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Benchmarking DoD Use of Additive Manufacturing and Quantifying Costs

Ryan C. Crean

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BENCHMARKING DoD USE OF ADDITIVE MANUFACTURING AND
QUANTIFYING COSTS

THESIS

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**BENCHMARKING DoD USE OF ADDITIVE MANUFACTURING AND
QUANTIFYING COSTS**

THESIS

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Air University

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In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Logistics and Supply Chain Management

Ryan C. Crean, BS

Captain, USAF

March 2017

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**BENCHMARKING DoD USE OF ADDITIVE MANUFACTURING AND
QUANTIFYING COSTS**

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Abstract

Additive Manufacturing (AM), or three-dimensional (3D) printing as it is commonly referred to, is a rapidly developing technology that has the potential to revolutionize the way that firms develop and produce parts, as well as how they manage their supply chains. AM allows organizations to “print” prototypes, parts, tools, fixtures, tooling and a variety of other items at their production location. This can remove long lead times and high inventory levels for one-time or rare items.

This research examines current AM use within the military services. Additionally, this study details the costs associated with fielding different levels of AM capability, specifically metal printing, production level polymer printing, and desktop level polymer printing. Finally, this research quantifies the cost of producing a metal part using AM. Ten parts with long lead times were chosen for analysis, and the cost calculated for AM production is compared to the price the Air Force currently pays to procure these parts. Topics for future research into of AM will be presented.

Acknowledgments

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Ryan Crean

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BENCHMARKING DoD USE OF ADDITIVE MANUFACTURING AND QUANTIFYING COSTS

I. Introduction

Background

Additive Manufacturing (AM), or three-dimensional (3D) printing as it is commonly referred to, is a rapidly developing technology that has the potential to revolutionize the way that firms develop and produce parts, as well as how they manage their supply chains. AM technology allows organizations to “print” prototypes, parts, tools, and a variety of other items at their production location. This can remove long lead times and high inventory levels for one-time or rare use items. AM technology has been adopted by a number of firms in industry, and by the services within the Department of Defense (DoD).

This research will be of particular interest to Air Force Materiel Command (AFMC), the Air Force Life Cycle Management Center (AFLCMC) and the Air Force Sustainment Center (AFSC). A combination of the DoD and AF budget situations, as well as recent advancements in AM technology and application make this an opportune time for this type of research. As the Air Force’s budget continues to shrink, it is important to find areas with potential cost savings. AM has the potential to change the Air Force’s supply chain for depot level maintenance, allowing AFMC and the AFSC to realize possible cost savings in a number of areas. The first possible area of cost reduction is through reducing downtime while waiting for parts. Another possible means

of reducing costs is decreasing the size of parts inventory needed to sustain depot maintenance operations. Finally, as the average age of the aircraft in the Air Force's inventory continues to climb, repair parts can become scarce or more expensive to purchase. Additive manufacturing can be used to produce small numbers of these rare or expensive parts without going through the time consuming and expensive process of restarting a conventional production line for what is ultimately a low volume production need.

Motivation

According to a report last year in the *Air Force Times*, the average age of Air Force aircraft at the time was 27 years old, and the oldest aircraft were 53 years old (Schogol, 2016). The Air Force's manning is at one of the lowest levels that it has been in the past 20 years (DMDC, 2017). As aircraft continue to age and the workforce gets smaller, the USAF needs to take advantage of technological advances like AM to decrease the labor time required to maintain aircraft and to increase aircraft availability.

Problem Statement

To determine the extent of opportunity for the USAF in terms of cost and time savings by evaluating a range of different AM technologies to affect supply and maintenance activities.

Purpose Statement

The purpose of this study is to examine the adaptation of AM within the DoD, and determine how AM activity at these organizations can be used to inform the United States Air Force's use of AM, specifically in depot level aircraft maintenance. Additionally, this study will examine the costs associated with AM, and perform a crude cost analysis for producing example parts with AM and compare these costs to the current cost the Air Force pays to procure the parts.

Research Questions

The goal of this study is to inform the Air Force, particularly AFMC and the AFSC, by conducting a survey of use cases for AM within the DoD, as well as the costs associated with employing AM. The paper will examine the following questions:

- 1) How do the military services incorporate AM into their operations?
- 2) What are the costs associated with employing different process technologies of AM?
- 3) What is the cost of producing a part using AM vs the cost that the AF currently pays to procure the part?

Scope

This research will focus on additive manufacturing processes in the military services and how they could possibly apply to the Air Force's depot level maintenance. Additionally, this paper will examine the costs associated with fielding an AM capability and the cost of producing specific parts with AM. It will give background information on

current additive manufacturing methods. There will be a brief description of the difference between AM and traditional manufacturing, and a discussion of advantages and disadvantages of AM. The cost comparison between AM and the current cost the Air Force pays for the example parts will assume that the current price is valid. The scope of this research is to focus on AM technology and what the military services have found as advantages and disadvantages of AM compared to original manufacturing methods.

Assumption and Limitations

There are a few potential limitations associated with this study. One limitation is that there are many organizations within the DoD that are using AM, and this paper will only be able to examine a handful of them. By looking at such a small sample, there is the potential to miss some best practices or lessons for the Air Force. This study does not address the technical risks of using AM to produce parts, as that is outside of the scope.

II. Literature Review

Introduction

To begin this research effort, the researcher surveyed the literature on the subjects being addressed by the study. First, there will be a brief description of AM and some popular AM technologies. Then there is a look at the Air Force's vision for AM use in future operations. Next, AM challenges that could prevent or hinder adoption of AM at the base level or in operational environments are presented. Additionally, studies that have addressed candidates for AM are discussed. Finally, AM cost models that provide the basis for the cost work done in this research are addressed.

Additive Manufacturing

The American Society for Testing and Materials (ASTM) defines additive manufacturing as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2009). AM technology was introduced in the 1980's, but has made great strides in recent years. It was originally used for inexpensive rapid prototyping, however manufacturing companies are now using AM to create parts and end use items that were previously made through traditional manufacturing processes. AM technology has evolved into a number of different production technologies, and allows users to work with a number of different raw materials. Below is a list and brief description of some popular AM technologies (Cotteleer et al., 2013).

Vat Polymerization – Vat Polymerization is a process where a UV light is used to cure specific areas of a pool of liquid photopolymer. The light hardens these selected areas in layers until the shape of the final item is achieved.

Material Jetting – in a material jetting process, a print head deposits droplets of the build material, usual a photopolymer and a support material onto the build surface. A UV light is then used to harden the photopolymer into the final part. After all the material has been deposited and cured, the support material needs to be removed.

Material Extrusion – A material extrusion machine deposits thermoplastic onto the build surface through a heated nozzle, which melts the material and deposits it layer upon layer until the part is completed.

Powder Bed Fusion – Particles in a bed of powder are fused together using a laser. Once a layer is fused, another layer of powder is spread over top of it and the process is repeated until the part is complete.

Binder Jetting – Particles in a bed of powder are fused together using a liquid binding agent, such as glue, then a new layer of powder is spread over top of the object. The process is repeated until the part is complete. Ink may be deposited into the powder to give the item color.

Sheet Lamination – Sheet Lamination is, as the name suggests, a process where an item is formed out of bonded sheets of material.

Directed Energy Deposition – Using Directed Energy Deposition an object is formed when focused thermal energy, produced by a laser, electron beam or plasma arc, fuses material as it is being deposited.

AFFOC

In September 2015, the Air Force released the Air Force Future Operating Concept (AFFOC). The document describes what the Air Force will look like in 2035, what mission sets will be important, and how technology will support these mission sets. The AFFOC specifically mentions AM as an important technology for the Air Force of the future. AM is mentioned in the Rapid Global Mobility portion of the document. The AFFOC gives a future example of operational AM use, describing the airdrop of polycarbonate to a remote SOF base. The SOF soldiers at the base use the polycarbonate to print a critical replacement part for their UAS ground control station. The AFFOC also makes the point of detailing the importance of secure cyber transport of the part's specifications from CONUS to the outpost. The story ends by saying "what would have taken days and millions of dollars to manufacture and airlift into theater from CONUS was now being built at the tip of the spear" (AFFOC, 2015). For polymer parts this is a very realistic scenario, and could happen in the next few years. AM is one of the required technologies for the Air Force's future vision of small forward bases, providing a print on demand capability to shorten the supply chain for mission enabling items. AM will also be a key component of the Air Force's future logistics and acquisitions enterprise, enabling rapid acquisition and fielding of new technologies (AFFOC, 2015).

Additive Manufacturing Challenges

There are several challenges that currently face the additive manufacturing community that need to be overcome before it can be widely adopted for military

logistics operations, particularly in the expeditionary or deployed environment. Many of these challenges were echoed by individuals from different organizations and in the literature. These challenges can be broken up into quality control and parts certification, proper design and drawings, information technology and data management, and the manufacturing environment.

Quality assurance and parts certification are both key issues that need to be addressed before the widespread adoption of AM, especially for any structural or any category of criticality parts. In traditional subtractive manufacturing, a process may be used to produce thousands of parts, whether this process uses a casting, tooling, forging, or a machining operation. A sample of these parts can be tested to determine if the process is producing quality parts within the tolerances of the end user. If these samples don't pass inspection, then all the parts produced can be examined and the process can be adjusted accordingly. However, in many cases an AM process is essentially a production run of one part (or more, depending on how many parts can fit on the machine's build plate). Several factors could change a part from one print to another, including differences in the process control, the computer file used, or differences in the machine used. There are process specifications which explicitly identify essential process variables for that exist for conventional manufacturing and these standards are readily available to manufacturing entities. These process specifications do not exist for AM, and they must be developed to support widespread reliable use of the technology (Gupta et al., 2012).

One of the benefits of AM is that “complexity is free” (Sheffi, 2017). It is possible to create complex geometries that would not be possible or would be prohibitively expensive if using subtractive manufacturing, which could decrease weight or increase the strength of a part (Gao et al., 2015). However, these benefits can only be realized if a part is redesigned for function and AM constraints. AM still has constraints, such as a difficulty producing parts with overhangs without extensive support, but these constraints are different than the constraints for traditional manufacturing processes and must be taken into account when redesigning a part. Using AM to produce a part from the original design might be quicker or cheaper than using subtractive manufacturing, but it loses out on some of the benefits that are possible with AM and may not address all of the challenges or limitations of AM such as material difference, the need for volumetric inspection, and size limitations. One of the challenges of being able to redesign for AM or even build a part with AM is the need for 3D drawings of the part. In most cases, the DoD doesn’t have 3D drawings for all the spare parts in its inventory. In many cases, due to the age of many weapons systems, there aren’t even reliable 2D drawings for a part (Parks et al, 2016).

There are also a few hurdles in information technology and data analysis that must be cleared for successful AM operations in the future. The most important is cyber security. For a global network of AM machines or deployed AM machines to be successful, digital files with part build details will need to be delivered from a central repository of files to the machine that needs to print the part. This data transfer must be secure so that the file arrives in the correct format without any tampering by adversaries. If our enemies were able to modify a schematic for a part before it was printed to

intentionally induce failure, it could result in the loss of an aircraft and the crew. A secure repository of engineering validated and approved designs and a secure line of communication from this repository or a management office to printers in the field is critical to the success of future AM operations. Data analysis could play a key role in certifying printers or individual parts for use by monitoring a build while it is in progress. Organizations could use melt-pool analysis to determine if a printer is operating correctly and if a part will be within specifications when it is complete (Frazier, 2014). This is done by looking at the build to ensure that the powder is being heated to the correct temperatures. In the future, organizations could even use a melt pool signature to identify that a printer or build file haven't been the victim of a cyberattack. However, melt pool analysis requires extensive real-time data analysis, which could require greater computing power than some organizations currently have. Additionally, if this data is going to be stored for future analysis or comparison, for example if a part failed earlier than expected, it would require a robust data storage and management capability. Being able to use real-time analysis of a build is a key component to having a strong quality assurance program, and must be a top priority in building an AM capability (Huang et al., 2015). In the future all process specifications and essential process variables need to be monitorable to ensure that the final part will be within the required specifications.

The AFFOC describes a scenario where a SOF unit prints a mission critical polymer part from a printer at their remote forward operating base. It isn't unreasonable to think that the Air Force or DoD could have the capability to print advanced parts in polymers in an expeditionary environment. This would shorten the supply chain for items and eliminate the need for forward operating bases to keep an inventory in certain

items. The biggest change to the Air Force supply chain would be the ability to print metal parts at main operating bases and deployed locations. However, there are a number of barriers to this capability due to the conditions required to use a metal printer, in addition to other barriers previously listed. Metal printers need to be kept in controlled environments, with temperature and humidity controls (Moylan et al., 2013).

Additionally, there are grounding and fire suppression requirements that need to be met.

This is due to the fact that some metal powders, such as aluminum and titanium, are reactive meaning that they are unstable and could cause an explosion if exposed to oxygen and an ignition source such as a spark. There are metal powders, such as stainless steel, that are non-reactive and would be easier to use in an expeditionary environment. Additionally, when cleaning the machines, operators are required to wear respirators to prevent them from breathing in any of the powder in the air. One barrier to printing in metal in a forward location that is not related to the environment or facility requirements is the need for post-processing of parts. Most items do not come out of the printer as final end use items, and require some kind of handling after printing to become a useable part. This could be heat treating or hot isostatic pressing the part to relieve internal stresses before it is removed from the build plate, or machining. Post processing requires other machines to be to make a final and functional item. Making a final and functional item requires more than just a printer, it requires other machines to be on hand to complete the work of the printer, as well as the required facilities and utilities, including energy, water, and inert gases.

Additive Manufacturing Part Selection

In 2006, Allen compared the cost of producing aerospace engine parts using AM with the cost of producing them through traditional subtractive methods. He focused specifically on the buy:fly ratio, which compares the weight of the raw material needed for a subtractive manufacturing process with the weight of the final part. Many subtractive manufacturing methods have very high buy:fly ratios, where upwards of 20lbs of raw material could be required for every 1lbs of material in the finished part. Allen found that parts with a higher buy:fly ratio, parts that were difficult to machine or took longer to machine were good candidates for cost savings with AM (Allen, 2006).

The parts examined in this paper were selected from a list of AM candidate parts developed in a study by Logistics Management Institute (LMI) and funded by DLA. This study looked at the approximately 4.5 million spare parts managed by DLA to determine which parts could be good candidate for AM. The overall pool of parts was narrowed down by which parts are made from material that can currently be used in AM (140,000 parts). Additionally, the number of parts was narrowed down by whether or not there was available dimensional data for the part, and if that part would fit into a current AM build chamber (20"x20"x20"). The final list of "suitable" candidates for AM was approximately 43,000 parts out of an original 4.5 million considered. It is likely that there are many more parts that are managed by DLA that would be good candidates for AM, but because they were missing the specific material they are made from or are missing their dimensions in the database records they were not considered. In addition to the technical attribute listed above (material and build envelope) the researchers also

collected the parts criticality and the availability of technical data and drawings. The study also collected relevant logistical data for all of the parts considered, including production lead time (PLT), administrative lead time (ALT), unit price, and demand for the past five years. The technical and logistical data was loaded into a part selection tool, that allows users to query parts based on their own criteria.

Additive Manufacturing Cost Models

There have been research studies in the past that examined the costs of producing a part with AM. In 2003, Hopkinson and Dickens compared the cost of producing a 35mm polymer lever and 210mm polymer cover using injection molding, Stereolithography (SLA), Fused Deposition Modelling (FDM), and Selective Laser Sintering (SLS). They considered machine costs, labor costs, and material costs for each of the AM processes. The study found that SLA and FDM were more cost effective than injection molding when producing less than 6,000 levers or 700 covers (Hopkinson and Dickens, 2003). SLS was more cost effective than injection molding for producing less than 14,000 levers (the cost of producing the cover with SLS was not considered). Hopkinson and Dickens found that the price per unit to produce the lever using SLS was €2.20.

Ruffo, Tuck, and Hague built on Hopkinson and Dickens working comparing the costs of injection molding with AM to produce low to medium volumes of a product. For their cost model, they considered material, production and administrative overhead, labor, and machine costs (Ruffo et al., 2006). Additionally, their model took into consideration the build time required based on the time necessary to scan the build area, deposit fresh

powder, and heat and cool the build area between scans. Their model found that the price per unit of producing the lever with LS was €3.25 when producing 16,000 units, nearly 50% higher than what Hopkinson and Dickens calculated, demonstrating the importance of considering all of the relevant costs when developing a cost model.

The US Army Logistics Innovation Agency published a study called “Additive Manufacturing Cost-Benefit Analysis”. This study looked at the potential impact of placing metal and polymer AM machines at different points in the Army’s contingency supply chain, using supply data from Afghanistan, Iraq and Kuwait from 2004-2014. Seven alternatives for AM were considered and compared against each other and the status quo of conventional manufacturing in the US. The alternative included placing AM machines at contingency bases, theater support bases, support installations CONUS or OCONUS, or OEM AM CONUS or OCONUS. The report considered the number of machines and personnel required to field an AM capability at different locations, as well as transportation and transportation security requirements. It concluded that while using AM to produce an item could cost 3-28 times more than using traditional methods, AM could reduce wait time by 6% to 99%.

III. Methodology

Introduction

This chapter will present the methodology used by the researcher to carry out this study. The first section will deal with the case study approach used to examine AM in the DoD. The next section will discuss how the parts examined in this study were selected. Finally, this chapter will address the cost model presented by this study to calculate the costs of producing the candidate parts. This will include a section on the assumptions the cost calculation is based on and a section on validation of the build time formula.

AM Use in DoD

The researcher will use a case study approach to examine the use of AM in the DoD. Yin describes the research method that is appropriate for a given study based on the type of research question, the need for control over the events being studied, and whether or not the study is dealing with a contemporary phenomenon (Yin 2003, p. 5). Table 1 depicts a table specifying which method to use in each set of circumstances. This study will examine how and why questions (as show in the research questions section of this paper), will not need control over the system being examined, and is dealing with a contemporary problem or situation. The United States Air Force, United States Navy, United States Army, and United States Marine Corps will be the cases investigated. Data was collected by interviews with members of the services, site visits to additive manufacturing operational locations, and a review of various publications. During the summer and fall of 2016, the researcher visited various DoD facilities involved in AM and academic institutions partnered with the DoD on AM research and development.

Table 1. Comparison of Research Strategies (Yin, 2003)

Strategy	Form of Research Question	Requires Control of Behavioral Events?	Focuses on Contemporary Events?
Experiment	How, why?	Yes	Yes
Survey	Who, what, where, how many, how much?	No	Yes
Archival Analysis	Who, what, where, how many, how much?	No	Yes/No
History	How, why?	No	No
Case Study	How, why?	No	Yes

The sites and organizations that were visited are as follows: Robins Air Force Base Component Maintenance Group (CMXG) and Software Maintenance Group (SMXG), Tinker Air Force Base CMXG and Aircraft Maintenance Group (AMXG), Joint Base McGuire-Dix-Lakehurst NAVAIR, The US Army Research Laboratory at Aberdeen Proving Grounds, USMC at the Pentagon, Pennsylvania State University, AFLCMC and the University of Dayton Research Institute (UDRI).

In order to determine the cost of fielding an AM capability, the researcher gathered information from current users of the technology and reviewed available publications to develop a sense of the requirements and costs for different levels of AM.

Part Selection

To select parts for examination, the researcher used the database of part developed in the LMI study discussed earlier. The researcher further narrowed down the

overall list of 43,000 parts by eliminating parts that did not have a demand in the past 10 years. Additionally, only parts that cost the Air Force over \$1,000 and had a combined production and administrative lead time of over 180 days were considered. Parts listed as screws, bolts, wire assemblies, or spacer plates were removed from consideration, because they are not generally good candidates for AM. These types of parts may not be the best candidates for AM because the ability to produce complex designs, reduce waste, and part simplification through redesign are all benefits of AM that may not be possible if producing screws, bolts, or spacer plates (Coykendall et al., 2014). Finally, the part dimensions had to fall within the 12"x9"x9" build chamber of the EOS M290 because that is the machine being used for the cost comparison portion of this study. The researcher selected ten parts from this list for further examination. None of the parts selected are considered flight safety critical. The engineering drawings for the parts considered were taken from Joint Engineering Data Management Information and Control System (JEDMICS), an online repository of engineering data.

Cost Calculations for AM

This study will also examine the costs of producing example parts with AM compared to the current cost the Air Force pays for them. The researcher will present an equation to calculate AM costs derived from pertinent research efforts. The total cost of producing a part through AM will be comprised of several different costs. The first cost is the cost of raw material, namely the metal powder used by the machine. The next cost is the amortization of the cost of the machine itself. In the case of metal parts the machine used in this analysis is the EOS M290, which is the machine being used by

UDRI and AFLCMC. Additional processing cost are the utilities required to run the machine and the annual maintenance contract for the machine. Labor cost will also be considered. The labor considered in the cost calculation will be the preprocessing or set-up required for the part and then any post-processing that is required. The primary labor cost for using AM may be the non-recurring engineering (NRE) associated with reengineering, “designing for AM” and setting up the build layout. Additionally, the mechanical requirements for the part must be established and incorporated into the AM design. However, this study will not include NRE in the cost of each part because the cost of NRE could vary widely from part to part based on part complexity, material, or mechanical requirements. NRE and its impact on the overall costs to produce a part with AM will be discussed, but no specific cost for NRE will be included in this study.

Any post-processing requirements are also costs that need to be considered when determining the cost of producing a part using AM. Locations have the option to have post-processing equipment in house or to send parts out to a contractor for post-processing. The cost of any testing or quality assurance inspections that must be done on the part before it can be used must be factored in to the total production cost. As with post-processing, it is possible to do inspections and quality assurance test in house or to contract a third-party firm to do the testing and inspections. Outsourcing near the point of need, especially for validation could be very costly.

There will be some cost savings realized through AM that will be difficult to calculate precisely. Savings in inventory holding costs and transportation costs will be different across parts and locations. AM could present some benefits that won’t have a

dollar amount associated with them, such as a decrease in supply chain vulnerability. Making parts at the point of use eliminates a potentially lengthy supply chain from the supplier's supplier to the retailer to then end user. Each step in this process has the potential for disruption and negative impact on mission accomplishment. Additionally, AM could lead to a decrease in lead time for parts, which could lead to an increase in readiness.

The formula used to determine the cost of producing a part with AM was adapted from a model published by Atzeni and Salmi in the *International Journal of Advanced Manufacturing Technology*. Atzeni and Salmi's model determines the cost to produce a part using selective laser sintering. This research will determine the cost for producing parts using the EOS M290 Direct Metal Laser Sintering machine, which is a similar process. Their model determines cost by adding material cost per part, pre-processing cost per part, processing cost per part, and post processing cost per part (Atzeni and Salmi, 2012). The equation used to calculate the cost of producing a part with additive manufacturing is as follows:

$$C_{AM} = C_{MAT} + C_{PRE} + C_{PRO} + C_{POS} \quad (1)$$

Where

$$C_{AM} = \text{Cost of Additive Manufacturing (\$)}$$

$$C_{MAT} = \text{Materials cost (\$)}$$

$$C_{PRE} = \text{Pre-processing cost (\$)}$$

$$C_{PRO} = \text{Processing cost (\$)}$$

$$C_{POS} = \text{Post-processing cost (\$)}$$

The materials cost is defined as:

$$C_{MAT} = M_C * (M_D * M_W * V_P) + M_C * (M_D * M_W * V_T) \quad (2)$$

Where

$$C_{MAT} = \text{Materials cost (\$)}$$

$$M_C = \text{Material Cost per Kg (\$/Kg)}$$

$$M_D = \text{Material Density (g/mm}^3\text{)}$$

$$M_W = \text{Waste Material}$$

$$V_P = \text{Part Volume (mm}^3\text{)}$$

$$V_T = \text{Test Sample Volume (mm}^3\text{)}$$

The preprocessing cost is defined as:

$$C_{PRE} = (E_T * E_C) + (T_S * C_O) \quad (3)$$

Where

$$C_{PRE} = \text{Preprocessing cost (\$)}$$

$$E_T = \text{Engineering Time (Hours)}$$

$$E_C = \text{Engineering Time (\$/Hour)}$$

$$T_S = \text{Set-up Time (Hours)}$$

$$C_O = \text{Operator Cost (\$/Hour)}$$

The processing cost is defined as:

$$C_{PRO} = [T_{BUILD} * (C_{DEP}/M_H)] + (T_{BUILD} * C_{ENERGY}) + [T_{BUILD} * (C_{MX}/M_H)] \quad (4)$$

Where

C_{PRO} = Processing cost (\$)

T_{BUILD} = Build time (Hours)

C_{DEP} = Machine Depreciation (\$/year)

M_H = Machine Hours per year (Hours/year)

C_{ENERGY} = Cost of Energy (\$/KwH)

C_{MX} = Maintenance Contract Cost (\$/year)

The post-processing cost is defined as:

$$C_{POS} = (T_{POS} * C_O) + C_{TEST} + C_{HT} + C_{MACH} \quad (5)$$

Where

C_{POS} = Post-processing cost (\$)

T_{POS} = Post-Processing Time (Hours)

C_O = Operator Cost (\$/Hour)

C_{TEST} = Test Cost (\$)

C_{HT} = Heat Treat Cost (\$)

C_{MACH} = Machining Cost (\$)

Many of these cost components have been included in previous AM cost calculations.

The researcher added the cost of building a test sample and testing the sample, as well as

the cost of NRE. The cost of producing and testing the test sample may not be a large portion of the final cost, but it is an important cost to capture. It appears that NRE will be a large portion of overall cost for producing an AM part, though it will vary from part to part based on complexity. Additionally, this research will present a more usable build time formula than other cost equations surveyed. The build time formula will be explained in the Assumptions section.

Assumptions

The cost calculation will be based on the following assumptions:

- Heat treatment is assumed to cost \$100 per part. This study will not consider Hot Isostatic Pressing (HIP) costs.
- Build time will be defined as:

$$N \left[10 \text{ secs} + \frac{A}{10^{-4}} \right] + 8 \text{ hours}$$

Where:

$$N = \text{Number of layers}$$

$$10 \text{ secs} = \text{fixed time between layers}$$

$$A = \text{Part Area}$$

$$10^{-4} = \text{beam velocity (1 m/s) * beam size (10}^{-4} \text{ m)}$$

- Time between layers is assumed to be 10 seconds, for recoating the build surface with fresh powder.

- Time before and after a build where the machine is unavailable for set-up before a build, heating the build chamber, cooling the build chamber after a build, and part removal from the machine, is assumed to be 8 hours total
- Build layer thickness is assumed to be 30 microns. This will give a conservative estimate of build time, as the number of layers has a significant influence on the amount of time it takes to complete a build, due to the assumed 10 seconds of fixed time between layers.
- Machine energy usage is assumed constant at 3.2 kW throughout the build. The assumed price for energy per kWh will be \$0.135, which was the average cost per kWh for the United States in 2017 (U.S. BLS, 2017).
- Volumetric inspection of the parts is not considered in this study.
- Each build will include an ASTM E8 Round test coupon, in order to conduct a room temperature tensile test. The assumed fixed cost of the test will be \$300, which included \$200 to machine the coupon and \$100 to test it.
- The assumed cost for setup and post-processing time is \$45 per hour. This represents the hourly wage for an E-5 equipment operator and machinist. The setup time is assumed to be two hours while the post processing time is one hour.
- The annual maintenance costs for the machine are assumed to be \$18,000. This is the cost of the OEM contracted maintenance, and locations may have higher maintenance costs due to high machine usage.
- The demand for a part over the next five years is assumed to be the same as the five-year demand documented in the LMI study. For parts that didn't have any

demand for the past five-years, this study will assume that there will be demand for a single part over the next five years.

To calculate the mass of the part, the part volume was calculated from the part drawing in JEDMICS, which proved to be difficult for some parts as the drawings were nearly 40 years old in some cases. The fill area of the part was also taken into account when calculating the volume so that empty space in the design wasn't considered in the part's mass. The volume was then multiplied by the density of the material to find the mass. The assumed density for Titanium, Aluminum, and Stainless Steel were 4.4 g/cm^3 , 2.67 g/cm^3 , and 7.8 g/cm^3 respectfully (EOS, 2016). To calculate part build time, the researcher determined the logical part build orientation, which determined the build height. This determination was in consult with researchers at the Air Force Research Laboratory. The researcher then calculated the area normal to the build direction of the part, again taking into account the fill area of the part.

The cost calculation will determine the cost under two assumptions: (1) manufacture of a single item and (2) maximizing the number of parts printable on a single build platform. Logically, as more parts are produced in the same build, the cost of each part goes down. When producing multiple parts in one build (even if they are different parts) the set-up cost and post-processing costs (part removal, the heat-treat and testing costs) are distributed across these parts.

Validation

In order to validate the build time formula used to calculate machine time for parts, the researcher used data collected by UDRI for three part they had printed. UDRI provided a 3D drawing, part volume, and build time for each part. The parts had a variety of geometries and fill areas. The researcher examined each 3D drawing in Solidworks to calculate the build height and build area for each part. Table 2 lists details for the parts, calculated build times and actual build times.

Table 2. Build Time Validation

Item name	Reaper Hook	Hinge	Reaper Lug
Actual build time	17 hours	52 hours	40 hours
Calculated build time	16.1 hours	52 hours	40.2 hours
Percent difference	5.3%	0%	0.5%

The build time calculation worked well on the parts provided. The fact that the 3D drawings were provided for these parts aided in the build time calculations. Solidworks has a measurement function that was used to calculate part size, as well as to calculate the area of voids in the parts. It is much more difficult to calculate the area of voids on 2D drawings.

IV. DoD Use

Introduction

This chapter discusses the cases studied to examine AM use within the DoD. The first case will be the USAF. Next, the chapter discusses the USN, followed by the USMC. The last case will be the US Army. Finally, there is a section that mentions some organizations that use AM that were not examined in this study.

United States Air Force

The USAF designated the Air Force Life Cycle Management Center (AFLCMC) Product Support Engineering Division as the “belly-button” for AM. AFLCMC has entered into a contract with the University of Dayton Research Institute to explore how new and emerging technologies can improve Air Force weapons system sustainment. AM is one of the technologies that is being considered and researched. UDRI has a Fortus 900mc polymer machine to conduct work in polymer printing. Also, UDRI currently has four EOS M290 metal AM machines with plans to purchase two more. The six printers will allow them to dedicate two printers each to the Titanium, Aluminum and Stainless Steel alloy families. UDRI has printed MQ-9 Reaper trailer parts for the Air Force Packaging lab, and is working with units at other bases to find opportunities for AM to improve aircraft availability.

Two units were visited at the Warner Robins AFB Air Logistics Complex (ALC), the Commodities Maintenance Group (CXMG) and the Software Maintenance Group (SMXG). The CMXG at Robins had two printers, a Fortus 400mc and a Fortus 900mc. Both machines can print polymer materials, particularly ABS and Ultem, with print

envelop of 16" x 14" x 16" and 36" x 24" x 36", respectfully. Robins had created one aircraft part, a F-15 air duct as a stop gap to use until conventional supply was available for the part. The depot maintenance line for the F-15 was unable to get the air duct through its normal supply channels and came to the CMXG for assistance. The part is normally produced in nylon and it was printed in ABS. Engineers compared the specifications between the regular duct made of nylon with the printed ABS part and approved the duct for use. Additionally, the AM group there designed a C-5 cooling effects detector to be tested for a part redesign. The part will go through testing alongside parts produced through traditional manufacturing processes.

The SMXG has a Fortus 250, Fortus 450, and Stratasys Objet 260. The mission these machines support at the SMXG is to provide the software for the flight control systems that aircrews interact with in the cockpit. In order to complete this mission there are mock-up cockpits and flight control stations to test the software. Since their mission only involves testing in an office environment, the SMXG is able to print "end use" parts for their mission. For example, they were able to print cockpit control panels for new airframes years before they would be able to get them from the OEM, allowing their engineers to work in a realistic cockpit environment while saving money.

Within the Tinker AFB ALC CMXG is the Reverse Engineering And Critical Tooling (REACT) group. The REACT group's mission is to improve depot maintenance performance through the use of reverse engineering tools and manufacturing technologies. The REACT group has a number of AM machines, including a Projet 860Prom, Fortus 450MC, and a Fortus 900. These are all polymer machines and range

from small hobby level desktop machines to larger industrial level machines (the Fortus 450MC and Fortus 900). Investigations are underway within the REACT group to assess the need for an EOS M290 metal machine during FY17.

The 809 Maintenance Support Squadron (MXSS) at the Ogden Air Logistics Complex is using AM to support depot operations there. They have two production level polymer machines, a Fortus 900mc and a 3DSystems Zprinter 650, as well as a desktop printer. They have used their printers to produce production support items like an F-16 drill template and an F-16 bulkhead template. Additionally, they printed F-16 simulator throttles for the SMXG at Ogden. By using AM they were able to iterate multiple times to come up with the best design for the throttle.

The 982 Maintenance Squadron (MXS) at Sheppard AFB uses production level polymer printers to support the base's mission of training USAF aircraft maintenance personnel. They currently have two Fortus 900mcs, a Fortus 360mc, and a Fortus Et. They have used their printers to produce training aids for the MQ-9 Multi-targeting System ball, MQ-9 propeller assembly, Hellfire missile, and other aircraft and munition components. Using a 3D printed training aid saves the USAF money over the alternative of purchasing the real part and potentially damaging it during training. Additionally, this practice keeps another part in the supply system for use in the field. One example of cost avoidance given by the unit is their production of the Minuteman III Re-Entry System. The part costs \$499,999 to procure from the manufacturer and only \$39,382 to produce using FDM saving over \$460,000.

A great example of what AM can do to support the Air Forces aging weapons system is the 552nd MXS, an E-3 AWACS unit at Tinker. The 552 Air Control Wing, the parent unit of the 552 MXS, received its first AWACS in 1977 (Air Force Fact Sheet). The 552 MXS has been printing non-flight-critical parts, as well as tools, jigs and fixtures for the E-3 AWACS. The 552 MXS has a Fortus 400MC and has been printing since August 2015. The two most notable items that they've printed are a bracket for the Environmental Control System and plastic end caps for seat armrests. These items show two important advantages of using AM in the Air Force and DoD supply chains, namely money and time savings and producing unprocurable parts. The 552 MXS has identified that producing the brackets through traditional methods took approximately 8 hours per and required \$4,000 of aluminum. The new process using AM takes approximately one and a half hours and uses \$80 in raw materials. The 552 MXS produces these brackets for E-3 isochronal inspections, of which there are about 22 per year. There are 4-6 brackets used per isochronal inspection, for a total of approximately 138 of these brackets a year, for a savings for \$542,000 and 897 man-hours per year. The 552 MXS was able to purchase their Fortus 400MC for about half of the standard price for a new model, at \$120,000. Based on the savings amount per bracket and the purchase price, it only took 37 brackets for the 552 MXS to break even on their purchase. While the armrest end caps provide a small cost savings, the biggest reason to use AM to produce them was that they were unprocurable through the normal supply system, as the manufacturer had stopped making them. The 552 MXS has also used their printer to produce items for other units at Tinker. They printed a KC-135 "trailing edge repair fixture", which is used

in 15 repairs a month, saving a total of 540 depot repair flow days per year. On average, the 552 MXS uses their printer 2-3 days a week for about 8 hours per day.

United States Navy

In the USN, The Deputy Chief of Naval Operations for Fleet Readiness and Logistics (OPNAV N4) is the lead for AM. The Navy is using AM throughout its operations, and as of October 2016 had nearly 90 printers at 22 different bases (US Navy, 2016). These printers are used at the Navy's Surface Warfare Centers, Air Warfare Centers, Fleet Readiness Centers (FRC), Shipyards, and at Walter Reed Medical Center (US Navy, 2016). The overwhelming majority of these printers are polymer machines, with only four metal printers reported.

The researcher was able to visit Naval Air Systems Command (NAVAIR) Support Equipment Engineering Department at Lakehurst, NJ. At Lakehurst NAVAIR is working on printing flight critical metal parts for the US Navy. They have been printing polymer parts since 2008 and currently have 3 polymer machines. Lakehurst also has an EOS M290 metal printer. They have had the metal printer for over a year and a half and have been using the printer for less than a year. They are currently working on qualifying flight critical parts that have been produced using AM. In July 2016, they conducted a test flight of a V-22 Osprey with an engine nacelle link that had been produced using AM (NAVAIR, 2016). This was their first flight using a flight critical part. As of September 2016, they had printed 50 different metal parts, two of which were considered flight critical.

The Navy's FRC system performs depot level maintenance on the Navy's weapons systems, similar to the USAF's depot system. One of these depot level activities, FRC East at Marine Corps Air Station Cherry Point, NC is using AM in their maintenance operations. They are using AM to make production support items like tooling, form blocks, guides, fixtures, and jigs. Additionally, they use AM for rapid-prototyping and fit-form tests, ensure that 3D models are accurate before producing an item in its final material.

The Navy has deployed fabrication labs (Fab Labs) both to shore installations and afloat aboard ships at sea. The first Fab Lab afloat was installed aboard the USS Kearsarge, a Wasp-class amphibious assault ship, in September of 2015. The Fab Lab included two polymer desktop 3D printers and a desktop Computerized Numerical Control (CNC) mill, and sailors on board the ship were trained in the use of different computer modeling programs (Wyatt, 2015). The most notable Fab Lab success story comes from the USS Harry S. Truman, an aircraft carrier. A clasp on the handheld radios used for communication on board the carrier was constantly breaking, and the replacement part cost the Navy \$615 each, in addition to the cost and lead time associated with delivering the parts from shore. Sailors on the USS Truman developed and produced what they called the "TruClip" using the 3D printers in the Fab Lab. It costs \$0.06 per TruClip to produce them on the ships 3D printer, for a savings of \$614.94 per broken clasp. The Navy reported that the TruClip saved more than \$42,000 over a seven month period (Vergakis, 2016).

The Navy has taken advantage of AM ability to cut time off production with an example case that involved creating a new part for the X-47B unmanned aircraft. During testing, the aircraft's tailhook wasn't operating properly and a new part needed to be created to solve the problem. The Navy was initially told by Northrop Grumman that it would take eight months to a year to develop a new part. Using AM processes, teams of Navy Engineers were able to prototype, test, and produce a new part in five weeks, a substantial time and cost savings (Myers, 2015).

United States Marine Corps

In September 2016, the United States Marine Corps (USMC) Deputy Commandant for Installations and Logistics released a document titled "Interim Policy on the Use of Additive Manufacturing (3D Printing) in the Marine Corps". The document describes what AM is, current materials that can be used and items that can be printed. It also provides clear guidance on what types of parts may be printed and the approval process for printing controlled or critical parts (Dana, 2016). This policy only applies to ground use items, and does not apply to aviation parts or ground support equipment, as those are managed through NAVAIR. Within the USMC, the AM office falls under the Deputy Commandant for Installations and Logistics. The USMC is working on printing general use parts and on developing a secure library of parts. Their goal is to have Marines in the field develop the model and design for an item or part, have it reviewed and approved by the cognizant engineer remotely, and then loaded into the parts library so that it can be printed by Marines around the world. The other services have similar goals for a secure parts library. The Marine Corps' strategy for identifying and

developing these lower level parts is to test print as many parts as possible. They determine if parts are good candidates for AM by test printing them and examining the result against the requirement for the part. This strategy promotes familiarity with the technology and its capabilities, as well as optimization of designs over multiple iterations.

The USMC's AM office has been providing desktop FDM printers to field units with an interest in AM. AM printers are not being forced on units, and this approach ensures that there is interest and buy in from the unit's command. By the end of calendar year 2016, there were approximately 20 USMC units with desktop 3D printers. Printers are being used for prototyping, fabrication, terrain modeling, facility planning, and training by units including a Maintenance Battalion, Intelligence Battalion, Machinist School, and a Raider (Special Operations) Battalion (USMC, 2016). One example of using AM to support field operations took place during an exercise at Camp Pendleton, CA. An EOD robot being used during the exercise was sustained damage and broke a critical part. Marines took the robot to a unit on base with a 3D printer and they were able to print a replacement part out of polymer, returning the robot to service.

The USMC depot facility at Albany, GA is using production level polymer AM in their operations. They use their Fortus 400mc to produce production support items such as fixtures, machining templates, and for rapid prototyping. Additionally, they use AM to conduct fit-form checks with polymer prints before producing the part out of its required material.

United States Army

Similar to the Navy's Fab Labs, the US Army Research, Development, and Engineering Command (RDECOM) and the US Army Rapid Equipping Force (REF) have partnered to create expeditionary labs (Ex Labs). Ex Labs contain a 3D printer, a CNC, computer modeling software, and a number of other production tools to allow soldiers to solve operational problems in a deployed environment (REF Forward, 2016). Ex Labs are currently deployed to Bagram Air Base, Afghanistan and Camp Arifjan, Kuwait.

AM Usage Undocumented by This Researcher

One of the limitations of this study is that there are units and locations in the Air Force and DoD that are using AM that the researcher was unable to interview or visit. While the researcher was able to visit or gather information from a number of Air Force units, there are undoubtedly other units within the Air Force making progress with AM. The researcher was able to obtain data from the Navy's FRC East, but units at the Navy's other FRCs are using AM in their maintenance activity. United States Special Operations Command (USSOCOM) is reportedly using AM. Follow-up research could explore the AM work being conducted by these organizations.

V. Cost of AM Systems

Introduction

This chapter discusses the costs for fielding different AM systems. The first level of AM to be discussed will be metal printing, which is the most expensive and has the most required support equipment. The next level is production level polymer printing with fewer requirements and less capability than metals printing. Finally, this chapter will discuss desktop polymer printing which has hardly any required equipment but is the least useful of the three levels.

Requirements for Fielding AM

Placing AM machines at different points in the supply chain to decrease lead time is an attractive proposition. However, there are a number of costs that need to be considered based on the type of printer. This section will examine the requirements for using different levels of printers, namely metal, production level polymer, and desktop polymer printers. The requirements and costs to be considered are labor, raw materials, testing equipment, and post-processing equipment, as well as infrastructure requirements such as facilities and energy. Additionally, this section will look at the training and education requirements for the labor force that will operate the machines, test equipment and post processing requirements.

It is important to note the differences in the quality and value of items produced by the different levels of AM technology. A metal printing machine is more expensive and requires more support equipment than the other two levels, but has the ability to print

end item parts for aircraft and vehicles. Due to the nature of the items produced by metal AM, the requirement for the quality of pre- and post-processing operations is higher than for production or desktop polymer parts. Production polymer printing is less expensive with fewer support requirements than metal printing, but is more expensive than desktop printing. Production polymer is capable of printing polymer aircraft parts, as well as high quality prototypes, drill guides and tooling. Desktop printing is the cheapest and easiest to use of the three levels of AM that are discussed in this study. However, the items that desktop printers produce are mostly noncritical, easily replaceable commodity items. The costs associated with each of these systems will be discussed to provide an estimate of the resources required to field different levels of an AM capability.

Metal Printing

Metal AM will be the most difficult type to employ at a location. The first item to consider is the safety requirements for metal AM. The metal powder used in metal AM has a number of risks associated with it, most notably that some metals are extremely flammable and explosive in nature. Care needs to be taken in both the facility setup and in the actions of the personnel operating the machine to ensure that the risk of fire or explosion is kept to a minimum. Class D fire extinguishers need to be available at the site in case of a fire. The metal powder also poses a health risk if it is inhaled or touches the skin, including gastrointestinal problems and Alzheimer's and pulmonary disease from chronic exposure (NIST, 2013). Due to these health risks, operators are required to wear specific personal protective equipment (PPE) while interacting with the machine including a respirator and protective clothing. Since printing in metal requires nitrogen

or argon gas to be pumped into the build environment, a lack of oxygen is also a safety concern and must be monitored for operator safety. Finally, any unused powder that can't be recycled and used again must be disposed of as HAZMAT using a wet vacuum. One of the sites visited by the researcher mentioned that waste metal powder caused a large fire when it was disposed of improperly.

Another important factor is facility requirements for a metal AM machine. The National Institute of Standards and Technology (NIST) within the US Department of Commerce released a report titled *Lessons Learned in Establishing the NIST Metal Additive Manufacturing Laboratory*. The report lays out several items to consider when establishing a metal AM capability at a location. While the EOS M290 printer is dwarfed in size by other large pieces of manufacturing equipment, it still requires a large area and material handling equipment to place it in its space. The M290 weighs approximately 2,756 lbs. and is 8.2 x 4.26 x 7.18 ft., and EOS recommends that there be 15.75 x 11.83 x 9.5 ft. of space set aside for the machine (EOS). It needs to be placed in a structure with level floors that can support its weight and the weight of anyone operating the machine. There also needs to be room and support for the bottles of nitrogen or argon gas used to create an inert environment for the build, as well as proper ventilation and a monitoring system to ensure that the oxygen levels don't go below a safe level. The room housing the machine also needs to be kept within a specific temperature and humidity range for optimal operations. While not in operation and empty of metal powder, the machine can be kept in a room with a temperature between 10°C and 40°C, with a relative humidity between 20% and 80%. When the machine is in operation, the temperature and relative

humidity needs to be from 20°C to 25°C and 60% humidity, or from 25°C to 30°C and 45% humidity (EOS, 2014). There also needs to be on-site storage for the metal powders used by the machine. The NIST report recommends that the powder be kept in “their original, tightly closed vendor-supplied containers with the desiccant, inside an approved metal, flammable storage cabinet that is cool, dry, and ventilated. This cabinet should protect against physical damage and be isolated from sources of heat, ignition, and moisture” (Moylan et al, 2013). Additionally, the facility housing the machine needs to have the appropriate utilities, including *reliable* power and running water. The EOS fact sheet for the M290 states that the power requirement for the machine is typically 3.2kW with a maximum requirement of 8.5kW (EOS, 2014). While supplying this level of power shouldn’t be a challenge for a main operating base, supplying this level of constant power over the course of a 200 or 300-hour build could be difficult and likely impossible at forward operating bases. The Air Force Institute of Technology (AFIT), spent \$61,000 preparing a facility for a metals AM machine, while NAVAIR spent \$80,000 preparing their AM facility at Lakehurst for metals AM operations.

The metal machine being used for this study is the EOS M290, which is the machine currently being evaluated by AFLCMC for metal AM production. The equipment and capabilities listed below are the items needed to support production of metal parts with the EOS M290. The equipment will be divided up into equipment that is used for preprocessing, while the machine is in use, and post-processing. The machine itself and included support equipment (transformer, air-water laser cooling system, fine and course filter systems, wet separator vacuum and antistatic mat) costs approximately

\$1,100,000. The yearly maintenance contract costs \$18,000 per year. It is recommended that a facility have one AM machine per alloy family that they are planning to print to prevent contamination. For example, if a facility was planning to print Aluminum, Nickel, Steel and Titanium, they should have four machines.

Preprocessing

For the purposes of this study, preprocessing will also include any non-recurring engineering or work that needs to be done to complete the part's data package, as well as production scheduling for the AM machines. A Coordinate Measurement Machine (CMM) takes detailed measurements of an object by touching and tracing the part with its probe. The CMM can be used to create a 3D drawing of a part for reverse engineering, or to ensure that a part or build plate are within tolerances after post processing. A CMM costs approximately \$100,000. A 3D laser scanner is similar to a CMM, but uses a laser to "paint" the exterior of a part to create a 3D image of the part. It costs approximately \$103,000 for a 3D laser scanner and two pieces of support software. Both pieces of software use the data from the 3D scanner to form the basis for a CAD drawing to create a 3D data package. However, the CAD file generated from a CMM or laser scanner doesn't have all of the required information needed to complete the 3D drawing, such as tolerances, materials, specifications, or surface finish. Two additional types of software are required to produce the part using AM, Computer Aided Design (CAD) and an AM design software. CAD software converts point cloud data from a structured light scanner into surfaces and volumes required to generate a 3D model. AM design software is used to orient the part to the build plate and build the support structure to print the part

correctly. Licenses cost \$20,000 per license for AM design software and \$7,500 per license for CAD software. It is recommended that there be one license for each software package per design engineer that is working at a facility. On-the-job training and some classroom instruction may be required for engineers or operators new to using these software packages. It is recommended that users have engineering experience or machinist experience. Finally, it is recommended that each AM facility incorporate a Product Lifecycle Management software and Enterprise Resource Planning software into their operations. A Product Lifecycle Management software is used to coordinate efforts throughout the production of an item, by ensuring design and revision control, and streamlining the design approval process. Enterprise Resource Planning software is used to manage resources in a production environment, by managing production planning, manufacturing equipment, and inventory management. Since AM is a production process, it is important to manage all of the inputs and resources to ensure that it operate efficiently. A Product Lifecycle Management software costs approximately \$80,000 and an Enterprise Resource Planning software costs approximately \$20,000. An additional capability required for pre-processing is a powder-receiving and evaluation laboratory with the appropriate equipment to ensure that newly received powder meets the required specifications. An AM facility can either have this capability in-house by buying the required equipment or contract out for the capability. As AM usage moves into the deployed environment it is likely that the equipment will be needed in-house.

In-process

During the build process, argon needs to be piped into the build chamber. One option to supply the argon is to use a High-Pressure Argon Change Over Regulator supplied by a High-Pressure Argon Manifold connected to high-pressure Argon cylinders. The manifold is connected to individual Argon cylinders and delivers the gas to the regulator. The regulator flows the correct amount of argon to the build chamber. The manifold costs approximately \$3,000, while the regulator, complete with alarm to let the operator know when the bottles are empty, costs \$3,500. The cost of Argon itself is not a significant cost as the AM lab at AFIT is currently purchases a 150,000 liter Argon Dewar for \$216 and use 15 liters of Argon per hour. As mentioned in the safety section above, the AM lab needs to have Oxygen sensors installed to make sure that operators know if the Argon starts to displace the Oxygen in the lab. There should be one Oxygen sensor per AM machine, and an additional sensor if the Argon is kept in a different room than the machine(s). Each sensor costs approximately \$1,500. Additionally, there are approximately \$500 to \$1,000 worth of consumables used during a build (such as rakes, filters, etc.).

Post-processing

The post-processing requirements for parts must also be considered when determining what is required to field a metal AM system. The part will need to be heat treated after the build is complete with a range of pressure, temperature, and gas environment requirements for the furnace. The part needs to be removed from the build

plate using at a minimum a band saw, although a Wire Electrical Discharge Machine (EDM) is common practice in regulated manufacturing environments. There needs to be a process to remove unsintered powder from around the part. There needs to be a process to remove any support material from the part as well as any additional machining as most AF parts require surface finishes smoother than as-printed material. If there is any requirement for quality assurance testing or certification, the testing equipment needs to be available as well.

Most support equipment will be needed for post-processing, turning an AM part on a build plate into a completed end item. A Heat Treatment Furnace is needed to relieve stress while parts are still on the build plate and possibly harden parts through additional heat treatment stops, possibly including Hot Isostatic Pressing (HIP). HIP machines require specialized facilities and are much more expensive than Heat Treatment Furnaces. It costs approximately \$26,000 per furnace, and a facility may need different furnaces for different alloy families that they print. For example, titanium requires a dedicated furnace that can't be used by any other alloy family. Next, a Band Saw or EDM are used to remove the part(s) from the build plate. A Band Saw costs approximately \$15,000 and while it is more than capable of removing parts from the build plate, it is a rough cut and the cut portion of the part may require additional machining to achieve the proper finish. The Wire EDM costs approximately \$160,000, and while it is much more expensive than the Band Saw, but it can cut a part off of the build plate so there is little to no need for additional machining on the cut edge to bring it to finished quality. The facility or its management need to decide whether their

requirements warrant spending the additional funds on a Wire EDM instead of using a Band Saw. A 4-Axis CNC Mill can be used to machine parts to bring them closer to a finished product. It can also be used to refinish build plates after parts are removed, which is required before the plate can be used to print subsequent builds. A 4-Axis CNC Mill costs approximately \$75,000. Media Blast Cabinets are needed to surface treat parts to the required surface finish. The Media Blast Cabinet is enclosed and uses feedstock alloy powder to blast the surface of a part. It is recommended that each AM facility have one Media Blast Cabinets per alloy family that they print for a cost of approximately \$10,000 per Cabinet. A Down Draft Table with Belt Sander can also be used to treat the surface of a part by sanding and grinding the part down to the required finish assuming that these methods are permissible for finishing the particular part. The table can remove metal particles and dust that are grinded or sanded off so that they aren't released into the lab. A Down Draft Table with Belt Sander costs approximately \$20,000. Finally, hand tools can be used throughout the lab for a variety of tasks before, during, and after the build. Hand tools can range in price, but \$10,000 is enough to buy a suitable set. There are specific requirements for tools that contact end use parts, such as with titanium parts and metals allowed to contact them. Table 3 is an example of all the required equipment and costs for a facility that prints in one alloy family.

Table 3. Metal AM Equipment and Costs (AFLCMC and UDRI, 2016)

Equipment	Quantity Needed	Approximate Cost
EOS M 290	1	\$1,100,000
EOS M 290 Maintenance	N/A	\$18,000 per year
Media Blast Cabinet	1 (1 per alloy family)	\$10,000
High Pressure Argon Change Over Regulator	1 (1 per AM machine)	\$3,500
High Pressure Argon Manifold	1 (1 per AM machine)	\$3,000
Heat Treatment Furnace	1 (1 per alloy family)	\$26,000
Horizontal Dual Column Band Saw OR Wire Electrical Discharge Machine (EDM)	1	\$15,000 – Band Saw \$160,000 – Wire EDM
4-Axis CNC Mill	1	\$75,000
Oxygen Sensor	1 (1 per AM machine)	\$1,500
Down Draft Table with Belt Sander	1	\$20,000
Coordinate Measurement Machine	1	\$100,000
AM Design Software Licenses	1 per AM design engineer	\$20,000 per license
CAD Software Licenses	1 per AM design engineer	\$7,500 per license
Personal Protective Equipment	1 set	\$7,000
Product Lifecycle Management Software	1	\$80,000
Enterprise Resource Planning Software	1	\$20,000
Hand Tools	1 set	\$10,000
TOTAL		\$1,516,500 (Band Saw) OR \$1,661,500 (Wire EDM)

Production Level Polymers

An example of a production polymer machine that is being used in the USAF is the Stratasys Fortus 900mc is 9.09 x 5.53 x 7.48 ft. and weighs 6,325 lbs. with a build envelop of 36"x24"x36" (Stratasys, 2015). As a reference, the 986 MXS purchased their Fortus 900mc for \$380,000, which is much less expensive than a metal machine. According to site preparation documents provided by Stratsys, the required operating temperature for the Fortus 900mc is 60° to 85°, the humidity requirement is between 20% and 80%, and the printer requires 230VAC 3-phase service at either 50 or 60 Hz (Stratasys, 2015). The power and environmental requirements shouldn't be a problem for a main operating base, but could provide more of a challenge in an expeditionary environment. Additionally, the printer requires continuous compressed air at 90-120 psi over the entire build time, which can amount to days. The 552 MXS purchased a Fortus 400mc, an older model with a 16"x14"x16" build envelop, for \$120,000 (Stratasys, 2015).

The 982 MXS has a few pieces of support equipment for their operations, and these pieces of equipment could be adopted for use at any location with a production level polymer machine. First is a Universal Power Supply, to ensure a constant supply of power to the machine during a power outage or interruption. The model that the 982 MXS purchased costs \$40,000. A Stratasys Smoothing Station allows FDM parts to have a surface finish that is similar to an injection-mold part, and costs \$35,000. An FDM cleaning station removes soluble support material from parts and costs \$46,000.

Additionally, an AM site needs a 3D design software like Solidworks, which costs \$7,500 per license.

Desktop Polymer Printers

Desktop polymer printers will be the easiest type of machines to field at a location. As the name suggests, these units are designed to fit on a desk or table top and are safe enough for use in homes, schools, and workshops. Desktop polymer printers are currently used by the military in a number of different environments, from such diverse locations as laboratories, aboard ships at sea, and in deployed environments in the Middle East. There few safety concerns associated with desktop polymer printers, although some components get hot during operations and could injure the user if they aren't following recommended safety protocols. Additionally, recent research has found that printing with acrylonitrile butadiene styrene (ABS) or nylon based filaments in a space that isn't well ventilated can expose the user to unsafe levels of ultrafine particles and hazardous volatile organic compounds (Azimi et al, 2016). It is recommended that desktop printers be installed in well a ventilated space, or that users not print with ABS or nylon based filaments. Desktop printers can range in cost from a few hundred dollars to over fifteen thousand dollars on GSA Advantage. Desktop printers do not require extensive support equipment.

VI. Cost Benefit

Introduction

This chapter discusses the cost calculations conducted in the study. The information for the candidate parts will be discussed, as well as the ability to produce them using AM. The costs to produce each part with AM will be presented, along with a breakdown of the average cost for the parts. Finally, the study will discuss the NRE costs and how these impact part cost and the breakeven point.

Parts Comparison

To determine the potential benefit additive manufacturing can provide to the Air Force's supply chain for aircraft parts, the cost of producing the part through AM and the current method of procurement were compared. This comparison rests on the assumption that there are no technical challenges regarding materials substitution to AM for the specified component, which is likely not true but beyond the scope of this study, and that the selected parts are capable of being produced using AM processes. The cost of producing the part using AM will consider the cost of raw materials, machine time used, labor, and any post processing that may be required. For the sake of comparison, this paper will use the price that the USAF currently pays for a part according to the Federal Logistics Information System (FLIS). This price could be paid to the original equipment manufacturer (OEM), a third-party contractor, or be produced by USAF personnel. This paper won't look at the components of the current cost of the part, as that is also outside of the scope of this study.

The researcher selected ten parts from the LMI study to conduct a cost analysis. The parts are listed by National Item Identification Number (NIIN) below. The information presented includes part dimensions, material, PLT, ALT, unit price, demand for the past five years, and the weapon system that the part is used on. Table 4 provides a detailed breakdown for each part, and those parts that were judged to be candidates for AM are italicized.

Table 4. Part Characteristics

NIIN	<i>011927581</i>	012251789	<i>014076208</i>	014955559	<i>015846976</i>
Length	<i>7.2 in</i>	5.9 in	<i>5.8 in</i>	18.3 in	<i>12 in</i>
Width	<i>4.4 in</i>	3.1 in	<i>1.8 in</i>	17.7	<i>Unavailable</i>
Thickness/Height	<i>4.72 in</i>	Unavailable	<i>2.0 in</i>	.060 in	<i>Unavailable</i>
Diameter	<i>Unavailable</i>	Unavailable	<i>Unavailable</i>	Unavailable	<i>Unavailable</i>
Material	<i>Titanium</i>	Titanium	<i>Titanium</i>	Polycarbonate	<i>Titanium</i>
PLT	<i>365 days</i>	454 days	<i>245 days</i>	213 days	<i>229 days</i>
ALT	<i>152 days</i>	73 days	<i>79 days</i>	99 days	<i>111 days</i>
Unit Price	<i>\$2,143.50</i>	\$4,507.00	<i>\$1,265.00</i>	\$16,663	<i>\$1,118.00</i>
Demand Last 5 Years	<i>0</i>	3	<i>182</i>	56	<i>52</i>
Weapons System		F-15		B-1	<i>T-38</i>

Table 4 (Continued). Part Characteristics

NIIN	<i>003094672</i>	<i>004000577</i>	<i>014414932</i>	<i>014484050</i>	<i>016175591</i>
Length	<i>11.8 in</i>	<i>10 in</i>	<i>5.1 in</i>	Unavailable	<i>2.5 in</i>
Width	<i>Unavailable</i>	<i>1.5 in</i>	<i>4.9 in</i>	Unavailable	<i>2.2 in</i>
Thickness/Height	<i>Unavailable</i>	<i>2.4 in</i>	<i>4.1 in</i>	.060 in	<i>1.2 in</i>
Diameter	<i>3.2 in</i>	<i>Unavailable</i>	<i>Unavailable</i>	Unavailable	<i>Unavailable</i>
Material	<i>Steel</i>	<i>Steel</i>	<i>Titanium</i>	Polyethylene	<i>Aluminum</i>
PLT	<i>324 days</i>	<i>461 days</i>	<i>262 days</i>	262 days	<i>276 days</i>
ALT	<i>54 days</i>	<i>150 days</i>	<i>118 days</i>	132 days	<i>133 days</i>
Unit Price	<i>\$3,550.26</i>	<i>\$1,837.76</i>	<i>\$3,812.86</i>	\$4,245.53	<i>\$1,659.69</i>
Demand Last 5 Years	<i>104</i>	<i>5</i>	<i>41</i>	0	<i>0</i>
Weapons System		<i>C-5</i>	<i>F-15</i>		<i>C-130</i>

with AM, there are most likely other manufacturing methods that would be much cheaper than AM, such as machining from Titanium plate.

011927581 – This part is an aircraft fluid manifold. After reviewing the engineering drawings from JEDMICS, it was determined that there were significant issues with using AM to produce this part. There is no feasible way to orient the part to prevent overhangs, which are known to have an adverse effect on surface finish and print quality. It would be extremely difficult, if not impossible to produce this part using AM. Most likely extensive support would need to be provided to the part during the build, and that support material would need to be removed during post-processing. Due to the requirement for

support and the details of the part, machining time and cost is likely to be a significant portion of the overall cost for this part. Additionally, due to the parts size, only one can be printed at a time.

014076208 – This part is a fan duct mounting bracket. After reviewing the part drawings, it was determined that this part could be produced using AM. Based on the parts dimensions, a total of 3 could be produced in one build. The part requires extensive machining after the build to attain the required surface finish and to complete part features.

016175591 – This part is a torque box for the C-130. The engineering drawings from JEDMICS show that this part can easily be built using AM. Very little machining would be needed after the build to drill holes and to attain any required surface finish. Nine of these parts can be produced in the same build.

014414932 – This part is a flap up-stop for the F-15. After reviewing the drawing in JEDMICS, it appears that this part will be difficult to produce without significant support material. There is no way to orient the part to prevent overhangs. The part will require significant machining after the build to remove support material and machine out part features. Due to the part's size, only one can be produced at a time.

004000577 – This part is a rail mount for the C-5. It was determined that this part could be produced using AM. It will require some machining after the build to remove support material and to complete the part fabrication, but the machining shouldn't be extensive or costly. Due to the part's size, only one can be built at a time.

003094672 – This part is a gear shaft spur for an aircraft. It is feasible to produce this part using AM. The part will require extensive machining after the build in order to finish the part fabrication, including drilling holes and completing the gear teeth. Five of these parts can be produced in the same build.

014955559 – This part is an interior panel lining for the B-1. More data is needed to assess the viability and cost of producing this part with AM than is currently in JEDMICS. The researcher was unable to determine the required surface finish or surface detail required for the part based on the drawing. The part's dimensions and material would require that it be printed through an FDM process in polymer. If it were feasible to print this part using AM it would likely be cost effective, due to the relatively high cost that the Air Force currently pays for it.

014484050 – This part is an aircraft structural support. The drawings in JEDMICS did not provide the level of detail required to determine if this part could be produced using AM.

012251789 – This part is an aircraft former for the F-15. The engineering drawings did not provide enough detail to determine if this part could be produced using AM. The part is visible in the drawings provided, but there are no dimension details.

Of the ten parts selected for investigation, production cost was calculated for seven based on their feasibility for AM and the availability of detailed drawings. Tables 5 and 6 detail the costs for producing each part in single or maximum part builds.

Table 5. Single Part Build Costs

NIIN	"015846976"	"011927581"	"014076208"	"016175591"	"014414932"	"004000577"	"003094672"
Material Cost per part	220.43	498.76	268.87	13.17	1241.52	581.43	581.43
Pre-processing Cost	90.00	90.00	90.00	90.00	90.00	90.00	90.00
Processing Cost	574.30	2881.73	548.92	217.63	1017.33	600.96	1888.42
Maintenance Cost	166.20	833.94	158.85	62.98	294.40	173.91	546.49
Energy Cost	6.23	31.27	5.96	2.36	11.04	6.52	20.49
Post-Processing	690.00	1390.00	1390.00	690.00	1390.00	990.00	1390.00
Build Time	46.17	231.65	44.13	17.49	81.78	48.31	151.80
Cost per part	1747.16	5725.70	2462.60	1073.78	4044.30	2442.83	4516.83
Number of Parts	1	1	1	1	1	1	1
Current Price	\$1,118.75	\$2,049	\$1,265.00	\$1,659.69	\$3,812.86	\$1,837.76	\$3,550.26
Cost Change with AM	(\$628.41)	(\$3,676.70)	(\$1,197.60)	\$585.91	(\$231.44)	(\$605.07)	(\$966.57)
Current Lead Time	340	517	324	409	380	611	378
5-year Demand	52	1	182	1	41	5	104

Table 6. Maximum Number of Parts per Build Costs

NIIN	"015846976"	"011927581"	"014076208"	"016175591"	"014414932"	"004000577"	"003094672"
Material Cost per part	201.71	498.76	255.56	10.06	1241.52	581.43	573.95
Pre-processing Cost	5.63	90.00	30.00	10.00	90.00	90.00	18.00
Processing Cost	168.32	2881.73	418.39	47.18	1017.33	600.96	1503.53
Maintenance Cost	48.71	833.94	121.08	13.65	294.40	173.91	435.11
Energy Cost	1.83	31.27	4.54	0.51	11.04	6.52	16.32
Post-Processing	136.88	1390.00	996.67	165.56	1390.00	990.00	918.00
Build Time	216.48	231.65	100.90	34.13	81.78	48.31	604.31
Cost per part	561.24	5725.70	1826.23	246.45	4044.30	2442.83	3464.91
Number of Parts	16	1	3	9	1	1	5
Current Price	\$1,118.75	\$2,049	\$1,265.00	\$1,659.69	\$3,812.86	\$1,837.76	\$3,550.26
Cost Change with AM	\$557.51	(\$3,676.70)	(\$561.23)	\$1,413.24	(\$231.44)	(\$605.07)	\$85.35
Current Lead Time	340	517	324	409	380	611	378
5-year Demand	52	1	182	1	41	5	104

Table 7 shows the average costs across the seven parts and a breakdown of total costs.

Table 7. Single Part Builds Cost Breakdown

Build Component	Average	Percentage
Material Cost	\$486.52	15.47%
Pre-processing Cost	\$90.00	2.86%
Processing Cost	\$1,104.19	35.11%
Maintenance Cost	\$319.54	10.16%
Energy Cost	\$11.98	0.38%
Post-Processing	\$1,132.86	36.02%
Build Time	88.76	N/A
Cost per part	\$3,144.74	N/A

Figure 1 is a graphical representation of the cost components of the average build of a single part.

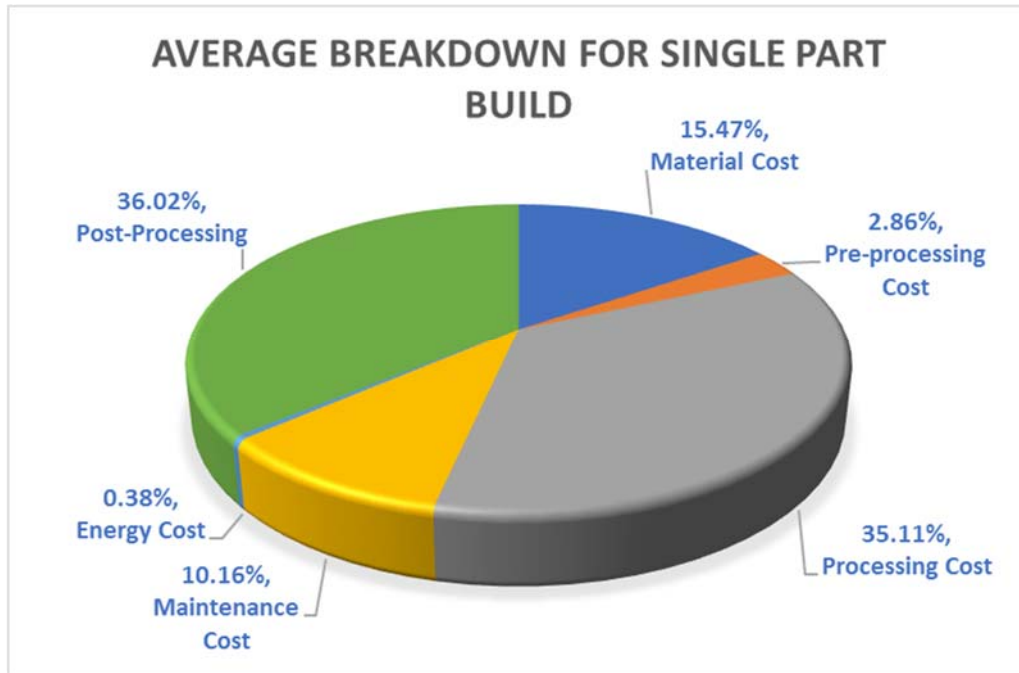


Figure 1. Average Breakdown for Single Part Build

Table 8 depicts the average cost breakdown for the maximum number of parts per build.

Table 8. Maximum Number of Parts per Build Cost Breakdown

Build Component	Average	Percentage
Material Cost	\$480.43	18.37%
Pre-processing Cost	\$47.66	1.82%
Processing Cost	\$948.21	36.25%
Maintenance Cost	\$274.40	10.49%
Energy Cost	\$10.29	0.39%
Post-Processing	\$855.30	32.70%
Build Time	188.22	N/A
Cost per part	\$2,615.95	N/A

Figure 2 is a graphical representation of the cost components of the average build of the maximum number of parts possible.

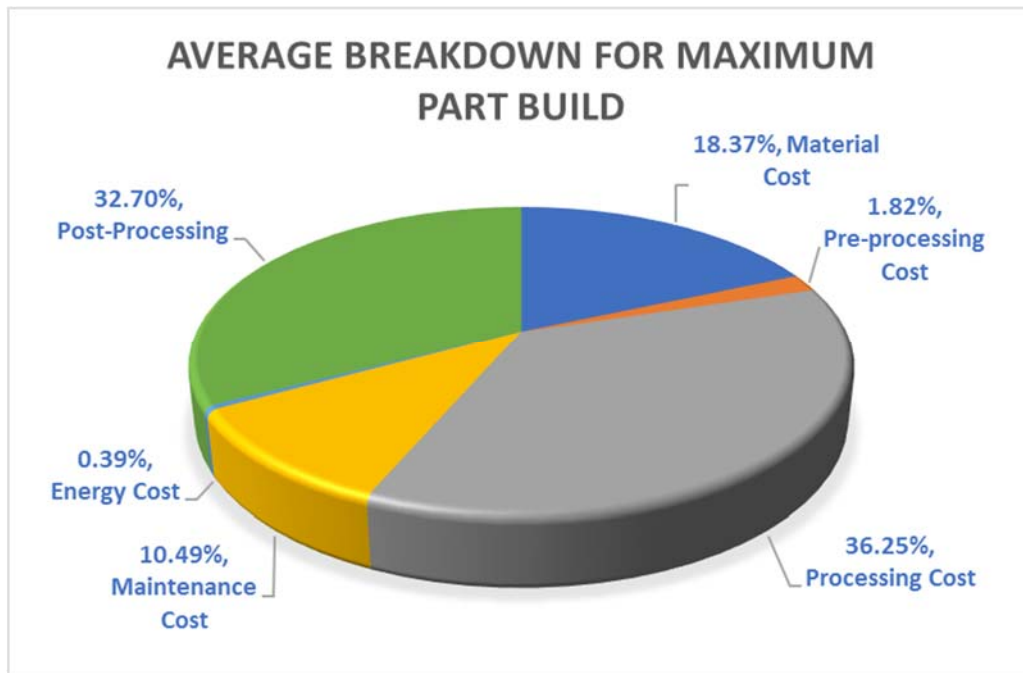


Figure 2. Average Breakdown for Maximum Part Build

Of the seven parts analyzed, only one cost less to produce one part at a time with AM than the current cost of acquisition. When the maximum number of a part is built at one time, three parts cost less to produce with AM than the current price the Air Force pays. However, this is before the NRE is considered, which will drive up the overall cost significantly.

Figure 3 depicts the lead time and the cost change with AM vs the current cost of procurement for printing a single unit of a part.

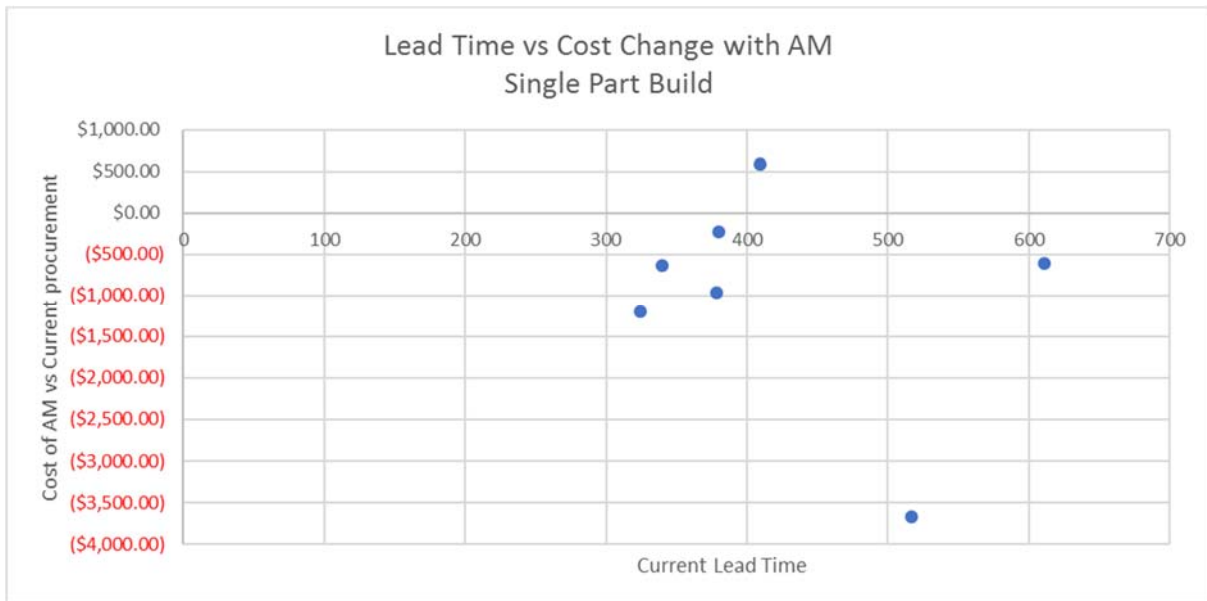


Figure 3. Lead Time vs Cost Change with AM Single Part Build

The part above the x-axis is a good business case for AM, even when only one part is printed at a time. Parts below the x-axis may also be good business cases for AM based on their lead time. Figure 4 shows depicts the lead time and the cost change with AM vs the current cost of procurement for printing the maximum number of units of a part that can fit on a build plate at one time.

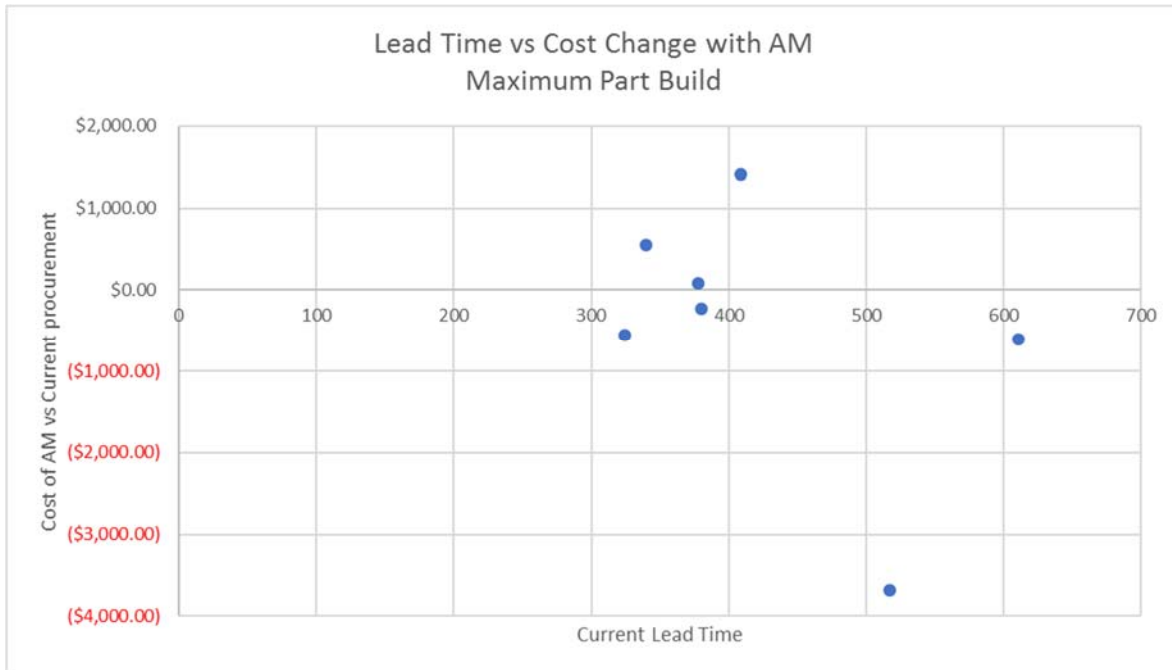


Figure 4. Lead Time vs Cost Change with AM Maximum Part Build

Again, parts that are above the x-axis are good business cases for AM, because the production cost for AM is lower than the cost of the current procurement method. Even the three parts located just below the x-axis may be good cases for AM because of their excessive lead times.

NRE

NRE could be the most expensive and time consuming component of producing a part using AM. This is due to the need to analyze a legacy part or legacy drawings, analyze the part's material and mechanical properties, and produce a printable 3D model. The DoD does not have reliable 3D information for many of the aircraft parts that it uses, and in many cases there are no reliable 2D drawings for a part. In order to produce a part with AM, there needs to be an accurate 3D model that can be loaded into the machine to

produce the part. The amount of engineering time required to produce a 3D model depends on the complexity of the part and the availability of schematics or data. Additionally, NRE time may depend on the material or mechanical properties of a part.

The AFLCMC estimates that it costs \$1,000,000 to complete the NRE to prepare a part to be produced with AM. If this \$1,000,000 included the cost to redesign the part to optimize it for AM, then it could have the added benefit of decreasing the amount of material required for the part, decreasing the part's weight, and increasing the part's durability. The benefits from this redesign could be a longer part lifespan, or a decrease in the parts weight which saves fuel over time, both of which would help defray the cost of the NRE.

The Tinker REACT group stated that on average it takes them 40 hours of labor to reverse engineer parts for AM. However, they only print in polymer parts and it is likely that reverse engineering for metal printing will take longer than polymer printing. There is obviously a difference between \$1,000,000 and the cost of 40 hours of work, but it is difficult to propose a blanket NRE cost across all parts. The NRE time and cost will differ from part to part, and in some cases may only take 40 hours of work and in other cases will cost close to \$1,000,000.

VII. Conclusion

Introduction

This chapter will detail the conclusions drawn from this research on AM in the DoD and the costs associated with employing AM. The research questions will be reviewed and answers will be provided based on Chapter IV, V, and VI. Then this chapter will discuss the potential for related follow-up research. Finally, recommendations based on the findings of this research will be provided.

Research Questions Answered

This research addressed four research questions. The results and analysis from Chapters IV, V, and VI were applied to these questions. Each question and the answer provided by this research are provided below.

1) How do the military services incorporate AM into their operations?

The research shows that all the military services are using AM in some capacity. There doesn't appear to be a service that is further ahead than the others. The USN, USAF, and USMC are all using AM within their depot maintenance systems to assist production. There is widespread adoption of production and desktop polymer AM within the DoD. There is limited use of metal AM in the DoD, and the metal AM currently in use is mostly used for research.

2) What are the costs associated with employing different process technologies of AM?

Metal AM is significantly more expensive than the other two process technologies examined by this research. It is estimated that it costs over \$1,600,000 to purchase a metal AM machine and the required support equipment. It is important to note that while metal AM is the most expensive process technology to employ, it has the potential to produce highest value parts of the three process technologies examined in this study. A production level polymer capability can be fielded for a cost of approximately \$250,000 to a cost of approximately \$510,000. Desktop printers can cost as little as \$500 or as much as \$17,000 depending on unit requirements.

3) What is the cost of producing a part using AM vs the cost that the USAF currently pays to procure the part?

The calculation for price per part included preprocessing time, processing time, post-processing time, and material cost. NRE cost was not included in the cost per part because it can change significantly from part to part. The cost analysis conducted in this research showed that the production costs per part for AM can be close to the price that the Air Force currently pays per part. Cost calculations were completed for seven parts, and four of these parts cost less to build than the cost the USAF currently pays for them.

Future Research

As a follow-on to this thesis, research should be conducted to determine the cost to produce polymer parts compared to the price the USAF currently pays. A polymer cost equation could be based off the equation presented in this research, with different material costs and a polymer specific processing time calculation. It could also be possible to conduct a similar cost comparison using parts for a specific weapon system. By partnering with a weapon system program office, a researcher may be able to examine

how the lead time savings from AM impacts aircraft availability. A key step in justifying the cost increase of an AM part over a traditionally procured part is the lead time savings that AM can provide. Determining the cost to the USAF of having an aircraft Not Mission Capable-Supply (NMCS) could help quantify this lead time savings. The cost of an aircraft NMCS could be a dollar amount or a tax on overall enterprise readiness, and most likely varies from weapon system to weapon system. Being able to compare the increased cost of an AM part with a cost savings or readiness increase would help justify a larger investment in AM technology. A third option for future research would be looking at possible applications for AM with vehicles and material handling equipment, and determining if there is a need for rapid part production to repair those assets.

Future research should consider basing strategies for metal AM machines to place them at locations that will be most beneficial to the USAF supply chain. If the USAF wants to take an enterprise-wide network approach, it is crucial that machines be placed at the correct bases. There are several factors that should be considered including location, skillsets available both on base and in the local community, and part need. To adequately determine location requirements the USAF must first decide which parts will be produced with AM, then research can be done to determine the need for these parts at individual bases. Metal AM machine locations can be evaluated by considering available transportation assets and proximity to other bases with demand. Finally, future research should investigate the skillsets required for a successful AM capability, and AM basing should take the availability of these skillsets into consideration.

The researcher looked at several AM cost models to develop the cost model that was ultimately used in this study. Each model had strengths and weaknesses. The first model presented, Hopkinson and Dickens, was a basic representation of AM costs, capturing material, labor and machine costs. While the authors considered utility costs, they didn't include them in their final model. Additionally, Hopkinson and Dickens don't present a method for determining part build time (Hopkinson and Dickens, 2003). Ruffo et al. built on the framework provided by Hopkinson and Dickens and considered more cost components in their model. They considered machine, labor, material, production overhead, and administrative overhead costs. Ruffo et al. also presented the components part build time, though they merely present the components without presenting a way to actually calculate build time for an individual part (Ruffo et al., 2006). Atzeni and Salmi's cost model considers material, labor, machine, and post-processing costs. Like the previous two cost models, they do not present a clear way to calculate build time. For the purposes of their research they got the part build time from the AM machine used for production (Atzeni and Salmi, 2012). Engineering cost and testing considerations are also significant costs that are missing from all three of the studies discussed. None of these studies addresses the time and cost of taking a part from a 2D drawing to a printable 3D model. While testing costs were a small part of the cost model presented in this study, they still contribute to the overall cost of using AM. Any future cost models should consider material, labor, machine, post-processing, testing, and engineering costs. Additionally, defining the engineering cost to prepare a range of parts for AM would be useful.

This research also considered part selection as part of the cost benefit analysis for AM. Future research could look to build a USAF part selection tool. Future part selection tools should consider part demand, criticality (flight safety), build dimensions of USAF fielded AM machines, part cost, the availability of technical data and drawings, and lead time. Having the appropriate technical data and drawings is crucial to determining if an individual part can be produced with AM, and the availability of that data should be an attribute considered in future part selection tools. A future part selection decision tool could allow a user to specify constraints for part attributes (i.e. not flight critical, demand over 10 in the last five years, part cost of over \$1,000), and return a list of parts that meet the criteria. Another option would be to allow users to input a part's attributes and have the system determine if the part is a candidate for AM based on pre-defined enterprise rules. It may also be possible on the work of LMI's DLA part selection tool to create an AM part selection tool for the USAF. LMI's tool does a great job of presenting parts that meet the user's query criteria, and provides technical and logistics attributes for parts.

Recommendations

While there is great potential for time and costs savings with metal AM, it is not currently feasible to use the technology to produce aircraft parts. More work needs to be done to codify the process for producing aircraft parts with AM. Numerous technological challenges need to be addressed before there is widespread use of metal AM at base level. However, there appears to be a great deal of potential in using production level polymer printers to support maintenance activities at the base level. Using polymer AM to produce tooling, fixtures, jigs, and to conduct fit-form tests could save time and money

for Maintenance Squadrons and Aircraft Maintenance Squadrons throughout the Air Force. The 552 MXS' use of AM to support their maintenance activities shows the type of savings that USAF units may be able to realize. Production polymer machines should be distributed to bases throughout the USAF. More research and testing may need to be done to approve the use of polymer AM parts on aircraft, but the technology can be used immediately to support maintenance.

After researching AM use in the DoD it doesn't seem that the USAF is behind the other services in the adoption of AM. However, the USAF should publish more guidance for Airmen on the uses of AM and the potential of the technology. Even after nine months of studying AM researcher doesn't know what rules the Air Force has for AM use. Can a squadron purchase an AM machine on their own? Is there a specific process technology that units must use? Is there a specific machine that units must purchase or are they free to determine which machine best suits their needs? Better Air Force guidance appears to be coming and will most likely address these questions. However, as AM becomes more popular and gets more publicity, more units will attempt to adopt the technology. In order to ensure that unit-level adoption supports enterprise-wide AM goals clear guidelines are needed.

Appendix A: Request For Exemption From Human Experimentation Requirements



DEPARTMENT OF THE AIR FORCE AIR UNIVERSITY (AETC)

26 August 2016

MEMORANDUM FOR AFIT IRB Reviewer

FROM: AFIT/ENS
2950 Hobson Way
Wright Patterson AFB OH 45433-7765

SUBJECT: Request for exemption from human experimentation requirements (32 CFR 219, DoDD 3216.2 and AFI 40-402) for an AFIT Research Study

1. The purpose of this study is to gain insight from technical experts on Additive Manufacturing's current practices and potential to support aircraft maintenance, and benchmark these practices with parts production methods now used at USAF air bases and depots. The results of this study will be presented to HQ AFMC/A4P leadership to help them understand the opportunities and limitations of Additive Manufacturing support to aircraft maintenance.
2. This request is based on the Code of Federal Regulations, title 32, part 219, section 101, paragraph (b) (2) Research activities that involve the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) Any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.
3. Methodology to mitigate personal identifiers/demographic information.
 - a) The data collected from in-person and telephone discussions, and electronic messaging will be stored in a password protected database. Any reference to the information collected from the subjects in any published document will exclude personal identifiers.
 - b) I understand that the names and associated data I collect must be protected at all times, only be known to the researcher, and managed according to the AFIT interview protocol. All interview data will only be handled by the following researchers: Dr. Alan Johnson, and Capt Ryan Crean. At the conclusion of the study, all data will be retained and protected by the principal investigator (Dr. Johnson).
4. The following information is provided to show cause for such an exemption:
 - a) Equipment and facilities: Discussions will be conducted in the subjects' office or work location, either in-person or over the phone. A researcher will use an audio recording device to record the discussions and a laptop computer or notebook to take notes during each meeting.
 - b) Subjects: Individuals chosen to be interviewed will be technical experts involved in Additive Manufacturing operations.

- i. Source of subjects: Technical managers, engineers and machine operators involved in Additive Manufacturing parts production.
 - ii. Total number of subjects: Maximum of 19 personnel
 - iii. Inclusion criteria: None
 - c) Timeframe: Discussions will be accomplished during the months of August through December 2016 via in-person visits, phone calls and in some cases site visits to see places of operation.
 - d) Data collected:
 - i. Individual name, work organization, education, experience and responses to factual and knowledge-based questions (Attachment 3).
 - e) Risks to Subjects: Minimal. Any disclosure of the human subjects' responses outside of the research will not place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.
 - f) Informed consent: All subjects are self-selected to volunteer to participate in the interview. No adverse action is taken against those who choose not to participate. Subjects are made aware of the nature and purpose of the research, and sponsors of the research. This will be communicated to the subjects in a consent form, which will require their signature (Attachment 4).
5. If you have any questions about this request, please contact Dr. Alan Johnson (principal investigator) – Phone 255-3636, ext. 4703; E-mail –alan.johnson@afit.edu.

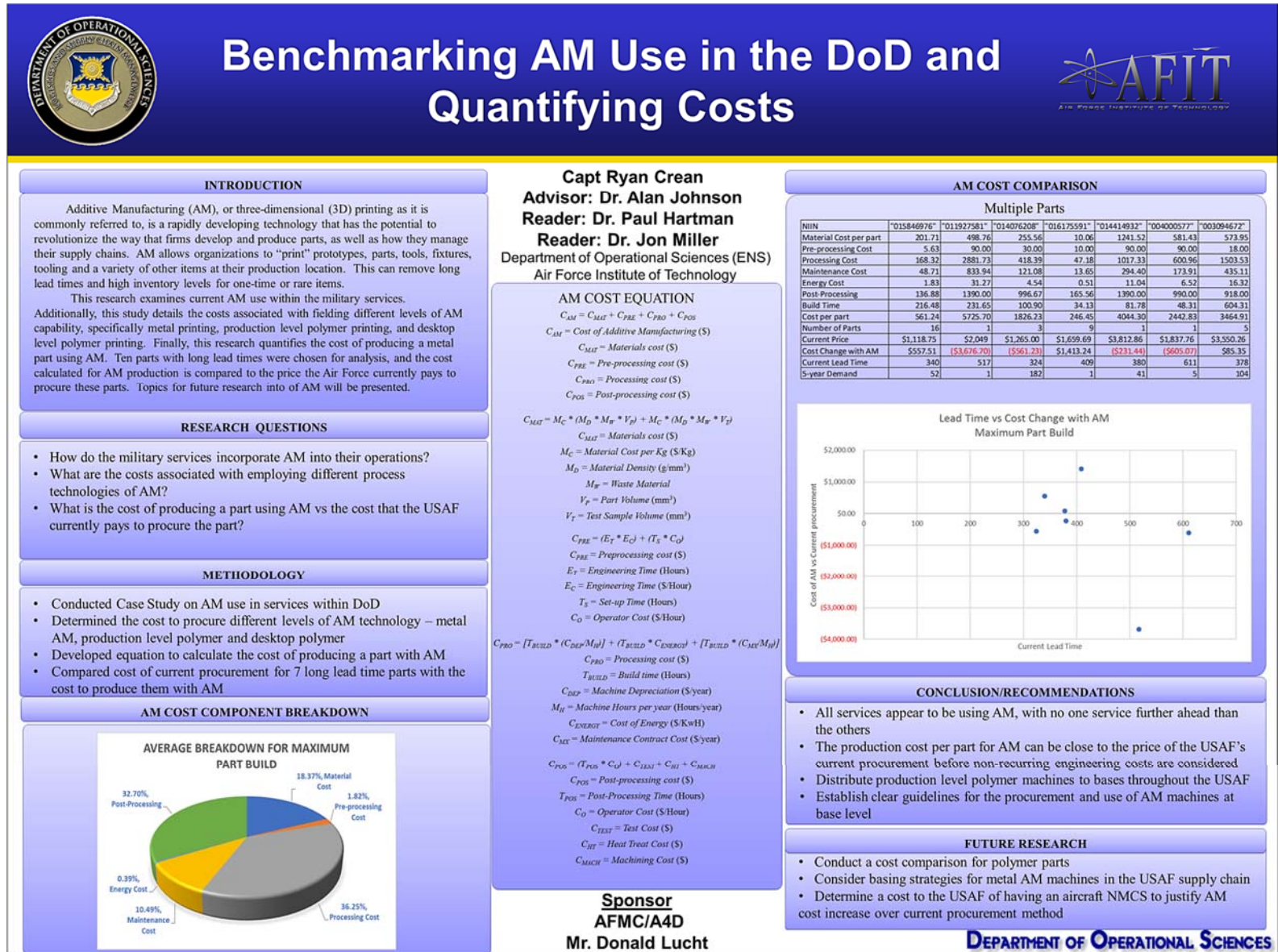


ALAN W. JOHNSON, PhD, Lt Col, USAF (Ret)
Principal Investigator

- Attachments:
- 1) CITI Completion Certificates
 - 2) Researcher CVs
 - 3) Additive Manufacturing Interview Questions
 - 4) Research Topic Description & Consent Form

Appendix B: Additive Manufacturing Contact List

Office	Contact Number
AFLCMC/EZP	937-656-6707
AFRL/RXC	937-255-5460
Robins CMXG	478-222-4082
Robins SMXG	478-926-7938
Tinker REACT	405-622-7607
NAVAIR Lakehurst	732-323-1945
HQ Marine Corps Installations & Logistics	571-256-2740



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14. ABSTRACT Additive Manufacturing (AM), or three-dimensional (3D) printing as it is commonly referred to, is a rapidly developing technology that has the potential to revolutionize the way that firms develop and produce parts, as well as how they manage their supply chains. AM allows organizations to “print” prototypes, parts, tools, fixtures, tooling and a variety of other items at their production location. This can remove long lead times and high inventory levels for one-time or rare items. This research examines current AM use within the military services. Additionally, this study details the costs associated with fielding different levels of AM capability, specifically metal printing, production level polymer printing, and desktop level polymer printing. Finally, this research quantifies the cost of producing a metal part using AM. Ten parts with long lead times were chosen for analysis, and the cost calculated for AM production is compared to the price the Air Force currently pays to procure these parts. Topics for future research into of AM will be presented.						
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