mask. Heat passes through the selected spots in the mask and sinters the powder below. As with all processes, it is repeated numerous times to create multiple layers. The mask allows the entire layer to be sintered at the same time vice particle by particle like the laser and electron beam processes. This drastically decreases the build time compared to other types of processes, making it suitable for applications requiring higher throughput.[73]

c. Solid-Based Systems

As the name suggests, these processes use solid raw materials as opposed to the liquid and powders of the previous processes. Although there are only two processes that use solid raw materials, they are very relevant.

(1) Fused Deposition Modeling

One of the most prevalent designs on the market today is the fused deposition modeling (FDM) process. The process was patented and produced by the company Stratasys. The FDM process uses mostly thermoplastic polymers including polycarbonate, polyphenyl-sulfone, and acrylonitrate butadiene styrene (ABS). FDM machines have nozzles that move on the X and Y-axes to deposit polymers in a two-dimensional layer.[74] Prior to reaching the nozzles, the polymer is fed into the system as a solid and is liquefied in a heating chamber. The liquefied polymer is pushed through the

[72] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 68.

[73] Ibid., 70.

[74] Grimm, *Rapid Prototyping*, 167.

nozzle and extruded on the build platform.[75] This process is continually repeated to build the product from the bottom up. Unlike most other processes, the build platform is not lowered, the nozzles are raised the same height as one layer and continue to extrude the semi-molten material layer by layer.[76] There is a separate nozzle that follows the first nozzle to deposit a different material to build the support structure.[77] The process is illustrated in Figure 4. The support structures are usually built out of a water-soluble material that makes for a relatively quick and easy step five.[78]

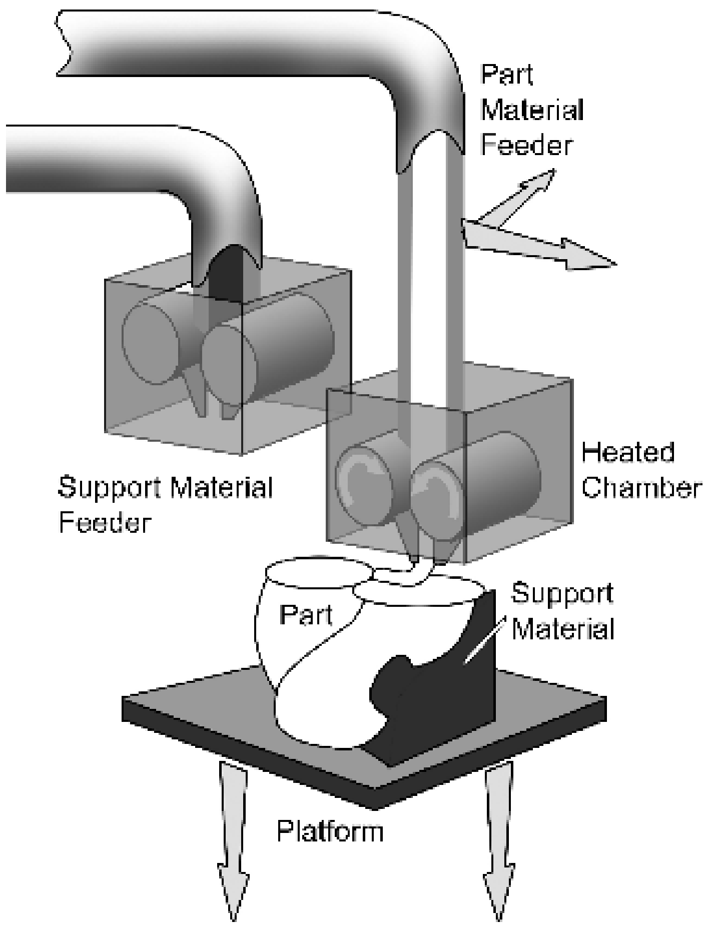

Figure 4. Schematic of fused deposition modeling process (from Hopkinson, Dickens, and Hague, 2006, 76)

[75] Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, 157.

[76] Grimm, *Rapid Prototyping*, 167.

[77] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing*, 75.

[78] Ibid., 76.

(2) Sheet Stacking Technologies

Sheet stacking technologies are different than other AM processes. They refer to processes that combine multiple layers of a material with a bonding agent and then use a laser to cut out the required shape. Its main advantage is that the process can use several types of raw materials ranging from papers and metals to polyvinyl chloride (PVC).[79]

3. Direct comparison

The previously mentioned AM processes are only a few of the myriad processes currently available. Each of the listed processes has its distinct advantages and disadvantages, many of which will be highlighted by the applications in Chapter III. This section will compare the four most prevalent processes: stereolithography, selective laser sintering, powder-binder printing and fused deposition modeling. The categories of raw materials, dimensional accuracy, stability, surface finish, environmental resistance, physical size, and production time, are used to compare the four AM processes.

a. Raw Materials

The range of materials varies greatly between the four types of processes. Of the four selected processes, stereolithography and powder-binder printing offer the fewest available materials. The materials used for stereolithography are limited to photopolymer materials since they must be cured with UV light. There are approximately 24 available raw materials with varying levels of strength, flexibility, and durability. Additionally, the materials are available through multiple suppliers unlike some of the materials for the other processes.[80] The powder-binder printer can only utilize three powdered materials. Two of the materials are cellulose and the third material is a plaster material.[81] One of its advantages, though, is that the finished part can be infiltrated with other materials to change its physical properties, vastly expanding its end usability. For example, one of the cellulose materials can be infused with elastomeric urethane to create a flexible, rubber-

[79] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 79.

[80] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,* 81.

[81] Grimm, *Rapid Prototyping*, 175.

like material.[82] Selective laser sintering and FDM offer the greatest range of raw materials, with selective laser sintering offering the most. Selective laser sintering's range of materials includes extremely strong plastics, stainless steel/bronze alloys, and flexible rubber-like materials. The most significant disadvantage, however, is that the raw materials are only available through the manufacturer of the printer, 3D Systems. While only able to use polymers, FDM has the second largest range of materials. It includes several variants of ABS, polycarbonate, rubber-like elastomers, and even a type of wax. The polycarbonate material closely resembles the strength characteristics of injection-molded ABS. Similar to selective laser sintering, the printer manufacturer, Statasys, is the sole supplier of the raw materials. Unlike the materials for selective laser sintering, the materials for FDM are created from a custom blend of commercially available resins.[83] These resins could theoretically be purchased separately and later blended to create the correct formula.

b. Dimensional Accuracy

In *User's Guide to Rapid Prototyping*, the author compared the dimensional accuracy of each of the four processes by printing a test part using a printer with each type of process. While there are numerous factors that will affect the results, it is possible to make some generalizations.[84] The stereolithography proved to have the highest accuracy and experienced the least amount of shrinkage compared to the other types of processes.[85] FDM was the second most accurate, but it experienced more shrinkage than stereolithography and selective laser sintering. Selective laser sintering proved to be fairly accurate and also had noticeable shrinkage. Of the processes compared, powder-binder printing proved to be the least accurate.[86]

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[82] Ibid., 176.

[83] Grimm, *Rapid Prototyping*, 174.

[84] Ibid., 180.

[85] Ibid., 181.

[86] Ibid., 183.

c. Stability

Initial dimensional accuracy does not matter much if the part does not keep its original shape and size after an extended period of time and/or after being exposed to various conditions. FDM is currently one of the most stable processes. Its properties do not change over time or when exposed to various conditions. These parts perform comparably to injection-molded parts. When appropriately infiltrated, parts produced using powder-binder printing are fairly stable, but before infiltration the parts can become brittle when exposed to heat and can soften due to moisture.[87] Parts produced using selective laser sintering are also fairly stable and perform like other plastic parts made using more traditional manufacturing techniques. The least stable parts are produced by stereolithography. These parts tend to shrink or otherwise distort over time, especially when exposed to heat, moisture, or chemical agents.[88]

d. Surface Finish

The surface finish property of 3D printed parts is a function of several factors to include the quality of the raw material used as well as part orientation as discussed previously. The type of process is another major factor that determines surface finish. Stereolithography provides the best surface finish of the compared processes.[89] The surface finish of the other processes is poor in comparison and all require extensive post processing to achieve a smooth finish.[90]

e. Environmental Resistance

Resistance to environmental conditions is extremely important, especially for any potential military application. Parts produced using selective laser sintering and FDM provide the most resistance to environmental conditions. They are both unaffected by moisture and can even be used under water. They are fairly heat resistant, resisting

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[87] Grimm, *Rapid Prototyping*, 185.

[88] Ibid., 184.

[89] Ibid., 185.

[90] Ibid., 186.

temperatures up to 400 degrees Fahrenheit and are resistant to most chemicals.[91] Parts produced using powder-binder printing are only resistant to environmental conditions when they are infiltrated with another substance.[92] The least resistant process is stereolithography. Environmental considerations such as heat, moisture, and certain chemicals all have a negative effect on parts produced using stereolithography.[93]

f. Physical Size

A printer's build envelope is the factor that restricts the maximum size of a part built. The build envelope varies with each make and model of printer and changes constantly. To date, stereolithography printers offer the biggest build size, offering a build envelope up to 59" x 30" x 22."[94] FDM offers the next biggest build envelope of 36" x 24" x 36."[95] Selective laser sintering offers a build envelope of 22" x 22" x 30."[96] The smallest available build envelop is that of powder-binder printing at 30" x 20" x 16."[97]

g. Time/Post-processing

The amount of time required to produce a part using a given process is hard to compare because there are numerous variables that affect the results. The resolution chosen, part size and features, number of parts, and material all affect the build time differently for each type of process. In general, powder-binder printing is fairly quick compared to the other processes. However, as mentioned previously the post processing

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[91] Grimm, *Rapid Prototyping*, 192.

[92] Ibid., 193.

[93] Ibid., 191.

[94] "ProX SLA Series Production 3D Printers," 3D Systems, accessed January 13, 2015, http://www.3dsystems.com/sites/www.3dsystems.com/files/prox_sla_series_0313_a4_us_web.pdf.

[95] "Fortus 900mc," Stratasys, Ltd, accessed January 13, 2015, http://www.stratasys.com/3d-printers/production-series/fortus-900mc.

[96] "SLS Production Series Production 3D Printers," 3D Systems, accessed January 13, 2015, http://www.3dsystems.com/sites/www.3dsystems.com/files/sls-series-0214-usen-web_1.pdf.

[97] "S-Print Technical Specs," ExOne, accessed January 13, 2015, http://www.exone.com/Systems/Production-Printers/S-Print.

can add a substantial amount of time to the overall production time.[98] FDM printers are usually slower than either stereolithography or selective laser sintering printers and require the removal of support structures once the build is complete.[99]

The comparison of these four processes is summarized in Chapter V. It combines several other factors from the next couple chapters to make a recommendation for which AM process the Marine Corps should select.

B. FUTURE TECHNOLOGY

The AM field is advancing rapidly with new technologies frequently introduced and subsequently improved upon. Even though the technology is over 30 years old, it appears to be early in its development.

1. Technology Shortcomings

Despite the rapid advancement in the AM field, there are still several areas that need improvement before it can be used routinely in a military application. A few of the major shortcomings are highlighted below.

a. Qualification/Certification Procedures

A major inhibitor for widespread adoption of AM is the fact that there are no standards for the qualification and certification of parts produced via AM processes. During the Additive Manufacturing for Government Conference in December 2014, the single most discussed topic was the lack of certification and qualification processes/ standards for AM. Companies and organizations such as General Electric, Lawrence Livermore National Library, NASA, the Joint Strike Fighter Science and Technology team, U.S. Army Research Laboratory, Department of Energy Advanced Manufacturing Office (AMO), and Sciaky Inc. all cited it as a major limiting factor.[100] Some companies have developed their own standards for certification, but their methods remain

[98] Grimm, *Rapid Prototyping*, 199.

[99] Ibid., 198.

[100] The Additive Manufacturing for Government Conference was held in Washington, DC from 8–10 December 2014 and included multiple U.S. government organizations and leaders from the AM industry.

proprietary.[101] In response, NASA penned a draft publication called "Nondestructive Evaluation of Additive Manufacturing, State-of-the-Discipline Report" that outlines the issues regarding process control, inspection, properties of materials, standards, as well qualification and certification. SAE International formed an AM task group to address standardization approaches for metallic materials used in several processes. Additionally, the American Society for Testing and Materials International recently developed ten standards related to AM processes and materials. To continue the forward progress NASA funded several efforts to develop additional standards for the technology.[102] Several organizations are developing non-destructive inspection (NDI) methods to certify parts after they have been built. Researchers and organizations have explored techniques such as Ultrasonic Testing (UT), X-ray, and computed tomography (CT). UT is effective, but the reliability is dependent on the shape of the part inspected. CT is slow, is not effective for large parts, and no standards have been developed for its use. Fluorescent Penetrant Inspection (FPI) is also used, but it can only detect surface flaws.[103] The Department of Energy AMO is also developing methods of using infrared to perform stress-mapping tomography.[104] A company called 3DSIM is taking a proactive approach rather than a reactive approach to ensure parts produced using AM can be certified. The company developed complex algorithms to accurately predict the structure of the end product.[105] Their methods could potentially be used for certification procedures. Lawrence Livermore National Laboratory is developing methods of controlling the

[101] James Zunino, "Enabling Technologies for Military Applications – Additive Manufacturing Method, Techniques, Procedures, and Applications," (lecture, Additive Manufacturing for Government Conference, Washington, DC, December 8, 2014).

[102] Ted Swanson, "Additive Manufacturing: Ensuring Quality for Spacecraft Applications," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 8, 2014).

[103] Scot Stecker, "Benefits and Challenges associated with Implementing Big Metal Additive Manufacturing," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 9, 2014).

[104] Blake Marshall, "Improving Manufacturing Competiveness and Process Efficiency with Additive Manufacturing," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 9, 2014).

[105] Brent Stucker, "Predictive Modeling of Metal Additive Manufacturing Processes," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 10, 2014).

microstructures of certain materials,[106] which will also aid in the effort to certify AM processes and materials. In addition to postproduction inspections and accurate predictive models, several organizations are developing procedures for conducting inspections as the part is built. The AMO is researching methods to conduct in-situ process monitoring to understand defects, porosity, and material behavior in each layer.[107] Likewise, General Electric is conducting their own research to determine methods of actively monitoring, and predicting distortion while the part is being built, but is also taking the process one step further by developing methods of mitigating the distortion during the build.[108] Furthermore, America Makes and the Air Force Research Laboratory (AFRL) recently awarded a contract to 3D Systems to develop similar closed loop manufacturing and monitoring platforms to control parameters at the layer level.[109] Through a combination of these efforts, the qualification and certification standards should be established in the near future. Until then, adoption by the Department of Defense (DOD) will most likely be limited to non-critical applications such as prototyping.

b. Repeatability

Current AM processes produce inconsistent results. Parts produced with the same machine using the same raw material do not produce the same quality of parts.[110] While the parts may look the same on the outside, the internal microstructures are different which leads to different material properties including strength and environmental resistance. U.S. Army researchers Holmes, Murphy, and Rodriguez determined the filaments used for the FDM process result in many voids and gaps that affect the overall

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[106] Wayne King, "Additive Manufacturing and Architected Materials," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 9, 2014).

[107] Marshall, "Improving Manufacturing Competiveness."

[108] James Y. Yang, "Metal Additive Manufacturing at GE: Opportunities and Challenges," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 9, 2014).

[109] Te Edwards, "America Makes and AFRL Award Million Dollar Contracts to 3D Systems for Aerospace Research Projects," 3D Print.com, February 3, 2015, http://3dprint.com/42017/million-dollar-contracts-3d-systems/.

[110] Amanda Gentry, "Additive Mfg: Acquisition Perspective on Development, Qualification, and Production," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 8, 2014).

integrity of the part produced.[111] Figure 5 shows the hollow compartments of the FDM filament identified by the U.S. Army researchers. The inconsistencies of AM processes further exacerbate the need for qualification and certification procedures. The predictive modeling process and the closed loop process currently under development that were mentioned in the previous paragraph will also alleviate the issue of repeatability when they are incorporated into the processes.

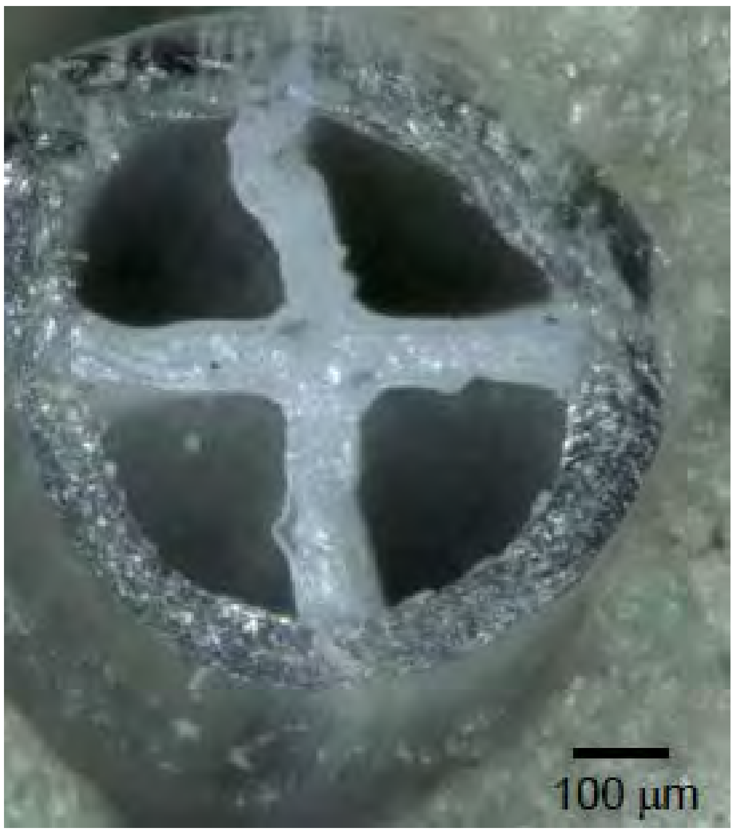

Figure 5. Magnified image of FDM filament showing internal gaps (from Holmes, 2014)

c. *Throughput*

Because 3D printers were not designed and developed for manufacturing purposes they are relatively slow. The slowest step in the process is often the construction of the

[111] Larry Holmes, "Advanced Manufacturing for the Army of the Future," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 10, 2014).

part in the printer. Depending on the size of the part and the process used, the construction step can take several hours.[112] Several companies and researchers are seeking methods of reducing the build time for parts. A research team from Trinity College Dublin in Ireland was awarded a contract to further develop cold spray manufacturing. While the technology currently exists, it is not as advanced and mature as other AM processes; therefore, it was not described previously. The research team is aimed at correcting the technology's shortcomings (precision, high costs, and limited materials). If successful, the cold spray manufacturing process has the ability to be almost 1,000 times faster than other processes. An additional benefit cold spray manufacturing could add is the ability to print material directly on existing parts. This capability is the same advantage that fused metal deposition systems offer; the capability to repair broken parts vice replacing them.[113]

d. Strength of Parts

Additive manufacturing has the ability to replicate many of the features of a traditionally manufactured part. One feature that is not the same is the overall strength of the part compared to parts produced with traditional injection molding processes. A company based in Indiana patented a technology that uses multiple lasers and other proprietary methods to control the mechanical properties and microstructure of each layer. The patented process will increase strength up to 20% over existing processes. Because the process controls the mechanical properties, the user will be able to design parts for other purposes such as weight savings, wear resistance, or heat resistance. Their process will also lead to further advancement of producing consistent results.[114]

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[112] Grimm, *Rapid Prototyping*, 51.

[113] David Jackson, "European Space Agency funds TCD engineers' Cold Spray 3D printing," EngineersJournal.ie, February 10, 2015, http://www.engineersjournal.ie/trinity-cold-spray-technology-esa/.

[114] "Purdue 3-D printing innovation capable of making stronger, lighter metal works for auto, aerospace industries," Purdue University, November 20, 2014, http://www.purdue.edu/newsroom/releases/2014/Q4/purdue-3-d-printing-innovation-capable-of-making-stronger,-lighter-metal-works-for-auto,-aerospace-industries.html.

e. Materials

Until recently, AM processes were limited to one type of material for a build. This significantly reduces a 3D printer's usefulness as it limits the number of parts it is able to print. A printer would not have the capability to print a simple object with rubber and plastic materials. Instead each component of the same material would be printed separately and assembled by hand. Companies such as Stratasys are making progress in this area and are now selling printers capable of using several types of materials with unique physical properties in the same build. The printers have the ability to print a part with both rubber-like materials and plastic materials integrated into one component. While a noteworthy advancement over most printers, its functionality is limited to variants of liquid photopolymers. It cannot combine metal and plastic materials, which would drastically increase its utility. Additionally, the build size for the most advanced printer offered is limited to dimensions of 19" x 15" x 8," indicating that there are tradeoffs for the increased functionality of printing with multiple materials.[115]

As mentioned earlier, the insufficient quantity of raw material suppliers is a distinct disadvantage. The raw materials for many of the patented processes are only available through the printer manufacturer. This poses obvious risks that must be considered. As patents expire, more companies will produce the printers. In addition to the printers, companies will most likely start producing raw materials as well.

f. Build size

Another factor that limits the utility of current 3D printers is their fairly small build size. As mentioned during the comparison of selective laser sintering, powder-binder printing, stereolithography, and FDM processes, the maximum build size is 59" x 30" x 24." Most printers do not have the capacity to print objects even close to that size. The company Sciaky Inc., with the assistance of organizations such as the Office of

[115] "Connex3 3D Production Systems," Stratasys, Ltd, accessed 3 February, 2015, http://www.stratasys.com/3d-printers/production-series/connex3-systems.

Naval Research (ONR), America Makes,[116] Defense Advanced Research Projects Agency (DARPA), Boeing, and Lockheed Martin,[117] developed an electron beam AM printer capable of printing a part up to 19’ x 4’ x 4’. The printer uses weldable metals such as titanium and nickel-based alloys to build the large structures. Although it is used for limited production, the printer is still in the research and development phase. Methods of better compensating for the distortion due to the size are still under development.[118] The Oak Ridge National Library (ORNL) and Lockheed Martin partnered to develop the big area additive manufacturing (BAAM) system. The BAAM is an extrusion-deposition system similar to FDM, but it uses standard feedstock materials like polymer pellets, powders, fiber reinforcements, and specialty additives instead of the limited filament feedstock.[119] This ability could reduce raw material cost by as much as 50 times compared to filament feedstock.[120] It is currently capable of building parts several feet long; however, further research is being conducted to produce parts that are unbounded in size. The concept involves the use of several of the robotic deposition systems working in coordination with each other to build massive components in an open-air environment.[121] ORNL demonstrated the current system’s capability by printing a replica of a Shelby Cobra.[122] The U.S.-based company CINCINNATI also partnered with ORNL and produced a prototype printer capable of printing components as large as 240” x 93” x 72.”[123] They used the printer to print a replica Shelby Cobra as shown in Figure 6. The

[116] America Makes was established in 2012 to facilitate collaboration among business, academia, non-profit organizations, and government agencies regarding additive manufacturing. They are a part of the National Network for Manufacturing Innovation and the National Center for Defense Manufacturing and Machining (America Makes website)

[117] Stecker, “Big Metal Additive Manufacturing.”

[118] “Metal Additive Manufacturing,” Sciaky, accessed January 13, 2015, http://www.sciaky.com/ca_product_sheets/Sciaky’s%20Additive%20Manufacturing.pdf.

[119] Christopher Holshouser et al., “Out of Bounds Additive Manufacturing,” *Advanced Materials and Processes* 171, no. 3 (March 2013): 15.

[120] Marshall, “Improving Manufacturing Competiveness.”

[121] Holshouser et al., “Out of Bounds Additive Manufacturing,” 17.

[122] “Auto Show Features 3D-printed Muscle Car,” ASM International, January 16, 2015, http://www.asminternational.org/search/-/journal_content/56/10180/23430692/NEWS.

[123] “Big Area Additive Manufacturing (BAAM) Specifications,” Cincinnati Inc., accessed March 13, 2015, http://www.e-ci.com/baam-specifications.

rapid technological advancement regarding the build size of printers has the potential to drastically increase the utility of AM.

Figure 6. Replica Shelby Cobra printed by ORNL (from Oak Ridge National Laboratory, http://web.ornl.gov/sci/manufacturing/media/news/detroit-show/)

2. Advances

There are several advances in AM technology that show potential military applications if further developed. Several of the advances may solve some of the biggest technology shortcomings as well.

a. Selective Inhibition Sintering (SIS)

This technology is in its infancy compared to the other processes and was not listed previously, but it promises a drastic reduction in costs compared to other metal producing AM processes. Because it does not use a laser or other expensive components, the SIS printer will be significantly cheaper to purchase and possibly maintain. Designed by researchers from the University of Southern California, the SIS process is designed for desktop style printers vice the industrial printers required by other metal processes. The SIS process is a combination of selective masking sintering and the jetting processes. SIS uses print heads to jet a special fluid called sintering inhibitor on specified locations of the powder bed. A radiating heat source is then applied to the powder bed. The powder without the sintering inhibitor sinters while the powder with the liquid does not. To maximize the functionality of this type of process it is important to fill the build space as much as possible. The less area that the jets have to spray with the sintering inhibitor, the quicker and more efficient the SIS will be. More recent SIS machines incorporate methods of controlling the heat on the radiating source to limit the amount of area the jets have to spray the inhibitor.[124]

b. Semi-solid Metal Printing

Another attempt aimed at reducing the cost of printing metal parts is the research on semi-solid metal printing. A combination of researchers from Lawrence Livermore National Laboratory, Virdis 3D, and Worchester Polytechnic Institute are developing methods of printing metal parts using extrusion, similar to the FDM process, but instead of using plastic filaments their printers will extrude a metal material. Although early in its development, the technology shows great potential and could alleviate some of the problems with current metal printing such as limited raw material availability and cost. Because this process does not require the use of a laser it could lower the energy requirements, which is a substantial benefit in austere environments. The new process could potentially work with a wide range of raw materials including superalloys that are used in medical and military applications.[125]

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[124] Hopkinson, Dickens, and Hague, eds., *Rapid Manufacturing,*70-72.

[125] Sharon Gaudin, “Researcher works to make 3D-printed metals stronger, customizable,” Computer World, October 24, 2014, http://www.computerworld.com/article/2838780/researcher-works-to-make-3d-printed-metals-stronger-customizable.html.

c. Printable Batteries

A Harvard professor is developing methods of using 3D printing techniques to build batteries. The goal of the research is to print the batteries inside of a larger component. The batteries are not restricted to standard shapes and sizes.[126] A New York based company is also making advances with printed batteries and has developed a printed design with the same amount of power as an AA battery. Its shape and size can also be modified to fit a specific application.[127] At its current level of maturity, it does not offer much utility to the military, but as the technology advances it could be useful in small powered applications.

d. Printing with Readily Available Materials

Using materials readily available without relying on specific materials that are often proprietary would be a significant advancement. A team of researchers at Washington State University proved the ability to use simulated lunar rock melted by a laser to print small objects.[128] A German designer developed a system called the Solar Sinter that uses sand instead of the typical resins to build glass parts. Additionally, it uses solar power instead of a laser to sinter the sand.[129] If combined with another substance to improve the physical properties of glass, this system could have several uses and would function well in previous theaters of operation.

e. Radiation Shielding

As the enemy threat evolves, protection of electronic sources is becoming increasingly important. NASA is experimenting with direct metal laser sintering

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[126] Joseph Flaherty, "This Harvard Prof's Printed Batteries Could Revolutionize Our Gadgets," Wired, December 23, 2013, http://www.wired.com/2013/12/3-d-printing-batteries/.

[127] Jasper Hamill, "Husband And Wife Team Unveil The World's First 3D-Printed Graphene Battery" Forbes, October 23, 2014, http://www.forbes.com/sites/jasperhamill/2014/10/23/husband-and-wife-team-unveil-the-worlds-first-3d-printed-graphene-battery/.

[128] "3D Printers Could Use Moon Rocks, Scientists Say," BBC, November 29, 2012, http://www.bbc.com/news/technology-20542496.

[129] Lou Del Bello, "Solar-powered 3D printer uses sand to make glass," SciDevNet, March 22, 2013, http://www.scidev.net/global/energy/news/solar-powered-3d-printer-uses-sand-to-make-glass-1.html.

processes to develop efficient radiation shielding.[130] This advancement could alleviate concerns of immobilization due to directed energy weapons and other similar enemy threats.

f. Electronics Printing

NASA is also researching the ability to print electronics. Specifically, NASA is interested in the ability to print circuit building blocks including crossovers, resistors, capacitors, chip attachment, power sources, and detector strips. A company called Optomec demonstrated the ability to print functional circuitry to include sensors and antennas.[131] This would prove to be a very useful capability for the military. The electronics would not dictate the overall shape of a system.

C. SUMMARY

There are numerous AM processes and each has its advantages and disadvantages. Processes such as stereolithography, selective laser sintering, powder-binder printing, and fused deposition modeling are relatively mature processes that could potentially benefit the Marine Corps. They offer a good balance across system attributes including raw material usage, accuracy, build size, and production time as well as end product attributes including surface finish, stability, and environmental resistance. In addition to these processes, there are several new technologies that could potentially benefit the Marine Corps in the future. Processes like SIS and semi-solid metal printing offer distinct advantages, but are not mature enough to consider at this time.

Despite the rapid advancement of the technology, there are still several limitations regarding AM. Issues such as the lack of qualification and certification procedures as well as inconsistent results are significant problems that need to be corrected. As discussed earlier, there are major advancements and efforts to improve in these areas. Other issues including small build sizes, low strength of end products, and slow

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[130] Swanson, "Ensuring Quality for Spacecraft Applications."

[131] Swanson, "Ensuring Quality for Spacecraft Applications."

throughput rates are also factors to consider, but are not as significant as no qualification and certification standards and low repeatability.

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III. ADDITIVE MANUFACTURING EXAMPLES

When considering using 3D printers to improve Marine Corps logistics procedures, it is important to understand there are numerous applications to evaluate. The printers are capable of several vastly different applications that offer unique advantages. These applications include prototyping/modeling, tooling/support aids, end product manufacturing, medical uses, and printing food. The utility of each application is illustrated through the use of examples in the civilian industry as well as cases throughout the military. The examples highlight how the Marine Corps might incorporate the use of 3D printers to improve logistics.

A. PROTOTYPING

When 3D printers were first developed, their primary purpose was to aid with prototyping and modeling. Until recently, this was the only useful application of the technology. There are numerous successful use cases in the civilian industry, some of which are for military products. There are also a few U.S. Army examples of using 3D printers for prototyping.

1. General Electric

Several large companies are using the efficiency of 3D printers to shorten the modeling and prototyping phase of their research and development for new systems. General Electric (GE) is one of the leading companies leveraging the technology for this purpose. GE is currently using 3D printers to develop a more efficient turbine combustor. By taking advantage of the intricate design capabilities 3D printers offer, GE developed a turbine with a 1% gain in efficiency. The efficiency gain equates to saving 205 Tbtu of energy and 12 million tons of carbon dioxide per year. The turbines were not only designed and prototyped using 3D printers; they will also be manufactured using the printers.[132] In addition to their own research and development, GE encourages other organizations to use the technology to improve efficiency. They held a contest to make

[132] Marshall, “Improving Manufacturing Competiveness.”

engines lighter by redesigning aircraft engine brackets. The contest included 689 total participants. The best design reduced weight by more than 80% over the original brackets.[133]

2. Lockheed Martin

As of 25 October 2014, Lockheed Martin has produced close to 14,000 parts using the FDM process. The company uses the printers for prototyping and modeling approximately 50% of the time. They use the printers to build models for display purposes, models for wind tunnel testing, and parts and components for form and fit functionality testing. The FDM printers have saved Lockheed Marin thousands of dollars and numerous hours with the ability to print models. For example, Lockheed Martin used the printers to produce a model of the F-35's fuselage and wing skins for testing in the wind tunnel. The FDM produced models cost $21,000. Conventional CNC machining would have cost the company $86,000 to produce, more than four times as much. Another example is the printed leading edge, trailing edge, wing tip, and spoilers of an aircraft. Conventional machining would have cost twice as much as the printed models. In addition to money, the FDM printers save Lockheed Martin time compared to conventional manufacturing. One particular example involves printing parts for flight testing. If Lockheed Martin relied on traditional milling procedures it would have taken them four weeks to produce the parts, but by using the FDM printers, Lockheed Martin produced the parts in five days. The printers reduced a month long delay to less than one week. Lockheed Martin also saves time by using the printers to rapidly produce parts for fit, form, and function such as the cockpit floor for the F-22. They are able to quickly make changes to the designs based on the testing completed. This would not be possible with traditional manufacturing methods.[134] These are merely a few of the many examples of how Lockheed Martin has used their 3D printers to save them money and time.

[133] Yang, "Metal Additive Manufacturing at GE."

[134] Mark Skeehan, "Additive Manufacturing: Changing the Way We Build and Test Aircraft," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 8, 2014).

3. Boeing

Lockheed Martin and GE are not the only aviation companies using 3D printers for prototyping. Another giant in the industry, Boeing, also uses the technology to improve efficiency when developing modifications to existing aircraft and designing new aircraft. They are using printers to prototype solutions to problems that surface during production like they experienced with the Ch-47 Chinook's ramp section. Boeing employees quickly designed and printed a prototype to fix the problem, keeping production on schedule. In addition to the time saved, the quick fix saved Boeing the equivalent of how much the printer actually cost them.[135] Unlike some of the other aviation companies, a large percentage of Boeing's efforts regarding 3D printing is focused on end product manufacturing, which is discussed later.

4. NASA

While NASA is not investing heavily in the technology they are using it for several applications. The 3D printers are critical components to many of the new technologies that were mentioned in the previous chapter. In addition to aiding in the research of new technologies, NASA is also using 3D printers for prototyping of parts for existing systems. One such application is a titanium part for a cryo thermal switch. The complex design of the part would take about three months to fabricate using conventional methods and cost as much as $20,000; however, it was delivered within two weeks and only cost NASA $1,200 by printing it.[136]

5. Ford Motor Company

The aviation industry is not the only industry taking advantage of 3D printing. Several automakers, including Ford Motor Company are using the printers to shorten the prototyping phase and deliver their products to the customer quicker. Ford invested heavily in the technology and has five prototyping centers across the United States and Europe that utilize numerous different processes including FDM, SLS, SLA, and binder

[135] Eric Carlson, "Boeing utilizes 3D printer," Boeing, accessed February 17, 2015, http://www.boeing.com/Features/2012/09/bds_3d_printer_09_11_12.html.

[136] Swanson, "Ensuring Quality for Spacecraft Applications."

jet printing. Just one of their prototyping centers produces 20,000 parts annually.[137] Over the course of the last few decades, Ford printed over 500,000 parts with their printers. As a result, the company calculates that they saved billions of dollars and millions of hours of work. Prototypes that normally cost half a million dollars and take four to five months to produce now only cost a few thousand dollars and are produced in a few days. The prototyping centers print parts that are used for modeling purposes as well as parts that are intended for use in a vehicle. Ford installed numerous printed parts into vehicles and subsequently tested them for hundreds of thousands of miles. The parts are even crash tested at 70 miles per hour. In the future, Ford anticipates that its dealers will have printers that are able to print replacement parts to expedite repairs.[138] As Ford continues to expand its use of 3D printers, it could provide a proof of concept for the Marine Corps. The idea of satellite repair centers with the capability to print their own repair parts is extremely beneficial to efficiently supporting distributed operations across the battlefield.

6. U.S. Army ARDEC

The U.S. Army's Armament Research, Development and Engineering Center (ARDEC) is exploring the capabilities of 3D printers to further their research. Two examples in particular are types of prototyping applications. The first example is designing wrap fins for the next generation precision-guided munitions (PGM). The designs for the wrap fins are often very intricate with lots of detail. Traditional manufacturing methods are not suitable for these types of designs. Additionally, several variants, each with unique differences, are needed to conduct comprehensive wind tunnel testing. To quickly produce several different uniquely designed fins, the ARDEC engineers use 3D printers. The 3D printers allow the engineers to make numerous changes to the design based on wind tunnel results. These changes were accomplished in days vice the months it would have required if traditional manufacturing methods were

[137] Lucas Mearian, "Inside Ford's 3D Printing Lab, where thousands of parts are made," Computer World, June 4, 2014, http://www.computerworld.com/article/2490192/emerging-technology-inside-ford-s-3d-printing-lab-where-thousands-of-parts-are-made.html.

[138] "Building in the Automotive Sandbox," Ford, accessed February 17, 2015, https://corporate.ford.com/innovation/building-in-the-automotive-sandbox.html.

used.[139] In the end, the engineers developed and produced superior PGM fins by leveraging the advantages of 3D printers. The second example resulted from a requirement to reduce the weight of the PackBot to make it light enough to be considered man portable.[140] The ARDEC engineers again leveraged the capabilities of 3D printers to aid in the development and prototyping of weight saving components for the PackBot. The engineers experimented with several components and designs and ultimately chose to implement lighter weight flippers. The engineers replaced the cast metal flippers with printed plastic flippers. This resulted in a weight and volume reduction of 45% compared to the original flippers. Additionally, the printers enabled the engineers to design and fabricate the new flippers in a few days instead of months compared to traditional manufacturing methods such as casting and machining.[141] The printed flippers are shown in Figure 7. Even though this is an example of using the printers for the purpose of prototyping, it also shows how the printers could be used for end product manufacturing. The example highlights how quickly the flippers could be produced if they were to break while on a mission and replacement flippers were not on hand.

Figure 7. Printed lightweight flippers for PackBot (from Zunino, 2014)

[139] Zunino, "Enabling Technologies for Military Applications."

[140] The PackBot is a robot designed for several missions such as bomb reconnaissance and disposal.

[141] Zunino, "Enabling Technologies for Military Applications."

7. Rapid Equipping Force

Another U.S. Army unit that is using 3D printers for prototyping purposes is the Rapid Equipping Force (REF). The REF packaged a 3D printer with several other systems such as a computer numerical control (CNC) machining system, several types of saws, and plasma cutters into a standard twenty foot shipping container. The total system, called the Expeditionary Lab – Mobile included several contracted engineers to assist the soldiers responsible for the system. It was deployed to combat operations in Afghanistan during the summer of 2012. The lab enabled the soldiers to conduct rapid prototyping of several potential solutions to problems that arose during combat operations. One problem was the battery life of hand-held ground-penetrating radar devices. Due to the extreme heat, the batteries only lasted approximately 45 minutes causing the soldiers to carry numerous replacement batteries. The soldiers, working in concert with the engineers from the lab, designed a special connector and power cable for the device so that it could be powered by a standard military-issue BA590 battery. One BA590 battery lasted up to 9 hours, which significantly reduced the required number of spare batteries the soldiers needed to carry. The connectors and power cables were prototyped using 3D printers.[142]

The 3D printers were also used to prototype solutions to fix an issue with valve stems on Mine Resistant Ambush Protected (MRAP) vehicles. When the tires of the MRAPs happened to brush against rocks or other structures, they would snap off causing the tire to deflate. The unit would then have to halt their mission, create a security perimeter, and change the deflated tire. If the unit did not have any spares, the unit would then have to tow the vehicle with organic assets or request assistance from the nearest coalition force. To fix the problem, members from the expeditionary lab used the 3D printers to prototype several different versions of valve stem covers to protect the vulnerable valve stems. The soldiers tested the prototypes and ultimately selected one for

[142] Matthew Cox, "Mobile Labs Build On-the-Spot Combat Solutions," Military.com, August 17, 2012, http://www.military.com/daily-news/2012/08/17/mobile-labs-build-on-the-spot-combat-solutions.html.

installation on MRAPs.[143] The lab was also used to prototype designs to prevent the bipod on M249 Squad Automatic Weapon (SAW) from breaking. Similar to the valve stem solution, the printers were used to produce several prototypes that were tested on the weapon. Once the best prototype was identified, the soldiers used the CNC machines in the lab to produce the final product that was installed on SAWs.[144] While these examples were not primarily focused on improving logistics efficiency, the second order effects did improve efficiency. The printed battery connectors and cables drastically decreased the number of batteries required for hand-held mine detecting operations. Fewer batteries equates to less demand on the supply chain and corresponding transportation requirements. While it may seem insignificant, one BA590 battery replaced the equivalent of approximately 12 original batteries. If one squad used two mine detectors for a patrol and every squad in an infantry battalion conducted one patrol per day, the new connectors would eliminate the need for approximately 144 batteries for one battalion in one day. In a similar fashion, the valve stem covers have several second and third order effects such as less replacement tires, reduced maintenance hours, and decreased fuel consumption.[145] The new component for the M249 SAW also reduced the required number of repair parts and maintenance hours.

Using 3D printers for the purpose of prototyping and modeling is crucial for many companies in the civilian industry and has proven to be a force multiplier for the U.S. Army. The Marine Corps has yet to utilize 3D printers for prototyping, but it could benefit from the same model the REF used for its expeditionary labs. The printers would enable Marines to create innovative solutions for problems that arise while on deployment. Instead of relying on an unresponsive acquisition system, Marines could rapidly produce prototypes for immediate testing similar to the soldiers described above.

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[143] Rapid Equipping Force United States Army. “Forward Expeditionary Labs Valve Stem Fix,” *YouTube* video, 3:29, August 26, 2013, https://www.youtube.com/watch?v=hSu1kNxBdsM&list=WL&index=18.

[144] Rapid Equipping Force United States Army. “Forward Expeditonary Labs M249 Bipod Fix,” *YouTube* video, 3:41, August 26, 2013, https://www.youtube.com/watch?v=MSFmbrs2-gA&list=WL&index=19.

[145] If the unit conducting the mission did not have the means to recover the vehicle, an additional convoy would have to be dispatched to recover the vehicle resulting in increased fuel consumption.

B. TOOLING/SUPPORT AIDS

Another highly valuable application for 3D printers is tooling. Tooling involves using printers to make items intended to assist production of other products. Examples of tooling are drill jigs, molds, braces, and other related items. It is an example of how 3D printers are used in concert with traditional methods to make the overall manufacturing process more efficient. Several civilian companies and military organizations use 3D printers for the purpose of tooling.

1. Joint Strike Fighter Program

The Science and Technology team for the F-35 Joint Strike Fighter program attempted to use 3D printers for a few different types of applications. One application the team explored was using 3D printers to make tools for the aircraft. The objective for the team was to reduce the tooling cost by 35% and the lead time by half. After investing $1.675M into the program, the team ultimately determined the tools produced using 3D printing techniques were not usable. The printed tools had poor flow characteristics, which resulted in porous end products. As a result, the team ceased attempts to use 3D printers for tooling purposes due to inferior results.[146] These results are not uncommon and were discussed in Chapter II.

2. Lockheed Martin

As mentioned previously, Lockheed Martin uses their FDM printers for prototyping purposes 50% of the time. They use the printers for tooling the other 50% of the time. Similar to the prototyping and modeling applications, the FDM printers save them both time and money over traditional manufacturing methods. They use them to quickly produce numerous tools including drill jigs and casting patterns. One specific example of FDM printed tools is inlet trim check tools. CNC manufacturing methods would cost Lockheed Martin over $98,000, but the printed tools cost just over $13,000 for a savings of over $85,000. Another similar tooling example saved the company $225,000 over traditional methods. During one application, the printed tools prevented

[146] Gentry, "Acquisition Perspective."

Lockheed Martin from exceeding their delivery timeline despite a last minute installation problem.[147]

3. Fleet Readiness Center East

After a hard landing on the USS Bataan (LHD 5), an AV-8B Harrier suffered structural damage to its nose cone. To repair the damage, the maintainers needed to create sheet metal reinforcements referred to as "doublers." This task was sent to Fleet Readiness Center East (FRCE) located aboard Marine Corps Air Station Cherry Point, North Carolina. FRCE acquired CAD files from the manufacturer and used its FDM printer to make tools to form the sheet metal. Upon receipt of the CAD files from the manufacturer, FRCE printed the first tool in five hours and the second tool in about 30 hours. In one week from receiving the task, FRCE formed the sheet metal and shipped it to the Marines aboard the USS Bataan, saving a considerable amount of time and money over conventional manufacturing methods.[148]

The Marine Corps is already using 3D printers for limited tooling applications, but there may be additional applications suitable for the printers.

C. END PRODUCT MANUFACTURING

End product manufacturing refers to printing repair parts or other components for use in a larger system. The Marine Corps stands to benefit from this use due to its expeditionary nature. The ability to print repair parts would enable a unit operating in a forward environment to be more self sufficient and less reliant on long supply chains. Despite its significant advantages, there are only a few military use cases. There are, however, numerous examples in the civilian industry that highlight its potential impact.

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[147] Skeehan, "Changing the Way We Build and Test Aircraft."

[148] COMFRC Public Affairs, "Fleet Readiness Center East Repairs Harrier Using 3-D Printing," Naval Air Systems Command, August 13, 2014, http://www.navair.navy.mil/index.cfm?fuseaction=home.NAVAIRNewsStory&id=5704.

1. General Electric

In an attempt to increase the efficiency of its new aircraft engine, General Electric Aviation explored the possibility of using 3D printers. After significant research and development, GE Aviation decided to use 3D printed fuel nozzles for its new engine, the CFM LEAP. As a result of leveraging 3D printing technology, the new fuel nozzles are 25% lighter and five times as durable as their predecessor. The printed fuel nozzles consist of one component compared to the 18 individual pieces of the old design. There are several thousand orders for the new CFM LEAP engine and each engine requires 19 fuel nozzles. The engines are scheduled for delivery starting in 2016 and by 2020, GE anticipates it will have produced over 100,000 of the 3D printed fuel nozzles.[149]

2. Joint Strike Fighter Program

In addition to attempting to use 3D printers for tooling, the Science and Technology team also researched methods of using printers to produce parts and components for the F-35. One initiative included making non-structural parts such as clips, brackets, and ducts out of high temperature plastics to save both money and weight. Over $8.5M was invested in this endeavor, but proved to be not worth considering. The printed non-structural parts were not as strong as the parts they were supposed to replace and they had electrical performance issues. Furthermore, the high cost of the raw materials needed to make the parts negated any cost savings gained by printing. The team also attempted to use 3D printers for structural parts. Of all of the attempts, this application has the most potential; however it is hindered by the lack of qualification and certification procedures. Despite having a business case, the F-35 program is unable to use 3D printers for structural parts because the process is not approved.[150] Until standards and qualification procedures are developed, the program will not be able to leverage the benefits of 3D printing.

[149] "3D Printing Creates New Parts for Aircraft Engines," General Electric, accessed 9 April 2015, http://www.geglobalresearch.com/innovation/3d-printing-creates-new-parts-aircraft-engines.

[150] Gentry, "Acquisition Perspective."

3. Boeing

As mentioned earlier, Boeing is focused on printing parts for the purpose of using them in aircraft. There are over 20,000 printed parts in operational Boeing aircraft today. Boeing uses 300 different printed parts for ten of their platforms. As evident by a patent filed by the company in 2015, they are eager to expand the use of printed parts throughout their aircraft. The patent refers to a central database management system that contains 3D design files for Boeing aircraft parts. Boeing wants to make the database accessible not only to its manufacturing centers, but also to its customers to allow them to print their own spare parts using the exact manufacturer specifications.[151] This concept was discussed during the first chapter; however, the major difference is that in this scenario the database is sourced and maintained by the actual manufacturer not a third party vendor. Boeing's database will be more reliable because it will also use the same database to produce its parts at its manufacturing facilities. The centralized database will potentially negate the requirement to maintain spare parts for the sole basis that the manufacturer terminates production of the part. Other companies that provide equipment for the military could adopt this concept if it proves successful. The Marine Corps can influence this action during the acquisition process.

4. NASA

In addition to using 3D printers for the purpose of prototyping on the ground, NASA deployed a printer to the International Space Station in November 2014 aboard a SpaceX commercial resupply mission. In the span of just over a month, the personnel aboard the space station used the printer to print 21 different parts using 14 different designs. Most of the designs were pre-installed on the printer before it left, but one of the designs was submitted via email once the printer was already at the space station. This validated the ability to send files remotely to space and print on demand when the need arises. NASA is also verifying the quality of the parts printed in space. Prior to deploying the printer, NASA used it to print each of the 14 different parts. The parts printed in

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[151] Abigail Phillips, "Boeing Reduces Lead Time and Saves Money by 3d Printing Aircraft Parts," Manufacturing Global, March 28, 2015, http://www.manufacturingglobal.com/technology/409/Boeing-reduces-lead-time-and-saves-money-by-3d-printing-aircraft-parts.

space were sent to Huntsville, Alabama to be compared to the ground control set. Materials engineers are in the process of performing durability, strength, and structural tests on both sets of parts. They will use electron microscopes to identify any differences in the two sets. All of the parts printed on the space station as of January 2015 are solely for test and validation purposes and will not actually be used by the space station crew. The crew, however, is developing a list of parts and tools currently used aboard the space station that could potentially be built by the printer.[152] NASA is validating several proofs of concepts with the tests they are conducting. The most relevant proof of concept for Marine Corps logistics is the ability to print parts on demand. To date, both NASA and the U.S. Army's expeditionary lab have printed parts on demand from remotely sent files.

5. Aerojet Rocketdyne

Aerojet Rocketdyne makes liquid rocket engines for spacecraft. Due to a limited number of manufacturers for certain parts and components for the engines, Aerojet Rocketdyne decided to experiment with Selective Laser Melting (SLM) printers to make their own parts. One particular part is an injector for a gas generator. Compared to conventional manufacturing methods, the SLM printer enabled the company to produce the same component with significantly fewer individual parts and without tooling. The printed part cost the company 70% less and took 60% less time to produce.[153] The injectors, which will be a part of a new engine called the AR1, were tested in early 2015. The injectors were tested at pressures exceeding 2,000 psi highlighting the advancements made regarding the strength of 3D printed parts.[154]

[152] "Special 3-D Delivery from Space to NASA's Marshall Space Flight Center," NASA, April 7, 2015, http://www.nasa.gov/centers/marshall/news/news/release/2015/special-3-d-delivery-from-space-to-nasa-s-marshall-space-flight-center.html.

[153] Jeff Haynes, "Additive Manufacturing for Liquid Rocket Engines," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 8, 2014).

[154] "Aerojet Rocketdyne Hot-Fire Tests Additive Manufactured Components for the AR1 Engine to Maintain 2019 Delivery," Aerojet Rocketdyne, accessed 10 April, 2015, http://www.rocket.com/article/aerojet-rocketdyne-hot-fire-tests-additive-manufactured-components-ar1-engine-maintain-2019.

6. ExLog VIII

One of the major 3D printing companies, 3D Systems, partnered with Marine Corps Logistics Command to simulate a logistics exercise which emphasized the use of 3D scanners and printers. In the scenario, the Marine Corps unit was using a small, unmanned ground vehicle (UGV) to assist in reconnaissance. One of the UGV's wheels broke and the unit did not have a replacement. The team proceeded to use 3D scanners to scan the wheel to create a 3D image. The image was automatically converted to a file type recognized by the printer. The team verified that the file was the right design and had the correct dimensions and subsequently printed the wheel. The printed wheel was scanned with the same 3D scanners to verify that the printed wheel matched the 3D image and was ready for installation. The complete process took less than 24 hours from the time the wheel was broken.[155] While purely a simulation, ExLog VIII is an example of how 3D scanners and printers can increase maintenance responsiveness. Instead of waiting for an unknown period of time to order and receive a direct replacement wheel, the unit was able to immediately design and print the wheel. It is important to note that the printed wheel was printed with plastic polymers, which is not necessarily the same material of the original wheel on the UGV. If this was a real scenario, the unit would most likely still order a direct replacement wheel from the manufacturer, but the printed wheel could still be used as a temporary solution until the replacement wheel was received. The UGV would be slightly degraded, but would still be considered operational. It is also important to note that this specific example does not require in depth certification and verification, as it is not a critical component.

7. U.S. Army ARDEC

In addition to the prototyping and modeling applications, the ARDEC also used 3D printers for end products. One particular example is a radio connector. ARDEC engineers were attempting to integrate PRC155 radios into fire control systems. The physical connection required a special connector that was not on hand. The engineers attempted to order the simple connector, but the connector was on back order for 3–4

[155] Orringer, "Manufacturing the Future."

months. Additionally, the minimum purchase quantity for the connectors was 50 even though the engineers only needed the one connector. At approximately $300 per connector, the total order would cost about $15,000. The engineers then decided to model and print the connector themselves. It took two hours to model the piece and an additional hour to print it for a total time of three hours compared to 3–4 months if they were forced to order the connector. Furthermore, the connector cost about 25 cents to produce, a mere fraction of the cost of ordering it, especially with the minimum order quantity.[156] This scenario took place in a lab environment and was conducted by engineers, but could easily be replicated by any unit with a 3D printer in any location.

Using 3D printers to produce replacement parts and components is becoming more commonplace. Companies are quickly realizing that as printers advance, they are able to use them for more advanced applications than solely prototyping. Due to its mission set, the Marine Corps is poised to reap the benefit of using 3D printers for end product manufacturing under the right circumstances.

D. MEDICAL

Using 3D printers for medical applications is not well known, but it is quite prevalent in the industry. Medical grade printers are used to print anything from hearing aids and prosthetic limbs to organs. Unlike the previous applications, medical uses are not organized by company or organization. The examples are organized according to the raw material used, either inorganic or organic. Inorganic applications will include devices that are made out of plastics and metals, whereas, organic applications are constructed using organic materials including human cells.

1. Inorganic Applications

The medical industry has used 3D printers since the early 2000s to print numerous items. Cranial, jaw, spinal, dental, and hip implants are all printed with 3D medical grade printers.[157] There is even one case of an entire skull that was printed and implanted in

[156] Zunino, "Enabling Technologies for Military Applications."

[157] C. Lee Ventola, "Medical Applications for 3D Printing: Current and Projected Uses," *Pharmacy and Therapeutics* 39, no. 10 (October 2014): 706.

2013. The printers are used for more than just structural implants as well. Researchers printed a prosthetic ear capable of detecting electromagnetic frequencies. Printers are used to print less advanced hearing aids, and are actually responsible for producing 99% of all hearing aids. The company Invisalign prints 50,000 of their braces every day. In addition to implants, 3D printers are also used to print surgical models. The surgical models are printed using digital files generated from CT scans. As a result, the surgical models are not only anatomically correct, but are an exact replica of the patient's organ. The surgical models are even printed with a material that resembles human tissue. Surgeons are able to use the models to study and practice a procedure before they even make the first incision on the patient. The models provide a considerable advantage over just studying images on a two-dimensional screen.[158] Pharmaceutical companies are also using the printers. The printers allow the companies to completely tailor the drugs to unique situations. Pharmacies may have the ability to print drugs with an exact dosage for a patient. Additionally, printing drugs enables the pharmaceutical companies to create complex drug-release profiles. The companies are able to print drugs that are released at multiple different rates at times that are the most beneficial to the patient.[159] Many of these applications do not offer much potential to increase the efficiency of Marine Corps logistics at the tactical level, but they do offer significant advantages at other levels.

2. Organic Applications

In addition to using traditional raw materials in 3D printers, there is a trend to investigate using organic material in its place. Researchers with the Wake Forest Institute for Regenerative Medicine (WFIRM) are rapidly developing the ability to print with human cells.[160] The research team created a two-chamber heart by placing human cells on a structure made of organic material. They used a similar process to create a human kidney. The organs cannot be used clinically yet, but the team is conducting further

[158] Ventola, 708.

[159] Ibid., 709.

[160] Connor M. McNulty, Neyla Arnas, and Thomas Campbell, "Toward the Printed World: Additive Manufacturing and Implications for National Security," *Defense Horizons*, no. 73 (September 2011): 3.

research to one day use the printed organs in that capacity.[161] In addition to creating organs that can be implanted, the institute developed methods of printing skin. They are able to print skin directly on a patient's wounds. The Armed Forces Institute of Regenerative Medicine (AFIRM) teamed with WFIRM and industry partners Lexmark and Organogenesis, Inc. to create a program responsible for developing a system used to print skin on the battlefield to treat wounds. The program successfully built a portable system capable of printing full-thickness human skin.[162] Researchers from Cartilage Engineering and Regeneration laboratory in Zurich have developed a method of printing cartilage directly to a patient's nose. The method uses cartilage cells from the patient and combines them with biopolymers to form the new cartilage. Unlike current methods, the cartilage will not form scar-like tissue. Instead, it will form a cartilage mass capable of growing and developing with the patient as time progresses. An additional benefit of the procedure is that it takes less than 20 minutes to complete.[163] In addition to these examples, researchers around the world have used bioprinting to produce a knee meniscus, heart valve, spinal disk, ear, liver, and even a network of capillaries.[164]

In contrast to inorganic applications of 3D printing, the organic applications of medical 3D printing offer obvious benefits to Marine Corps logistics at the tactical level. The ability to print skin directly on a Marine's wound in a trauma center has the capability to change how patients are treated. The impact on tactical logistics and how the Marine Corps treats combat injuries will only increase as research advances in this area.

E. FOOD

Another unique and emerging application of 3D printers is food production. As unappealing as it may sound, it has the potential to increase the Marine Corps' efficiency when feeding its forces. Food printers are rapidly advancing and are in use throughout the

[161] McNulty, Arnas, and Campbell, "Toward the Printed World ," 5.

[162] Ibid., 9.

[163] Lecia Bushak, "Bioprinter Seamlessly 3D-Prints Nose Cartilage In 16 Minutes, Offers Improved Reconstructive Surgery," Medical Daily, March 20, 2015, http://www.medicaldaily.com/bioprinter-seamlessly-3d-prints-nose-cartilage-16-minutes-offers-improved-326452.

[164] Ventola, "Toward the Printed World ," 706.

world. To date many of the applications of food printers are ornamental and use nothing but chocolate; however, in the Netherlands, all of the microwave pancakes available in supermarkets are produced using food printers. There are also major advancements in Europe to make printers that are capable of making soft replacement foods enriched with nutrients for nursing homes.[165] Students at Cornell University have even researched the design and construction of a printer capable of making items as complex as a burrito.[166] The U.S. Army, NASA, and other civilian companies also recognize its potential and are currently researching how it can improve the food industry in other areas.

1. Natural Machines

Aimed initially at professional chefs, Natural Machines developed a printer called the "Foodini" that is capable of printing numerous types of food products including pizza, filled pasta, burgers, and cheese. As of now, the printed food must still be placed in an oven to be cooked, but the company is developing a printer that will form and cook the food without interaction. Similar to an FDM printer, the food printer uses extrusion methods to squeeze ingredients out of stainless steel capsules onto a build platform.[167] Unlike other printers designed for ornamental foods, these printers are designed to print traditional meals.

2. NASA

In an effort to feed its crewmembers on long duration, deep space missions, NASA awarded a contract to a Texas-based company to develop a system to print food in space. The goal for the system is to feed the crewmembers for up to five years and meet safety, acceptability, variety, and nutritional stability requirements. It must also require minimal spacecraft resources and crew time to prepare the food. The current food system is not suitable for long duration missions and the processes used to prepare the shelf

[165] Adam Hadhazy, "Will 3D Printers Manufacture Your Meals?" Popular Mechanics, March 25, 2013, http://www.popularmechanics.com/technology/gadgets/a8816/will-3d-printers-manufacture-your-meals-15265101/.

[166] McNulty, Arnas, and Campbell, "Toward the Printed World ," 5.

[167] Jacopo Prisco, "Foodini Machine Lets You Print Edible Burgers, Pizza, Chocolate," CNN, December 31, 2014, http://www.cnn.com/2014/11/06/tech/innovation/foodini-machine-print-food/.

stable foods degrade the micronutrients in the foods. The new system must offer extended variety and increased nutritional value to ensure the crew maintains their health and performance. In addition to offering greater variety and better nutrition, NASA also desires that the new system be less wasteful than the current system. NASA invested $125,000 into this six-month Small Business Innovation Research Phase I contract.[168] The Texas-based company, Systems and Materials Research Consultancy (SMRC), is developing the system to be used for long and short duration missions. The difference between the two systems will be how the ingredients are stored. The short duration missions will use pastes; whereas, the long duration ingredients will be stored separately and combined as necessary to make the paste for the food printer. Both systems will have virtually no waste. As the company develops the food printer for NASA, they will also develop the system in mind for other applications such as military use. The company assesses their current technology readiness level (TRL) at three and expects to be at a TRL of four at the conclusion of the contract .[169] If SMRC is able to develop a suitable system, it could provide a huge benefit to the Marine Corps. Based on its TRL, the Marine Corps will not benefit from this technology in the near future.

3. U.S. Army's Natick Soldier Research, Development, and Engineering Center

Recognizing the potential benefit of fully customizable and prepared on demand meals, the U.S. Army's Natick Soldier Research, Development, and Engineering Center (NSRDEC) is developing a food printer built for the rigors of military operations. One of the goals is to provide soldiers customizable meals that are more appetizing than current meals such as MREs. There are several benefits of printing food vice pre-packaged meals. One benefit is that the meals could be customized for the individual soldier and will be a meal he or she chooses; therefore, the soldier will want to eat it and there will be less waste. Another distinct benefit of printing food is the ability to control the exact amounts of key vitamins, minerals, and other nutrients that a soldier intakes. If the soldier

[168] "3D Printing: Food in Space," NASA, May 23, 2013, http://www.nasa.gov/directorates/spacetech/home/feature_3d_food.html#.VUmBHqYk-n0.

[169] "Form B – Proposal Summary," NASA, accessed April 12, 2015, http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sbir/phase1/SBIR-12-1-H12.04-9357.html?solicitationId=SBIR_12_P1.

needs more protein, the meal will be printed with more protein. The meal will be printed with whatever the solder needs and can be changed for each soldier. In addition to printing food on demand, NSRDEC is investigating methods of making the printed foods shelf-stable. One such method is ultrasonic agglomeration. The process produces compact snack items that are nutrient-dense and shelf-stable. Currently Army researchers are focused on using ingredients that are commonly consumed, but are open to the idea of utilizing locally foraged items for use in the printers.[170] Researchers at the Dutch Organization for Applied Scientific Research may make this a possibility in the near future. The researchers are experimenting with sustainable caloric sources such as algae protein and insects. The team has already printed a shortbread cookie with milled mealworm for extra protein.[171]

Food printers focused on sustaining soldiers are early in the development phase, but in the near future could enhance how the armed services feed troops. The customization the printers offer have the potential to provide nutrient dense meals designed to meet each individual's dietary needs. Combined with producing less waste than current feeding procedures, food printers are worth considering. As the technology advances and the U.S. Army's NSRDEC continues its research, the Marine Corps could be sustaining its Marines on the battlefield with highly efficient and fully customizable food printers.

F. SUMMARY

There are several applications of 3D printers. Each type of application offers its own unique benefits to the Marine Corps and may increase the efficiency of logistics if chosen for the correct use and is implemented correctly. The following chapter will explore the impact these applications have on implementing them in the Marine Corps. When both the benefit and impact are taken in consideration, a more sound decision can

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170 Jane Benson, "Chow From a 3-D Printer? Natick Researchers are Working on it," Army.mil, July 18, 2014, http://www.army.mil/article/130154/Chow_from_a_3_D_printer__Natick_researchers_are_working_on_it/

171 Hadhazy, "Will 3D Printers Manufacture Your Meals?"

be made as to what type of 3D printers should be procured as well as how they should be used in the Marine Corps to improve logistics.

IV. IMPLEMENTATION

Understanding which AM processes to invest in as well as which applications are most desirable are two very important factors. Another equally important factor is how and where 3D printers should be incorporated. It is critical to evaluate the impact of integrating 3D printers on the entire system. This chapter will illustrate the impacts of using 3D printers for each of the five applications (prototyping/modeling, tooling/support aids, end product manufacturing, medical, and food) at three different levels in the Marine Corps. The three levels that will be evaluated are the Marine Expeditionary Unit (MEU), Marine Expeditionary Brigade (MEB), and depot maintenance facilities operated by Marine Corps Logistics Command (LOGCOM). The overall impact of implementing 3D printers on each level will be evaluated by assessing the impact on current doctrine, organization, training, material, leadership, personnel, and facilities (DOTMLPF). In addition to integrating 3D printers into Marine Corps models, this chapter will analyze the potential benefits and impacts of relying on a network of distributed civilian printing services across the world.

A. PROTOTYPING

Despite its obvious advantages in the civilian sector, the prototyping application of AM does not offer much potential to increase the efficiency of Marine Corps logistics, but is still beneficial. Additionally, the likelihood that units at the MEU and MEB level would use the printers for prototyping and modeling is very low.[172] Models like the expeditionary lab deployed by the U.S. Army could be beneficial but are limited in their utility. Of the three different levels, the depot maintenance facilities are the most likely to use AM for prototyping. The depot maintenance facilities would have the ability to design repair parts that perform better than the parts they are replacing.

One way that the prototyping application could be used to increase efficiency is by enabling the production of major end items that cannot be produced by traditional

[172] Designing and printing prototypes would require a high level of skill and knowledge of CAD software designing and printer operation and manipulation.

manufacturing methods. The gas turbines designed by GE are just one example of how 3D printers enabled the production of a more efficient product.[173] Another example is the use of Topologically Interlocking Structures (TIS) that are produced using AM processes. Researchers from U.S. Army RDECOM are evaluating how to use TIS to make stronger and more lightweight ground vehicles.[174] A lighter vehicle would have several second and third order effects. The lighter vehicle would be more efficient and require less fuel. Less fuel for the ground vehicles equates to less frequent transportation and distribution of fuel to the end user. Less frequent transportation and distribution equates to an even further reduction in fuel consumption for the vehicles used to transport the fuel. Additionally, a lighter vehicle puts less stress on the other components of the vehicle. As a result, components such as suspension systems would be less likely to break. Parts that are less likely to break decrease the amount of maintenance required as well as decrease the amount of required repair parts. Less required repair parts reduces the overall logistics footprint, making the maintenance section lighter, smaller, and more responsive. Additionally, maintenance sections would not be reliant on the supply system infrastructure to order the repair parts once the on hand quantities are depleted. Another method of reducing the required number of repair parts is designing parts for major end items that do not have as many pieces. AM enables parts to be manufactured as one seamless component rather than multiple pieces that must be assembled, similar to GE's fuel nozzle for the CFM LEAP engine that reduced the part count from 18 to one.[175] An assembled part is subject to breaking at each connection, leading to more required repair parts.

The impact on Marine Corps logistics could potentially be quite significant if future major end items are designed with fewer moving parts and are smaller and lighter. Despite the great potential, the Marine Corps is unlikely to lead the effort in designing these major end items. The Marine Corps could, however, encourage industry to design the less logistically demanding products by ensuring its product requirements necessitate

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[173] Marshall, "Improving Manufacturing Competiveness."

[174] Holmes, "Advanced Manufacturing for the Army of the Future."

[175] Yang, "Metal Additive Manufacturing at GE."

smaller, lighter, and more efficient designs than current models. These newly designed products would ultimately increase Marine Corps logistics efficiency by decreasing overall demand. Senior Marine Corps leadership and acquisition professionals' knowledge and understanding of these benefits is essential to its future development.

B. TOOLING/SUPPORT AIDS

Unlike prototyping, using AM processes for tooling and developing support aids could improve current Marine Corps logistics procedures. The printers could be used to print drill jigs, molds for injection-molded parts, support brackets, or any number of products designed to assist maintenance efforts similar in nature to companies like Boeing and General Electric. This application could benefit maintainers at both the MEU and MEB, but would most likely provide the most benefit at the depot level of maintenance. This assumption is made based on the industry examples described in the previous chapter. As a result, the impact across DOTMLPF will only be analyzed at the depot level while referencing the comparative impact at the MEU and MEB level.

1. Depot

As mentioned previously, some depot level maintenance facilities already have 3D printers installed in their facilities, therefore the impact on DOTMLPF is mostly known. This assessment will consider the installation of multiple different types of printers (i.e. FDM, selective laser sintering, or powder-binder printing) at all depot maintenance facilities for the purpose of printing tools and support aids.

a. Doctrine

Installing multiple different printers at depot level maintenance facilities would not change doctrine. The printers would change current standard operating procedures and would have to be updated as necessary.

b. Organization

The impact on the organization as a result of installing 3D printers would be minimal. There would be no need to realign the personnel structure. A new section may need to be created for the AM section, but the overall impact is low.

c. Training

The impact on training is closely related to the impact on personnel. To achieve a necessary level of proficiency with the printers, the Marine Corps could either train existing personnel at the depots or hire new personnel that possess the necessary skill sets. The skill sets required for 3D printers include CAD software design and manipulation, printer operation, and printer maintenance. Personnel who are trained on CAD software should also be trained on printer operation since the two skill sets rely on each other. The printer operators should also be trained on basic user-level maintenance as well. There would be no need to perform intermediate and depot level maintenance on the printers because this should be part of the maintenance contract included with the purchase of the printer. Unlike MEUs and MEBs that are forward deployed, the depots located stateside would have the capability to call the manufacturer to send a service technician to fix the printer.

d. Material

The impact on material as a result of integrating 3D printers at the depot maintenance facilities for printing tools and support aids is minimal. To print the tools or support aids, the depot would require the raw materials for the printers. As discussed previously, the supply chain for the raw materials is not fully developed. The manufacturer of the printer is the sole producer of the raw materials for most of the printers. In addition to the raw materials for the printer, some processes require additional materials that are infused in the printed tool. These types of applications would necessitate the acquisition of the additional materials.

e. Leadership

Impact on leadership as a result of using printers to produce tools and support aids would be insignificant. Leadership would have to understand the capabilities of the printers and how they could be used to print tools and other support aids. They should also have the knowledge to determine when other methods of making the same products are quicker and/or more economical. Other than these few cases, there would be no additional impacts on leadership.

f. Personnel

As discussed during the training section, the only impact on personnel would be if the Marine Corps decided to hire personnel with the necessary skill sets vice training current personnel. The benefit of using printers at the depot level instead of at the MEU and MEB level would be that it requires fewer personnel because there are fewer depots than MEUs or MEBs. Furthermore, personnel turnover is considerably less frequent at the depot maintenance facilities. The MEUs generally operate on an 18-month rotation with personnel changing each time.[176]

g. Facilities

Compared to either the MEU or MEB, the impact on facilities would be less demanding. The depot maintenance facilities are not as constrained as shipboard space. The printers require a space for the actual printer, space to store the raw materials, and space to perform any post processing required. It is unlikely that new facilities would be needed to house the printers. The printers could even replace aging and outdated equipment to reduce the impact on facilities.

2. Summary

The impact across the full spectrum of DOTMLPF as a result of integrating 3D printers for the purpose of tooling and producing support aids would be minimal especially compared to the potential impact of integrating 3D printers at either the MEU

[176] "The MEU Cycle," 24th Marine Expeditionary Unit, accessed April 19, 2015, http://www.24thmeu.marines.mil/About/TheMEUCycle.aspx.

or MEB level for the same purpose. Furthermore, the benefit of using the printers for tooling and creating support aids would be much higher at the depot maintenance facilities. The lower impact and higher benefit would result in a considerably lower cost-benefit ratio in favor of integrating 3D printers at the depot facilities for tooling and support aids.

C. END PRODUCT MANUFACTURING

The ability to print parts on demand and on location would be a noteworthy step to alleviating several of the issues identified during the gap analysis. Printing repair parts could potentially reduce the total maintenance cycle time of repair processes that rely on parts to be shipped. It could also reduce the amount of repair parts a unit needs to transport. The 3D printers have the additional benefit of producing parts that are difficult to acquire or are produced by a single supplier. Even with these obvious advantages, it is important to understand the full impact of attempting to use 3D printers to manufacture repair parts prior to procuring them.

1. MEU

The organization poised to reap the most benefit of printed repair parts is the MEU. It is the smallest, most tactical unit of the three organizations. It would have the biggest positive impact and biggest impact across DOTMLPF when compared to the other organizations.

a. Doctrine

Incorporating 3D printers on the MEU to print repair parts would not change how the organization fights; therefore, impact on war fighting doctrine would be minimal. It would change how the MEU sustains itself; however, and those relevant publications would need to be updated as required. Furthermore, current maintenance publications do not mention AM and would therefore need to be updated if the MEU were to use 3D printers. The maintenance publications would need to include a list of approved uses of AM. They would also need to outline procedures for printing parts that have not yet been certified.

b. Organization

Implementing 3D printers at the MEU level would have little to no impact on the organization. There would be no need to reorganize the MEU or its maintenance capabilities to use 3D printers. The only impact on the organization is where the printers would be located. The printers could be assigned to each maintenance section resident in the command element (CE), ground combat element (GCE), air combat element (ACE), and logistics combat element (LCE) or the printer(s) may be assigned solely to the LCE where most organizational maintenance is performed. The most logical placement of the 3D printers would be with the LCE. This decision will become clearer once the impact on training and material are evaluated.

c. Training

The addition of 3D printers at the MEU level would have a noticeable impact on training. The proper use and maintenance of 3D printers involves three different types of training, CAD software design and manipulation, printer operation, and maintenance of the printer. CAD software design and manipulation includes the first two steps of the AM process described in Chapter II. The user must have basic knowledge of the CAD software that is coupled with the 3D printer. The user must be able to load files from a pre-determined database, have the ability to manually build the files using the software, or be able to create files using a 3D scanner. Once the blueprint for the file has been created and/or loaded to the CAD software, the user must convert the CAD file to a format that is recognized by the 3D printer.[177] This step is usually automated in the CAD software, but the user must know how to manipulate the file in the event of any errors. The CAD software design and manipulation training is highly technical and will require the user to have a base knowledge of computers and software prior to learning the more advanced skill sets. As 3D printing becomes more mainstream the software will become more intuitive and user friendly. Future software will be designed for users that do not

[177] The format recognized by 3D printers is generally either STL or AMF.

have prior experience nor have the desire to get training on how to use the software.[178] These changes would eventually lessen the amount of training needed by MEU personnel if needed at all.

The second type of training required is printer operation. This type of training includes the middle five steps of the AM process. As highlighted in the second chapter, the operation of the 3D printer is considerably more comprehensive than just pressing a single button to print the product. The user must know how to properly configure the printer to achieve the desired results. Most printers have the ability to change the resolution, layer thickness, and other key parameters that will drastically affect the outcome. The user must know how to properly choose the part placement and orientation to maximize the printer's efficiency and ensure a good quality surface finish. Additionally, the user must be trained how to properly store, handle, choose, and load the raw materials for the printer. The available materials range from plastic filaments to powdered metals and they all have different conditions in which they can be stored and procedures for handling. Companies such as 3D Systems are producing printers that have hands off powder handling. This ensures the powder does not get contaminated or be affected by atmospheric conditions.[179] The user must know what types of materials are required for each style of printer. Printers such as FDM have the capability to print with numerous different materials all with unique physical characteristics;[180] therefore, the user must know how to choose the correct raw material for the specific application of the part. Other skill sets required for this type of training include techniques of post processing. Depending on the AM process used, extensive post processing is required.

[178] John Hermann, "How to Get Started: 3D Modeling and Printing," Popular Mechanics, March 15, 2012, http://www.popularmechanics.com/technology/design/how-to/a11854/how-to-get-started-3d-modeling-and-printing/.

[179] Orringer, "Manufacturing the Future."

[180] "FDM Technology," Stratasys, accessed April 17, 2015, http://www.stratasys.com/3d-printers/technologies/fdm-technology.

This entails everything from removing support structures,[181] sanding, and even coating or infiltrating the printed part with another material.[182]

The third type of training required is maintaining the printer. As with all major end items in the Marine Corps, there would be three categories of maintenance: organizational, intermediate, and depot level.[183] Personnel on the MEU should be capable of performing both organizational and intermediate maintenance on the printer. Organizational maintenance includes preventive maintenance checks and services (PMCS) and other basic levels of maintenance. Users would have to be trained how to properly clean the printers after each build to prepare it for the next build. Organizational maintenance includes calibration and the repair or replacement of damaged or unserviceable parts.[184]

Like the integration of most new technologies, there would be a reliance on civilian experts to fill the void regarding training until Marines are trained appropriately. The amount of reliance on civilians would be inversely proportional to the impact on training. The more robust the civilian support structure, the least impact training would have. In order to become self-reliant, the Marine Corps would inevitably have to institute methods of training Marines on the three types of training required for 3D printing proficiency. The level of training would be based on the level of proficiency desired. If the Marine Corps desires its maintainers have the ability to manufacture intricate and high value repair parts, it should develop a comprehensive curriculum resident in its formal schools. If the Marine Corps desires that its maintainers only have the ability to print a limited number of non-critical repair parts then informal training via mobile training teams (MTT) and on-the-job training (OJT) might suffice.

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[181] AM processes with a powder bed do not require the removal of support structures.

[182] Applications that require the part to be non-porous may require the part to be coated with a separate material or resin.

[183] U.S. Marine Corps, *MIMMS Field Procedures Manual*, MCO P4790.2C (Washington, D.C.: Government Printing Office, 2012), 1–3.

[184] U.S. Marine Corps, *MIMMS Field Procedures Manual*, MCO P4790.2C (Washington, D.C.: Government Printing Office, 2012), 1–4.

In addition to the level of proficiency desired, the target recipients of the training would have to be chosen. While it makes sense that the Marines trained on 3D printers should be maintainers, it would be time consuming, labor intensive and very costly to train every maintainer. It also may not be feasible to train every type of maintainer. The senior maintenance officer or chief may need to prioritize the training. For example, the motor transport mechanics and the small arms repairmen may have priority over the other maintainers. The selected individuals would become the experts and would be responsible for advising and assisting the other maintenance sections to print repair parts as required.

The impact on training of integrating 3D printers at the MEU level would potentially be significant. According to researchers from ORNL, basic training consists of anywhere from three days of hands-on training to two weeks of training just for basic operation skills.[185] Its impact would vary greatly and would be dependent on the proficiency desired and the accepted level of reliance on a civilian support structure.

d. Material

The addition of 3D printers for the MEU would be a material solution to the gaps identified. The solution would have a generous impact on overall material as well. The most obvious impact on material would involve the supply chain. The ability to print repair parts on demand would alleviate the necessity to order parts not in the unit's class IX block. Instead of ordering the repair part, the MEU would have the ability to print the repair part. The range of parts the MEU would be able to print is dependent on the actual type of printer selected. The 3D printers would not eliminate the need for a repair part supply chain, but it would decrease reliance on it. Conversely, 3D printers would create a new burden on the supply chain in that the raw material for the printers would have to be shipped. This impact would be minimal because the raw material could be purchased ahead of time and stored on the ship. Proper planning prior to the deployment of the MEU would ensure enough raw material is embarked on the ship. Only materials that

[185] Amelia Elliot and Lonnie J. Love, "Overview of Additive Manufacturing Technologies for the Rapid Equipping Force: Final Report," Oak Ridge National Laboratory, (September 2014), 46.

were not forecasted would have to be ordered. The supply chain of raw materials could be a source of frustration. As mentioned in Chapter II, some raw materials are hard to procure. Furthermore, some materials are only provided by a single source, usually the printer's manufacturer. These are all items to consider when selecting a printer to install on the MEUs.

Maintenance would also impact the category of material. When evaluating maintenance, it is important to look at maintenance from two different perspectives. The first perspective is the maintenance of the printer and it was previously discussed during the impact analysis on training. The second perspective is the impact of the 3D printer on the MEU's maintenance operations.

e. Leadership/Education

The impact on the leadership and education by integrating 3D printers at the MEU level would be minimal. The leadership should understand the capabilities and limitations of 3D printers, but there would be no requirement for the leadership to understand how to operate the systems. They should have the knowledge to employ the printers in the most effective way possible based on the recommendations from their maintainers. Additionally, the leadership would have to understand how 3D printers fit into the complete maintenance structure. When faced with the decision whether to print a part that has not previously been certified, the leader would have to be able to appropriately apply operational risk management (ORM) techniques to determine if the risk would be worth the benefit. This decision process would be the most important role the leadership would play in the integration of 3D printers at the MEU level.

f. Personnel

The only impacts on personnel as a result of integrating 3D printers at the MEU level have already been examined during the analysis of organization and training. The most significant impact on personnel would be that subject matter expert (SME) civilians would have to be integrated as well. The civilian support structure would not necessarily have to be attached to the MEU as long as there were multiple reliable communication channels between the civilians and the maintenance personnel on the MEU. The model developed by the REF for their Expeditionary Labs is a good starting point for the development of the required civilian support structure.

g. Facilities

When analyzing the potential impact on facilities of integrating 3D printers at the MEU level, it is important to understand that the specific printer that is chosen makes a substantial difference. Another aspect that makes a considerable difference is the employment of the printer. The printer could either be restricted to employment on the ship or designed for transportation ashore to be used in a forward deployed environment. The size of the printer would vary the impact of integration. Some printers such as FDM printers can be relatively small and can fit inside of a pallet container (palcon);[186] whereas other printers such as the Cincinnati BAAM are too large to even fit into a twenty foot International Standards Organization (ISO) shipping container.[187] If the desire is to employ the printer off of the ship, it must be restricted in size. A MEU only has the capacity to transport containers the size of a twenty foot ISO container and smaller; therefore, the printer selected should be able to fit inside of the container. Similarly, there is limited space aboard amphibious ships. It would have to fit into existing vacant spaces or it would have to replace equipment currently installed. Another consideration is power requirements. Additive Manufacturing processes that involve the use of high powered lasers such as stereolithography and selective laser sintering would require considerably more power to operate than AM processes that do not use lasers. Power consumption would be more of a concern for off ship employment, but should also be considered when installing 3D printers on the ship and using its existing power grid. Environmental considerations would also impact facilities for the 3D printers. Every printer has its own operating parameters, but almost all of them require relatively high control of the temperature and humidity. The printers would most likely have to be

[186] Printers such as the Stratasys Mojo have dimensions as small as 25” x 18” x 21” and weigh only 60 pounds, but its build size is limited to 5” x 5” x5” and can only print with one material (“Mojo,” Stratasys, accessed April 17, 2015, http://www.stratasys.com/3d-printers/idea-series/mojo.).

[187] The Cincinnati BAAM’s dimensions are 35’ x 13’ x 11’ and weighs 40,000 pounds (“Big Area Additive Manufacturing (BAAM) Specifications,” Cincinnati Inc., accessed March 13, 2015, http://www.e-ci.com/baam-specifications.).

installed in spaces that have air conditioning to help control these factors. The ship's movement at sea would also determine the impact of installing printers. Most printers are affected by motion when constructing parts; therefore, they should be installed in locations aboard the ship that are the most stable. The company Made In Space manufactures a printer called the Zero-G Printer that is not affected by motion. It supplied the printer that is currently on the international space station.[188]

In addition to space requirements for the printer, there are also space requirements for the raw materials. The impact of storing the raw material would be minimal since it can be stored in the space originally identified to store the repair parts that the printers would be able to print. Unlike most repair parts, the raw material should be stored in a place with specific environmental considerations that may limit the areas it could be stored.

The impact on facilities of integrating 3D printers at the MEU level would largely be dependent on the specific printer that is chosen for installation. To reduce the impact on facilities, it would be imperative to acquire printers that are small enough to be installed in existing spaces on ship or be transported in regular shipping containers and to have relatively low power consumption.

2. MEB

The MEB would also greatly benefit from using 3D printers to produce repair parts for major end items. Its overall impact would be similar to that of the MEU; therefore, only the differences will be discussed.

a. Doctrine

The impact of integrating 3D printers at the MEB for the use printing repair parts would be the same as the impact on the MEU. The printers would not affect how the MEB fights, only how it sustains itself. All maintenance related publications would need to be updated.

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[188] "Zero-G Printer," Made In Space, accessed April 16, 2015, http://www.madeinspace.us.

b. Organization

Similar to the MEU level, the impact on the MEB organization would be nonexistent. There are more individual units that could benefit from the printers, but would not necessitate any structure changes.

c. Training

There are only three standing MEBs compared to the seven traditional MEUs[189] which means approximately half as many personnel would need training when compared to the MEU. The three different categories of training would still apply to the MEB and so would the methods of training. One advantage the MEB has over the MEU regarding training is the number of organic maintenance units. A small cadre of highly skilled 3D printer operators/maintainers at the Command Element (CE) or Logistics Combat Element (LCE) would have the ability to train considerably more maintainers when compared to the MEU. These factors are the reason that the impact of training on the MEB would be slightly lower than the impact on the MEU.

d. Material

As with the previous categories, the impact on material would be similar to the MEU. Compared to the MEU; however, the impact would be less. The MEB is designed to self sustain itself for twice as long as the MEU and is comprised of approximately nine times as many personnel; therefore, its logistics footprint is considerably larger than the MEU. As a result of its much larger footprint, adding a few printers to the MEB would have a much lower relative impact. It has the potential to have a much larger positive impact on the supply chain of repair parts because of the increased number of units the printers could benefit. All subordinate units could reduce the quantity of repair part in their class IX blocks with the understanding that the organic 3D printers could produce the repair parts if required. If integrated with the LCE, the printers would enable them to be an on demand parts supplier, lessening the burden on the supply chain. Another benefit of the MEB is that the Marine Corps would not have to procure as many printers

[189] U.S. Marine Corps, *Organization of Marine Corps Forces*, MCRP 5–12 (Washington, D.C.: Government Printing Office, 1998), 1–4.

as it would if it were to implement printers at the MEU level. While similar to the MEU, the impact on material would be less when printers are integrated at the MEB.

e. Leadership

The only difference in the impact of implementing printers at the MEB level vice the MEU is the level of leadership that would require education. For the MEB, commanders at the regimental level would need to know how to properly incorporate the systems in their logistics plans and would need to have the knowledge required to make decisions on certification procedures.

f. Personnel

When compared to the MEU, the impact on personnel would be less. The printers would still require the use of civilian SMEs, but there would be fewer civilians required because there are less MEBs. Additionally, the MEBs are not always permanent structures and are not constantly deployed like the MEUs. As a result, the Marine Corps could limit the required number of civilians by using SMEs from LOGCOM when a MEB deploys.

g. Facilities

The same considerations for the MEU would be valid for the MEB when analyzing the impact on facilities. The only other consideration for the MEB is whether it would be beneficial to position 3D printers on one or both of the Maritime Prepositioning Ships Squadrons (MPSRON). If the MPSRONs had 3D printers, they would also require personnel trained to maintain the printers, which would impact the previous category, personnel.

3. Depot

The impact of integrating 3D printers at the depot level for the purpose of producing repair parts would not be any different than if the printers were installed for the purpose of producing tools or support aids. Consequently, its impact across DOTMLPF will not be analyzed. The only foreseeable difference is the impact on organization and personnel. If the printers were used to manufacture all parts that currently have a single source of supplier (one of the identified gaps), the depot would have to create an organization that coordinates with the Defense Logistics Agency (DLA) to reconcile requisitioned parts, prints parts, and ships the parts to requesting agencies. The new sub organization would require new personnel to fill the void. While certainly beneficial, it may not be the most feasible course of action.

4. Summary

For the application of printing repair parts, the biggest overall impact across DOTMPLF would be at the MEU level, followed by the MEB. The MEU would also be the level that would benefit the most from 3D printers. The ability to print repair parts at any remote location would be a force multiplier and has the potential to greatly lessen its dependency on a lengthy supply chain. Since it would have both the highest potential positive and negative impact, it is not completely clear whether the MEU would be the best level to implement printers for the purpose of printing repair parts.

D. MEDICAL

Despite being used for several years, 3D printers do not currently offer much benefit if implemented at either the MEU or MEB level. The capabilities of the current medical 3D printers would be best suited at Level IV and above medical facilities. However, if medical printing applications continue to advance, it may be worthwhile installing printers on the MEU and MEB for medical purposes. The ability to print organs on demand as needed such as skin would significantly increase the medical capabilities without increasing the footprint. Most of the negative impact of integrating medical printers would affect the U.S. Navy not the Marine Corps. The U.S. Navy would be responsible for any organizational changes and to train their personnel as required. The only direct impact on the MEUs or MEBs would be the impact on facilities. The MEUs and MEBs would be responsible for ensuring adequate facilities are allocated to the medical units. Space and power requirements would have to be considered.

E. FOOD

Another application that could potentially provide a benefit to the Marine Corps in the future is printing food. Its current maturity level is limited and would not provide any utility to the MEU or MEB; however, once the technology advances to the point when printers are able to make foods that are highly nutritious and can be printed on demand, it would enhance logistics at every level including the MEU and MEB. Printed food that provides only the needed nutrients and nothing extra would weigh less than the rations currently in use. Additionally, since the nutrients could be tailored to the situation (i.e., cold weather) there would be no need for enhancements or supplements further reducing weight and storage requirements. In addition to weight, current feeding programs require extra fuel and water. The Tray Ration Heating System (TRHS) that is designed to feed 250 Marines requires about two gallons of fuel and 20 gallons of water every day not including the extra water used for cleaning the system.[190] These requirements are for serving Unitized Group Rations-Heat and Serve (UGR-H&S). When using the Unitized B-Ration (UBR), the water requirements increase to 187 gallons a day not including water required for sanitation.[191] Another advantage that printing food would have is scalability. Unitized rations are designed to feed groups of 50 or 100; therefore, food is wasted unless the supported unit happens to be a multiple of 50 or 100.[192] When combined, these weight and space savings could add up to substantial reductions in logistics.

The overall impact across DOTMLPF would resemble that of the impact of integrating printers to produce repair parts. If printers were implemented at either the MEU or MEB to print food, they would have minimal impact on doctrine. Like the other applications, it does not affect how the organization would fight, only how it would sustain itself. Applicable publications would have to be updated. It would require no changes to the current organization. Food service personnel in each unit would be

[190] The TRHS require 30 gallons of fuel to serve 700 Marines for seven days. Each TRHS requires 10 gallons of water per use and additional water for sanitation (U.S. Marine Corps, *Marine Corps Field Feeding Program*, MCRP 4–11.8A (Washington, D.C.: Government Printing Office, 2004), 4–4 and 4–5).

[191] MCRP 4–11.8A, 4–5.

[192] Ibid., 2–3.

responsible for the operation of the printers. There would be a sizeable impact on training, similar in scale to the impact of using the printers to produce repair parts. As the system parameters and raw materials are completely different, the scope of the training required is yet to be determined. Another weighty impact of integrating food printers would be on material. As discussed earlier, the printers could potentially lessen the required logistics to feed a Marine unit. The raw food material for the printers would replace the UGRs currently in the supply chain. As with all new systems, maintenance would need to be considered. The impact on leadership would be insignificant. The unit's logistician would be responsible for developing a feasible feed plan, incorporating the food printers based on recommendations from the mess chief. Unlike using 3D printers for producing repair parts, there would be no need for a commander to make certification decisions. The mess chief would be more than capable to ensure safe handling of the printed food. The only impact on personnel would be the addition of civilians for the purpose of maintaining the printers if necessary. It is not possible to accurately determine the impact of food printers on facilities. The printers designed for military use would most likely not resemble the current food printers on the market since those printers are mostly used print with sugars and chocolates. It is reasonable to assume that the printers would not impact facilities more than current feeding systems. In fact, storage requirements might decrease based on the efficiencies gained by using printed food.

While too early to determine the exact impact across DOTMLPF as a result of integrating printers to print food, it appears the benefits may outweigh the costs. A more thorough analysis can be completed after the U.S. Army conducts further research.

F. NETWORK OF PRINTERS

The Marine Corps does not necessarily have to invest in 3D printers to reap their benefits. The Marine Corps could utilize existing printing services around the world to print needed items as necessary. The consulting firm, Deloitte Consulting LLP, recently mentioned this concept and it merits discussion.[193] The concept is very similar to the existing supply chain structure except that instead of using suppliers around the world, it

[193] Joyce, "3D Printing Supply Chain Overview."

uses companies located around the world that have printers to produce the requested item on demand. This would alleviate the Marine Corps from procuring and maintaining their own printers; therefore, the impact on DOTMLPF would be nonexistent compared to the impact of actually integrating printers. It would have no impact across DOTMLPF. The only impacts would be on training, material, and leadership. Regarding training, supply Marines would need training on how to locate and request parts from the printing services. In order to reduce the impact on training, the Marine Corps could accept a larger impact on material by developing increased functionality within its parts requisitioning and maintenance system, GCSS-MC, to automatically select the most efficient method of requisitioning a part whether it is through existing supply chains or utilizing a nearby printing service. With this built-in functionality, the supply Marine would use existing procedures to requisition parts and would not require additional training. The only impact on leadership and education would be to ensure commanders understand the potential benefits and risks of using distributed printers. One of the risks that the commanders would need to be cognizant of would be the potential to requisition uncertified parts and components from one of the printing services. This risk exists in current supply chains and would most likely exist in a newly created structure until it is fully established.[194]

As a result of its minimal impact across DOTMLPF, the concept of using distributed printing services around the world is a solid alternative. It would not be as responsive as actually owning and operating 3D printers, but it has the potential to be more responsive than relying on a single supplier 4,000 miles away. The concept could easily be implemented and could serve as an intermediate step until the Marine Corps fully integrates 3D printers if it chooses to do so. There are considerable risks that must be evaluated prior to using these outside suppliers.

[194] Lee Ferran, "Counterfeit Chinese Parts Slipping Into U.S. Military Aircraft: Report," ABC News, May 22, 2012, http://abcnews.go.com/Blotter/counterfeit-chinese-parts-slipping-us-military-aircraft-senate/story?id=16403599.

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V. RECOMMENDATIONS AND CONCLUSION

A. SUMMARY

The goal of the research was to examine how 3D printers could be integrated into the Marine Corps to improve logistics efficiency. This was accomplished by examining the different types of AM processes including fused deposition modeling, selective laser sintering, powder-binder printing, stereolithography and numerous other processes. The research identified the processes' strengths and weaknesses. The research also examined five basic applications of 3D printers and how each could benefit the Marine Corps. Lastly, the impact across DOTMLPF as a result of integrating 3D printers at several levels was analyzed to determine where the Marine Corps should incorporate the printers. The results combined with the current limitations of the technology were considered to make the determination of how 3D printers could improve Marine Corps logistics. These recommendations are listed in the next section; however, there are several limitations of the printers that should be addressed before the Marine Corps considers widespread adoption of the technology.

1. Policy Changes

The first and potentially most important limitation that should be addressed prior to widespread adoption is the lack of established certification and qualification procedures. Traditional manufacturing methods like cast molding and milling are strictly governed by established certification and qualification procedures that ensure the quality of the end product. Everything from the source of the raw material to the actual procedure itself is controlled. If a company follows the specific certification and qualification procedures, the client knows the product is as specified.[195] There are no corresponding procedures for AM. Fortunately there is significant progress towards developing standards as discussed in Chapter II. With assistance from organizations like NASA,

[195] The lack of qualification and certification standards for additive manufacturing was the most discussed topic at the Additive Manufacturing for Government Conference held from 8–10 December 2014.

standards may be developed in the next couple of years.[196] When NIST publishes approved standards, then the Marine Corps should not hesitate procuring 3D printers according to the recommendations in the next section.

A second policy related reason that should be addressed is the legal ramifications associated with AM. Even though the military owns equipment with numerous parts, it does not necessarily own the intellectual property (IP) for those parts. It is against the law for the Marine Corps to scan a repair part and subsequently produce it with a 3D printer if it does not own the IP for the repair part.[197] Before the Marine Corps uses 3D printers for end part manufacturing, it must fully investigate the IP agreements with its parts suppliers to avoid legal battles. As the Marine Corps continues to procure new equipment it is recommended that the contract with the manufacturer clearly give the right to reproduce repair parts.

2. Technology Improvements

In addition to policy changes, there are needed technology improvements. The first technology improvement is closely related to the first policy related issue. Current 3D printers do no produce reliable results. The same printer using the same CAD file does not always produce the same results. While the product looks exactly the same on the outside, the interior structure and microstructure is not always the same.[198] The inconsistencies further highlight the importance of established certification and qualification standards for the industry. If the printers were highly reliable, it would mitigate the need for standards, but this is not the case with printers on the market as of 2015. Fortunately, companies are improving the printers' reliability. Several companies are experimenting with processes that closely monitor the printer while it is building the product. One company is even developing a closed loop process that makes minor changes throughout the build to compensate for any distortion along the way.[199]

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[196] Swanson, "Ensuring Quality for Spacecraft Applications."

[197] William J. Cass, "Intellectual Property Issues In Additive Manufacturing," (lecture, Additive Manufacturing for Government Conference, Washington, D.C., December 10, 2014).

[198] Gentry, "Acquisition Perspective."

[199] Edwards, "America Makes and AFRL Award Million Dollar Contracts."

The last subject that should be considered before widespread adoption at this time is the rapid advancement of the technology. This may sound counterintuitive, but when considering the rather slow DOD acquisition process it is not feasible to procure a printer that will not be obsolete by the time it is distributed throughout the Marine Corps. The rapid pace of advancement is one of the main reasons that NASA is not procuring their own printers.[200] Researchers from ORNL suggest periodic evaluations of the technology every year, stating that it is rapidly evolving.[201] By the time printers are actually fielded to the intended units, they will possess outdated technology. Additionally, prices for the printers are dropping significantly.[202] Therefore, the Marine Corps will not only have outdated technology, but will be paying significantly more than market price for the old technology by the time the printers are in use. By the time the other limitations are addressed, the prices and advancement of the technology may stabilize enough to safely invest in AM.

There are several other less significant reasons that should be considered, but they are not important enough to stop the procurement of 3D printers.[203] Issues such as the lack of certification and qualification standards, inconsistent product results, uncertain market for 3D printers, and legal issues are all significant problems that should be addressed prior to a full implementation of 3D printers throughout the Marine Corps. As soon as these problems are corrected, the Marine Corps should pursue further utilization of 3D printers beyond the limited uses at a couple of its maintenance facilities. The purpose of the rest of the chapter is to identify which type of process should be used, the applications it should be used for, and where the printers should be located to benefit to partially fill the gaps in Marine Corps logistics that was identified in the first chapter.

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[200] Swanson, "Ensuring Quality for Spacecraft Applications."

[201] Elliot and Love, "Overview of Additive Manufacturing Technologies."

[202] Thomas Campbell, et al., "Could 3D Printing Change the World?" Strategic Foresight Initiative, (October 2011), 9.

[203] Other reasons that 3D printers are not recommended include raw material supply chain maturity, questionable durability of the printers in austere conditions, and throughput.

B. RECOMMENDED USE OF ADDITIVE MANUFACTURING

1. Type of Process

After the technology advances and the limiting factors are appropriately mitigated, the Marine Corps must decide which process is best suited to fulfill its requirements. The numerous AM processes vary greatly in the way they function and the results that they produce. It is important to understand the key differences between the processes to make an informed decision on which type of process to invest in. Some of the newer technologies are tempting, but they pose a significant risk that should not be overlooked. Processes including stereolithography, selective laser sintering (for polymers, metals, and ceramics), powder-binder printing, and fused deposition modeling are prevalent in the civilian industry and have proved to be reliable over the course of numerous years and applications. Leading companies including GE, Lockheed Martin, and Boeing use these processes.[204] Additionally, the companies that manufacture these printers are well established, especially in the AM industry.[205] As a result, the Marine Corps should only consider these four processes. Each of the processes has its advantages and disadvantages. In an attempt to select the most appropriate process, the four types of AM were analyzed in Chapter II. The results from the comparison are summarized in Table 1.

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[204] Each of these companies presented their success stories during the Additive Manufacturing for Government Conference in Washington, D.C., December 8–10, 2014.

[205] Stratasys was established in 1989 (John Cobb, "The Next Industrial Revolution," (lecture, Additive Manufacturing for Government Conference, Washington, DC, December 8, 2014).). 3D Systems was also established in 1989 (Orringer, "Manufacturing the Future.").

Table 1. Comparison of AM processes (after Grimm, 2004)

	Stereolithography	Selective Laser Sintering	Powder-binder	Fused Deposition Modeling
Materials	24 materials, multiple supply sources	Largest range of materials including metals, proprietary	3 powders, but can be infiltrated with metal alloys	Second largest range of materials, proprietary mixtures
Accuracy	Highest	Next highest, but prone to shrinkage	Least	Third highest
Stability/ Durability	Least, distortions over time due to environmental conditions	Highly stable, resistant to both heat and moisture	Only stable when infiltrated with another material	Most stable, resistant to both heat and moisture, comparable to injection-molded
Surface Finish	Highest	Poor	Poor	Poor
Maximum Size	59”x30”x24”[206]	22”x22”x30”[207]	30”x16”x16”[208]	36”x24”x36”[209]
Time of Production	Relatively quick	Relatively quick	Quickest build, but lengthy post-processing	Slowest

Even when organized in a different manner, there is no clear best process. If speed is the most important key performance parameter, then a powder-binder printer is the best choice. The powder-binder printer, however, is the least accurate of all of the processes. The products produced using this method are not as durable or stable unless they undergo a separate process to infiltrate them with another material such as a metal alloy. The extra processing negates some of the time saved during the production of the part. If accuracy and the quality of the surface finish are the most important key performance parameters,

[206] 3D Systems, “ProX SLA Series.”

[207] 3D Systems, “SLS Production Series.”

[208] ExOne, “S-Print Technical Specs.”

[209] Stratasys, “Fortus 900mc.”

then a stereolithography printer is the best choice. Despite a high initial quality, these parts degrade over time, especially when exposed to environmental conditions including heat and moisture. There are minimal products in the Marine Corps' inventory that are not exposed to either heat or moisture; therefore, a stereolithography printer may not be the best option either. In comparison, FDM printers produce highly stable parts that are also very accurate. On the negative side, FDM printers are the slowest of the processes and the surface finish is very poor. FDM products require significant post processing to smooth the outer edges as well as remove support structures. If range of raw materials is the most important key performance parameter, selective laser sintering printers may be the best option. Its range of materials includes strong plastics, stainless steel/bronze alloys, and flexible rubber-like materials. Of the four processes, selective laser sintering is the only process that prints with metal alloys. Powder-binder printers use polymers, but are later infiltrated with a metal alloy. Similar to FDM, parts produced in a selective laser sintering printer have poor surface finish quality. The parts are also subject to some shrinkage immediately after production. After the initial shrinkage, the parts rival FDM parts for stability and durability. The selective laser sintering parts are resistant to both heat and moisture. After all factors are considered including the environment and climates the Marine Corps operates in, powder-binder printers are not the best option. The parts are not as accurate and require significant post-processing to include infiltrating the printed parts with a second material. Stereolithography printers are also not the best option due to the tendency for the parts to distort over time when exposed to certain environmental conditions. With those two processes eliminated, that leaves FDM and selective laser sintering. While not perfect, these two processes offer the best performance with the least tradeoffs. The most significant disadvantage for these printers is the supply chain of the raw material. As of 2015, the two printer manufacturers are the only source of supply for the raw material required by the printers. In addition to a thorough maintenance contract, the Marine Corps needs to include procedures that ensure the supply chain is sustainable if it procures printers from either of these manufacturers. If the company is not able to guarantee a sustainable supply chain, it makes no sense to procure the printers.

In addition to FDM and selective laser sintering printers, there are two additional technologies that will be very beneficial to the Marine Corps when they are fully developed. The first technology is an AM process called cold spray manufacturing. This process, discussed in Chapter II, has the potential to be 1,000 times faster than either FDM or selective laser sintering processes. However, the biggest advantage that cold spray manufacturing offers is the ability to print material directly onto a part or tool.[210] If a wrench breaks, cold spray manufacturing would allow a maintainer to fix it by adding more material to the affected area. The Marine Corps should consider the technology once it is fully developed. The second technology that could be very useful to the Marine Corps in the future is the BAAM system that ORNL and Lockheed Martin are developing. Not only will it reduce the operating costs,[211] BAAM may be able to print components that are unbounded in size.[212] A printer with an unlimited build size is extremely valuable to the Marine Corps. It would enable the Marine Corps to build bulky items on site that are costly and inefficient to ship via the supply chain.

2. Applications

There are five basic applications for 3D printers that are useful to the military. Prototyping, tooling, end product manufacturing, medical uses, and food printing each have the potential to increase the efficiency of logistics whether it is in a direct manner or indirectly. Chapter III discussed numerous case studies for each of the five applications. As a result of its relative immaturity, the application of printing with food does not offer the Marine Corps any benefit. In its current state, the printers can only make simple items, none of which can replace any of the foods currently consumed. Printing food does, however, have the potential to drastically change how the Marine Corps sustains itself when it is fully developed. Class I supplies (food and water) exhaust organic resources quickly. Any effort to reduce the amount of class I required to sustain a unit is

[210] Jackson, "European Space Agency."

[211] According to the Department of Energy presentation on December 10, 2014 at the Additive Manufacturing for Government Conference, the cost of raw materials for BAAM could be reduced by as much as 50 times compared to filament feedstock.

[212] Holshouser, "Out of Bounds Additive Manufacturing," 15.

worth considering. If either the U.S. Army or the civilian company contracted by NASA is able to successfully design and produce a printer capable of providing highly nutritious meals tailored to its recipients, then the Marine Corps should procure it. The research is in its early stages; therefore, it will not benefit the Marine Corps for several years.

Like using 3D printers for printing food, using 3D printers for medical purposes does not provide the Marine Corps much value as it is used today, especially at the tactical level. The only substantial advantage that medical grade printers potentially provide the Marine Corps is the capability to print skin directly on a person's wound. The printer is still under development and is not certified for use as of 2015. The Marine Corps should encourage U.S. Navy medical to coordinate with AFIRM for the continued development of the system. A printer capable of printing skin directly on a wound could conceivably give trauma centers the capacity to appropriately treat injured Marines closer to the point of injury. The U.S. Navy would have to invest in this system for it to benefit the Marine Corps. It would procure, maintain and employ the system based on Marine Corps operations. The printer's negative impact on the Marine Corps would be insignificant, but its potential for positive impact could be great. The Marine Corps needs to monitor the printer's progress and influence its production if able.

In the civilian industry, printers used for prototyping purposes save companies a substantial amount of time and money. It aids their research and development and expedites the time to production. The 3D printers enable the companies to design systems that are otherwise not achievable with traditional manufacturing methods. The technology affords them the opportunity to efficiently make minor design changes to meet their objectives. For some companies, the printers make them more self-sufficient by not having to outsource to another company to make their prototypes. Even the U.S. Army benefits from using 3D printers for prototyping. Their research organizations as well the REF use the printers to advance their research and to develop innovative solutions to problems on the battlefield. The Marine Corps could also benefit in this capacity; however, the benefits may not outweigh the costs associated with using printers for the sole purpose of prototyping. As identified in Chapter IV, there is a significant impact on units when integrating printers. It is a weighty investment for a system that may only produce a few worthwhile products. Furthermore, the new products may not improve logistics in the same magnitude as the examples in Chapter III. This does not mean that the Marine Corps is not able to reap the benefits of using 3D printers for prototyping. To reduce the impact, the Marine Corps could establish an agreement with the U.S. Army to use the REF's assets, most notably its Expeditionary Labs. The Marine Corps could institute a program that solicits novel technological solutions to problems from Marines in the operating forces. The solutions are then vetted through the science and technology sections of each Marine Expeditionary Force (MEF) to Combat Development and Integration (CDI). The CDI then forwards the solutions to the REF to develop the prototype. These procedures are sustainable for CONUS operations, but can be expedited if in a theater of operations like OEF or OIF. If Marine Corps units are deployed to the same theater as the Expeditionary Labs, then the units could submit their plans directly to the lab for prototyping. Cross service integration is seldom simple nor seamless, but as the DOD budget decreases, solutions to mitigate duplications of effort should be considered even if they require more coordination.

Another means of reaping the benefits of using 3D printers for prototyping is to convince and incentivize defense contractors to use the printers for prototypes of systems they are developing for the Marine Corps. Rapid prototyping would not only bring the new systems to production quicker, it has the potential to make the systems lighter and more efficient. As discussed earlier, lighter and more efficient designs have second and third order effects that decrease demand on the logistics infrastructure, making the unit more efficient. In addition to making the systems lighter and more efficient, 3D printers facilitate designs that are stronger and more durable that can withstand the demands of a combat environment decreasing the likelihood of breaking and requiring corrective maintenance.

Unlike the other applications, the Marine Corps is already using 3D printers for the purpose of tooling. Its use to date is minimal and is only at a couple of locations. The Marine Corps could easily integrate more printers for tooling applications. Just like prototyping, there are numerous successful examples of tooling assisted by 3D printing in the civilian industry. There are failed attempts at using 3D printing for tooling such as the

Joint Strike Fighter, but the Marine Corps can learn from those mistakes. Instead of using the printers to manufacture tools that require strict specifications such as the aviation community, the Marine Corps can use the printers to make tools like the wrench printed at the International Space Station. The Marine Corps can also use the printers in conjunction with traditional manufacturing methods to make the overall process more efficient, similar to the case of the damaged nose cone on the AV-8B Harrier. The printers can produce the molds for cast injection molded tools and parts.

The last application, end product manufacturing, is the application that initiated this research. The idea of printing repair parts on demand is a novel idea that could drastically impact Marine Corps logistics. The Marine Corps tends to operate in environments around the world that are not always the most conducive to ordering repair parts. The supply chains are not always established and when they are, they can be lengthy. Even after a decade of combat operations in Iraq and Afghanistan, parts requisitioning was a long process. Every day a piece of equipment is inoperable because of a repair part is another day that a unit's overall capability is degraded. The best maintainers in the Marine Corps cannot properly fix a piece of equipment without the right repair parts on hand. Knowledgeable and experienced maintenance officers and chiefs can decrease the chance of not having the right repair part by properly planning and selecting the appropriate repair parts for inclusion in the unit's class IX block. They cannot, however, plan for every scenario and are often limited on the amount of repair parts they are authorized to pack due to space and weight limitations. Printers designed to manufacture repair parts may be the solution for this dilemma. This increased capability does not come without substantial costs as evident from Chapter IV, but compared to other applications it offers a substantial advantage. The primary application of the printers should be to manufacture repair parts and other components. The printers need to be incorporated in a logical and progressive manner. For example, the first printed repair parts should not be the most complicated designs. The Marine Corps should start with simple non-critical repair parts made out of plastic. After lessons are learned and procedures are perfected, the printers could be used to print more complicated designs and eventually print products using metal alloys. If certification and qualification standards are not yet established, the printers should only be used to produce non-critical repair parts.

Of the five applications, tooling and end product manufacturing provide a considerable benefit compared to cost and negative impact. It is important to understand that printers that are procured for a specific application are not limited to that one application. For example, a printer located with the maintenance section that is used to print repair parts can still be utilized to print prototypes and models. There is nothing preventing the same printer from printing a rubber-like seal in one build followed by a realistic model of a building for a terrain model right afterwards. Obviously food and medical printers are application specific and are not used for other types of applications.

3. Level of implementation

The purpose of Chapter IV was to examine the impact across DOTMLPF of integrating 3D printers at the MEU, MEB, and depot maintenance facility level to assist in determining where the technology should be implemented to increase logistics efficiency with the least negative impact. The greatest impact is on the MEU, the smallest, most tactical unit. The next biggest impact is on the second smallest unit, the MEB, followed by the depot maintenance facilities. The printers provide the most benefit to the MEU, followed by the MEB, and finally the maintenance facilities. Therefore, it is not readily apparent as to where the Marine Corps should integrate printers. There are a few printers already in use at some of the depot maintenance facilities. Using the printers at the depot level maintenance centers is a solid starting point. It is a relatively controlled environment with civilian expertise and substantial resources compared to the rest of the Marine Corps. The civilians operating the printers are afforded the opportunity to hone their skills and learn lessons. They will be critical when it comes time to distribute printers down to other levels. While it does not offer as substantial of a benefit as it would at the MEU level, the printers still provide a needed capability. As highlighted with the example of the AV-8B Harrier in Chapter III, the printers are reducing total maintenance cycle times. Based on the minimal negative impact and obvious benefits, the

Marine Corps should procure 3D printers for the rest of its high-level maintenance facilities.

The MEU should be the next level of unit that receives 3D printers if they are not already installed on the ships. The Marine Corps should coordinate with the U.S. Navy to ensure there is no duplication of efforts. To reduce costs and impact, the Marine Corps should influence the U.S. Navy to install printers on all of its amphibious ships. If it does not install printers, the Marine Corps should equip every MEU with a 3D printer. The trained civilians from the maintenance facilities with 3D printers will serve as the SMEs aboard the MEU. If it is not possible to send the civilians on the MEU, the Marine Corps should establish a support structure at the depot maintenance facilities that the maintainers on the MEU can contact for assistance. This concept is similar to the one established to support the U.S. Army's Expeditionary Labs deployed to Afghanistan in 2012.[213]

The next unit in line for 3D printers is the MEB; however, instead of distributing the printers to each of the MEBs and eventually installing them on the maritime prepositioning squadrons (MPSRONs), the printers should be distributed to each of the three Maintenance Battalions resident in each of the MEFs. If one of the MEBs is mobilized and deployed, it could deploy with the printer from the corresponding Maintenance Battalion. Because the MEBs are not often deployed, this would ensure the valuable asset is actually utilized and provides a quicker return on investment vice sitting in a storage unit or on one of the maritime prepositioning ships (MPS). It would also enhance the printer operators' level of proficiency on the systems.

Unlike other types of 3D printers, the food printers are an immature technology that is not ready for adoption by the Marine Corps. When food printers are ready for integration, they should be distributed first to the MEUs. After the MEUs are sufficiently resourced with the printers, they should be distributed to the Food Service Company in each Marine Logistics Group (MLG). The food printers at the Food Service Company would deploy with the MEB if it is mobilized. While in garrison, the MEF could task the

[213] Cox, "Mobile Labs."

MLG to support division training exercises to maintain proficiency on the system and to develop standard operating procedures for employment of the systems.

Chapter IV also mentioned the idea of relying on a network of 3D printers located throughout the world. These printers would not necessarily be government owned assets, but would be civilian companies that offer on demand printing services. A client simply places an order for a specific part and the company prints it and ships it to the client's location.[214] This process is similar to the existing supply chain except that there are no warehouses with parts, but warehouses capable of producing repair parts on demand. Due to its minimal impact across DOTMLPF, it is a worthwhile consideration. Further research is recommended to determine the feasibility of relying on such a network to augment the existing supply chain.

C. SUGGESTED AREAS OF FUTURE RESEARCH

During the course of this research, costs were not a major factor in deciding which printers are best suited for the Marine Corps. Factors such as quality, dependability, and utility were the focus. Prior to the Marine Corps purchasing printers, the appropriate organization must conduct a comprehensive cost analysis. Even though there are numerous examples from the civilian industry that cite substantial cost savings as a result of using 3D printer, it does not mean that it will translate to cost savings for the Marine Corps. As identified in Chapter III, the majority of the savings were realized during prototyping applications. The Marine Corps would most likely not use 3D printers in this capacity as widely as the civilian industry. It would most likely use the printers for tooling and end product manufacturing. There are business cases for using the printers for tooling applications. Lockheed Martin saves thousands of dollars by utilizing their printers for this purpose.[215] There are not as many business cases for using 3D printers for the purpose of manufacturing end products, but that does not necessarily mean there is not a business case for the Marine Corps. Unlike civilian companies, the Marine Corps operates in forward deployed locations. Existing supply chains are frequently not

[214] Joyce, "3D Printing Supply Chain Overview."

[215] Skeehan, "Changing the Way We Build and Test Aircraft."

established and when they are established, the supply chains are often lengthy and complicated.[216] The lengthy supply chains often rely on multiple modes of transportation that all contribute to increased costs. The total cost of a simple and inexpensive repair part will escalate quickly depending on how far it is shipped. If the unit had a 3D printer, it could print the part and not pay for the costs of the shipping. This is purely a hypothetical scenario, but is nonetheless realistic. When building a business case, scenarios such as this one must be considered to ensure it is comprehensive. All of the costs that are associated with the impact analysis completed in Chapter IV will contribute to the cost analysis as well. Integrating 3D printers is more costly than just procuring the systems. The additional life cycle costs including training and maintenance are significant costs associated with the printers. As explained in Chapter IV, the training required for 3D printer operation and maintenance is extensive if the expectation is to have proficient operators able to take full advantage of the printer's functionality. The only method of mitigating the expenses of training is to augment the individual units with civilian SMEs. The cost of the additional civilian personnel will most likely offset any money saved on training, but this will be determined through an all-inclusive cost analysis.

As mentioned earlier, narrowing the type of printers or processes down to one or two is only part of the process of selecting the appropriate printer. There are numerous FDM and selective laser sintering models currently on the market. Further research should be conducted to develop detailed system requirements for the printer. The additional research will establish key performance parameters (KPP) and key system attributes (KSA) that are deemed the most critical regarding the printer. The KPPs will consider parameters such as maximum build size, power requirements, part resolution, build speed, accuracy, raw material variability, compatibility with other systems, printer dimensions, printer durability, ease of use, and other printer features. After the KPPs are developed, they would then be compared to existing printers. The Marine Corps may decide that one of the printers on the market meets the desired specifications. In this

[216] Joint Chiefs of Staff, *Distribution Operations*, JP 4–09 (Washington, D.C.: Government Printing Office, 2010), I-12 and B-4.

event, the acquisition process is shortened and the Marine Corps could procure the printers as a commercial off the shelf program. If there were no suitable printers, the Marine Corps would utilize all steps of the acquisition process, which will take considerably longer. Because AM technology advances so quickly, it is difficult to design and procure a relevant system using the government's acquisition process. By the time the printer is ready for distribution it would most likely be obsolete. As a result, it may make more sense to procure a commercial system immediately even if it does not meet every KPP. More research would identify the appropriate method.

D. CONCLUSION

The technology for AM processes is advancing at a rapid pace. Based on its rate of advancement, it may not be long before many, if not all of the limitations mentioned earlier are corrected. Despite the limitations of the technology, there are actionable items that could be implemented to benefit from the technology. The following are recommendations as a result of this analysis:

- Develop and execute a plan for limited experimentation of AM in the Marine Corps to fully understand the implications and barriers that it may present.
- Complete the steps of the DOD Acquisition process necessary to initiate a program for 3D printers in the Marine Corps.
- Select printers that use the FDM and/or selective laser sintering processes.
- Use the printers primarily for end product manufacturing and tooling applications. Prototyping applications are secondary to these applications.
- Increase use of the printers at the maintenance facilities and document the lessons learned for the benefit of other units in the future.
- Influence the U.S. Navy to install 3D printers on all amphibious ships. Train and equip the MEUs with printers if the U.S. Navy does not install more printers.
- Encourage civilian manufacturers to use printers for both prototyping of new systems in the development phase and as a method of producing their parts.
- Obtain IP ownership of repair parts for existing and future equipment.
- Evaluate the feasibility of utilizing a network of civilian 3D printers located throughout the world.

Additive manufacturing has the potential to greatly increase the efficiency and responsiveness of Marine Corps logistics if the recommendations are appropriately implemented. While it may possess limitations as of now, the Marine Corps should plan to incorporate printers to be prepared for when the limitations are corrected. When appropriate, the Marine Corps should fully incorporate the technology to assist logisticians in sustaining the force and support distributed operations throughout the battlefield.

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