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Providing Rational for Further Funding Additive Manufacturing Efforts in the Air Force

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Additive Manufacturing Efforts in the Air Force

THESIS

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Providing Rational for Further Funding

Additive Manufacturing Efforts in the Air Force

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Abstract

Extremely long lead times for legacy aircraft replacement parts often exceed 120 days and cost 3 to 4 times the original price drives a search for alternative manufacturing methods such as additive manufacturing. Currently, the method to procuring a legacy replacement for aircraft such as the C-130 is daunting and at times, impossible. Through a comprehensive knowledge collection of organizational data the Air Force body of knowledge increases and provides actionable data to decision makers which has the potential of dramatically decreasing part wait times and procurement. The proposed, intuitive decision analysis framework mapped out in this research provides relevant direction for potential candidates considering additive manufacturing alternatives within their organizations. As result of this study, interested parties now have an abridged guide to costs, expenses, and challenges of setting up an Additive Manufacturing facility within their establishments.

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Chap 1. Introduction

Overview

Within the past few years AM (Additive Manufacturing) has become an industry disruptor throughout the AF (Air Force) and aerospace industries alike. The USAF (United States Air Force) AM Strategic Implementation Plan [1] includes AM as an essential element to the war effort. The Strategic plan is based on a crawl, walk, and run strategy where research on AM starts slow and increases to a fully operational program where expensive hard-to-create parts can be made on demand. Fiscal constraints in recent years have affected the United States AF's (USAF's) spending and sustainment of weapons systems being used beyond their programmed life cycle; thus, it is imperative that processes be thoroughly assessed for improvement, innovative approaches, and/or best practice implementation. This research will investigate if funding for AM is the best option and worth the cost to the AF and specific organizations within the AF as well as provide a comprehensive guide to pros and cons of AM.

The objective of this study is to provide tools and information to help key decision makers decide if AM operations are feasible within their organizations. Accomplishing the mission in a timely and expeditious manner is a key objective of every unit. However, complexities in procuring replacement/spare parts, due to the age of when the planes were made, making the acquisition of old legacy parts exhaustingly slow. Parts that should be simple to supply will take as long as 1 1/2 years to obtain [2]. Not only do the parts take long to receive, they can be very expensive as well. The requirement for low batch sizes contribute also to the high price of the parts. Proper research should be conducted to find out the benefits of AM in reducing costs and lead time of parts.

This study will be relevant to AF Material Command (AFMC), Air Force Life Cycle Management Center (AFLCMC), Air Force Research Labs (AFRL) Additive Department, and Air Force leadership in that results will provide a clear and understandable assessment of how much and to what degree AM funding should be focused on. Providing clear and actionable Insight will help decision makers know how much funding and manpower should be provided to further development of this technology. Achieving a high degree of importance will indirectly help reduce costs, waste, and wait times associated with traditional manufacturing. The background section will give context to this complex question.

Background

The USAF is always looking for ways to improve, innovate, and speed up processes. AM is a disruptive technology, meaning it significantly alters the way businesses or entire industries operate. It often forces companies to change the way they approach their business for fear of losing market share or becoming irrelevant [3]. To find replacement/spare air craft parts often takes 3-6 months, in some cases taking as long as 2 years [4]. Wait times of such magnitude are unacceptable to the USAF. AM aims to fix this problem by rapidly producing replacements that will sustain the plane until the permanent part can be provided.

Both the DoD and AF have seen the need to further advancement and development of AM. Funding for additional research has come from both. In 2016, America Makes (the National

Additive Manufacturing Innovation Institute) received more than 50 million dollars in federal funding to "enhance national economic and military competitiveness"[5]. It is key to national defense and military readiness to partner and fund AM efforts. The paragraph below is an excerpt of current government effort to expand AM abilities and the image below shows federally funded research labs throughout the country, many of which currently research AM.

> *"Demonstrated below is an update on the status of the manufacturing institutes most closely tied to AM will be discussed. These institutes are part of a larger and growing AM research ecosystem of federally-funded manufacturing efforts that include the Office of the Secretary of Defense (OSD) and Service-specific programs such as the Air Force Office of Scientific Research for basic efforts, Commander's Research and Development Fund for basic/applied research, and the Small Business Innovative Research Program. As of 2018, the federal government committed over $1 billion, which has been matched by more than $2 billion in investment by industry, academia, and state and local governments."*[1]

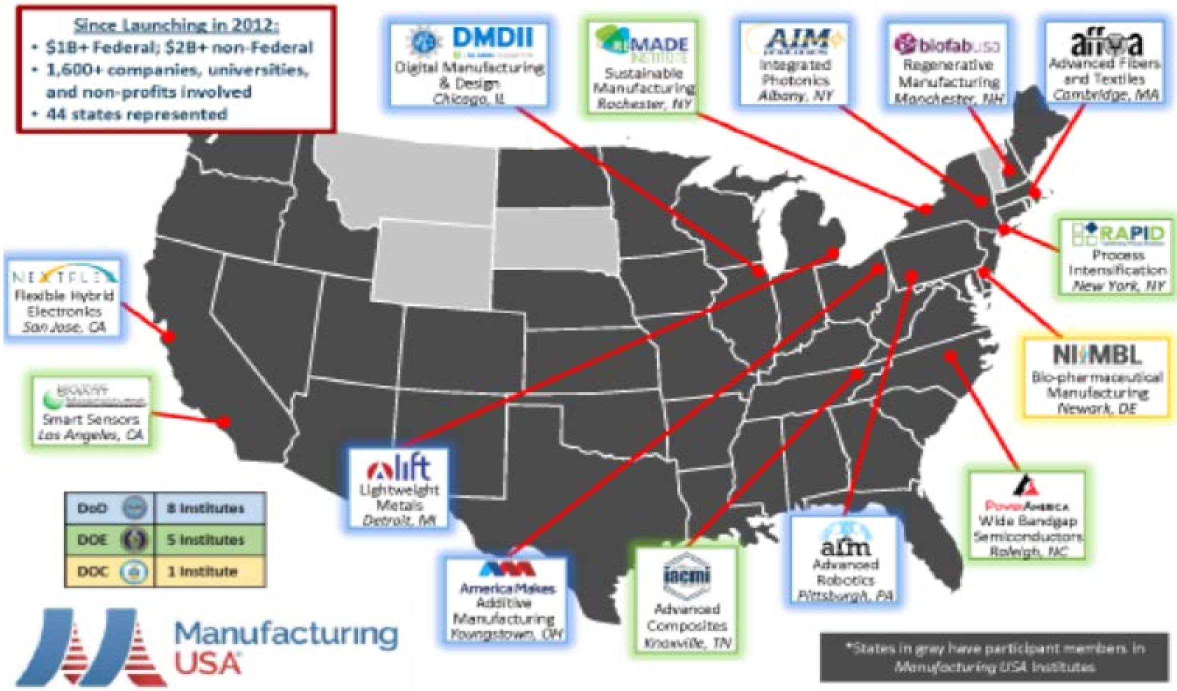

Figure 1. 1 Map Of Federally funded Research Labs [6]

Since its introduction in 1984, AM started gaining traction and popularity as a fast way to build complex parts, such as the one shown in Figure 1.2, that could not be created by traditional manufacturing methods. In the beginning, AM was very expensive and was relatively complex; over past 30 years though, costs to own and operate a 3D printer have decreased significantly. Even today one can purchase relatively a high quality printer that will produce excellence products for as low as $500.00 [8]. The ability to print and create parts that were very technical at a low cost caught the attention of the military.

More funding in this area would increase the cost of research and development for a few years but the payoff could be huge, meaning the AF would have the ability to replace any part on the aircraft on demand. For example, if a construction excavating company investing in a piece of equipment that would speed up the process by which dirt was transported to the conveyer belt, that company would benefit greatly, as would the AF if they committed funds to AM efforts . In the beginning the cost would be high for research, but over time the new method would pay for itself due to the added benefit it brought. AM will likely pay for its self over the next 10 years or so if further funding is provided for its development. The image below is a geometrically complex printed part which could not be created using traditional engineering methods.

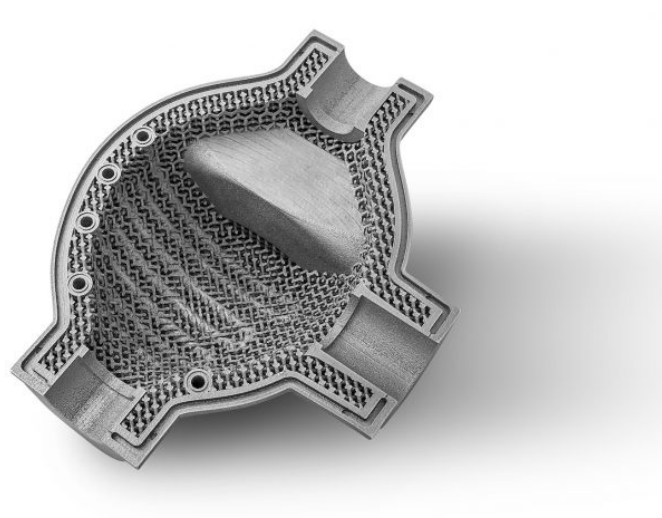

Figure 1. 2 Geometrically complex part [7]

Problem/Purpose statement

There is a need for fast replacement parts and prolonged sustainment calls for a critical look at the process by which those parts can be procured and delivered. When planes that were designed to fly 3,000 hours are now flying 10,000 hours, substantial funding and maintenance is required to keep the aircraft is good working order. Because of these unforeseen sustainment costs additional investigation needs to be done regarding the use of AM technology. The purpose of this research is to determine to what degree this technology should be investigated and/or funded, and what type, if any, savings could be realized, as well as the importance of funding AM should play in the future of the AF. This study will also address the different uses, benefits, and applications AM plays in an operational and maintenance environment. Additionally, this study will examine the costs associated with AM, by performing a simple costs analysis for producing example parts with AM, and comparing these costs to the current cost the AF pays to procure the parts.

Research Objective

Given the large scope of the AM, the research must be narrowed to a specific Objective. The focus of this research is to: “Provide a comprehensive knowledge base and model for organizations and members within the AF to determine if AM capabilities are beneficial to their unit/element.”

Investigative Questions

To better help readers understand the objectives of this study the researcher compiled a list of questions that are of great importance to the AF. Throughout the study each question will be analyzed and further explained in detail.

1. How much does it cost to set up an AM lab from start to finish with all support equipment?
2. Is it possible to determine whether a part is a good or bad candidate for AM?
3. How much time if any will be saved by printing a part through AM methods?
4. How much money if any will be saved by printing a part through AM methods?
5. How much resources, money, time, and people is the Air Force currently spending on AM research and development?

Methodology

A mix of quantitative and case study approaches will be taken to determine the importance of AM in the AF and. Data will be collected and patterned matched to a theoretical proposition by examining the personnel perceptions (Interviews), parts lists, wait times, and cost of materials. Pictures, internet sources, and physical paper copies will be used as a visual for better understanding the subject matter. The rationale for selecting the qualitative/case study approach employed in this research and the elements that lend to this study to case study design, as well as the data collection and analysis procedures will be detailed in Chapter 3.

Assumptions and Limitations

The scope of the AM domain is broad and will need to be narrowed in order to provide clear and precise data for a specific area. A large amount of data has been gathered on the topic. One major challenge will be combing through the data to find relevant information that will be of use. Determining costs and obtaining data is difficult due to the private nature of the reports. Secondly, limitations exist because much of the AM work is presently out-sourced to parties not within military organizations, meaning the AF does not have full organic control of the operation. This makes it hard because much of the data is proprietary, meaning members outside the organization will not have access to it. It is assumed that much of the data obtained will come from maintenance manuals, DLA catalogs, and data collected from personal experiences. By narrowing down the sample to a small handful of items, there is the potential to miss some best practices or lessons for the AF. This study does not address technical risk of using AM to produce parts, which is outside the scope of this thesis.

Summary

This chapter introduced the current problem, research question, investigative questions, and provided a summary of the methodology used in this study. Chapter II presents an in-depth review of the existing literature on AM. Chapter III further describes the research and data collection methodology used to accomplish the objectives of this study. Chapter IV presents the analysis, while Chapter V provides conclusions, recommendations, and offers areas for further research.

Chap 2. Literature Review

Introduction

Chap 2 covers a broad range of topics including what is AM, the different process that fall under the umbrella of AM, current research in AM, benefits of AM in maintenance, AM batch sizes, Innovation, and mission readiness. With the security of the nation always at threat, it is important to maintain readiness at all times and plan for the future. Excessive lead times and difficulties in obtaining supplies for legacy aircraft has forced the DoD and AF to look for alternatives to the usual way of obtaining parts. Funding has been set apart by DoD and AF alike to research and develop faster methods of procurement for unique parts. This literature review presents a neutral opinion of whether the government should invest more funds for AM technology used in the military to obtain more cost effective replacement parts at shorter durations.

Information is obtained by researching current up to date articles about work currently being done in this field. Literature that pertains to the topic will be reviewed. Publications that have been reviewed by other expert peers in the same field will be thoroughly cited, and a brief history will be given to help the readers understand the content and background of the topic.

Additive Manufacturing

In the world of defense where there is a growing demand for quick complex parts, AM can deliver legacy replacement parts faster, cheaper, and lighter than ever before. AM is a technology dating back almost 40 years and is poised to transform the industrial economy [10].

The private sector has been working on AM from as early as 1983 [11]. Recently within the past 10 years or so, the military has become increasingly interested in its applications in war efforts. AFMC, as well as AFLCMC, have decided they will be dedicating resources to research and develop AM technologies for current future weapons and sustainment of Legacy Aircraft[13]. AM is a technique that combines planar layers of material, similar to that of ink-jet printers, sequentially to form three-dimensional (3-D) objects.

An example that helps the reader better visualize AM technologies is as follows: “Consider, for example, the possibility of machining a ship inside a bottle. How would [the author] machine the ship while it is still inside the bottle? Most likely [the author] would machine both elements separately and work out a way to combine them as an assembly and/or joining process. With AM [the author] can build the ship and the bottle all at once”[14]. The emphasis is on creating something quickly and that the output is a prototype or basis model from which further models and eventually the final product will be derived. 3D Printing is used to create quick models or expressly unique pieces which remain hard to make traditionally due to the shape or manufacturing process which the item has to go through. AM is made possible by a uniquely innovative process data point assembly. All that is required to create a part is digital data. This means physical prototypes can created directly from digital model data like CAD (Computer-Aided Design) and data files. That data transforms into the product. The data furnishes reference points which then can be printed into thin layers. The thinner each layer is, the closer the final par will be to the original product [14]. The literature reveals that 3D printing, rapid prototyping, additive processes, layered manufacturing, free-form manufacturing, and rapid manufacturing remain synonymous with each other [15]. When referring to any of the mentioned methods, most people state they work with AM technologies. Below is an example of a geometrically complex part that is only able to be created by AM and a part being created through subtractive engineering (traditional engineering).

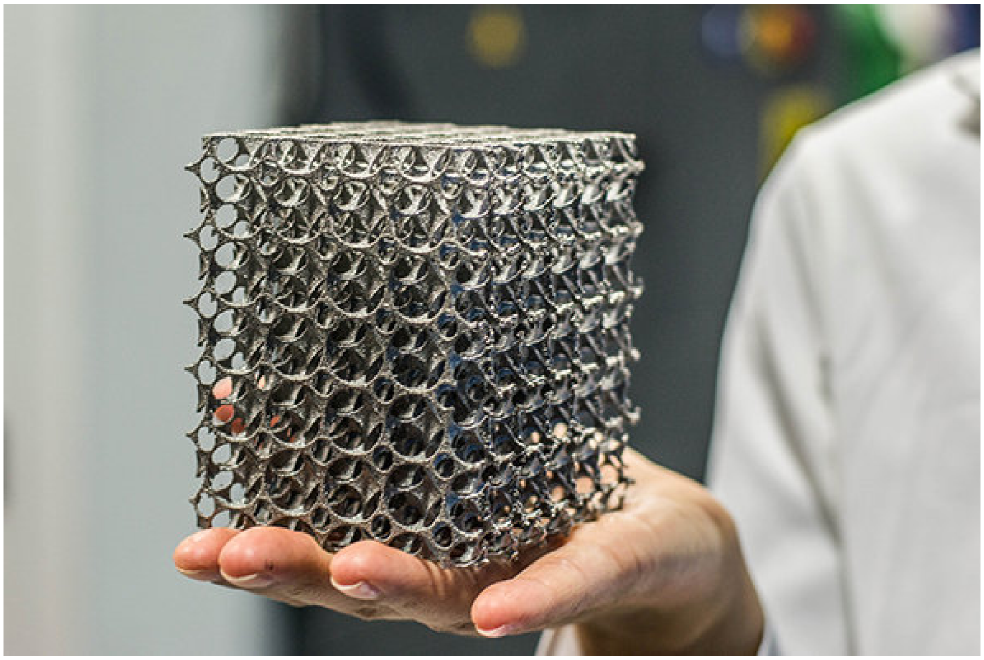

Figure 2. 1Geometrically Complex Part 2

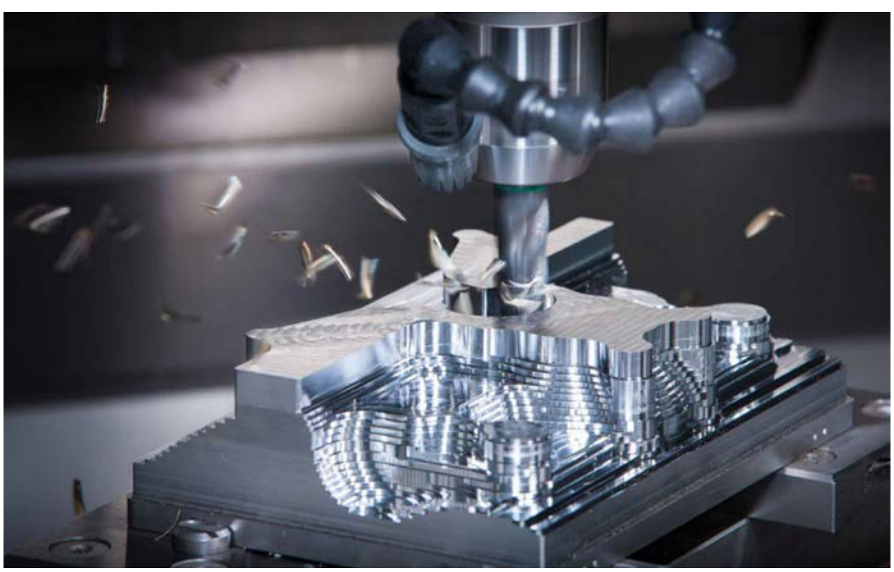

Figure 2. 2 Subtractive Engineering [9]

The AM process can create complex parts with unique geometries that traditional subtractive manufacturing is not able to create. More recently, the ability to directly manufacture metal components with complex part geometries without tooling (e.g. molds, dies or fixtures) has been a topic of great interest [17]. AM does have advantages over traditional subtractive manufacturing. Subtractive engineering is the milling out a piece of material until the desired shape is complete, similar to what would be expected from a standard machine shop. The higher the geometric complexity, the greater the advantage AM has over subtractive engineering AM yields solutions to technically advanced parts [18].

AM is ideal for customized parts with short fabrication series--its extreme flexibility not only allows for easy customization of goods, but also eliminates assembly and enables products to be designed or redesigned for a higher performance. The properties and materials that can be printed "have higher strength to weight ratios and also demonstrate good resistance to metal fatigue and corrosion"[19]. For these reasons AM is gaining a significant market share, by 2026 the projected value of AM is 23.33 Billion dollars [20].

AM is growing in popularity among all manufacturing fields. For instance look to the medical field. "The medical industry is projected to be among one of the fastest-growing application of the AM with a CAGR of 16.1%"[21]. Medical equipment manufacturers using a wide scope of high-quality and biocompatible 3D printing materials can "create tissues and organoids, surgical tools, patient-specific surgical models and custom-made prosthetics"[22].

The AM field is showing no signs of slowing progress, “The global AM market, reached sales of $3.0 billion in 2013, on annualized growth of 35 percent over sales of $2.3 billion in 2012. AM industry growth over the last 25 years has been 25.4 percent, and 29 percent in the last three years”[21] as of 2014. Research reveals a decrease in the cost of parts required for printing. “Recent advances in technology now allow a modern Cell Phone using its inbuilt camera can now produce a high-quality 3D scan from a meager few hundred dollars. Even just a few years ago that same part would have required an expensive laser-scanning or stereoscopic camera system costing more than 100,000$” [14]. Proving that AM is becoming more cost effective. Subsequently, AM has many applications that could prove useful to the military such as replacement and hard to find parts which bring the reader to the next section, rapid prototyping

Different types of Additive Engineering

- Rapid prototyping
- Cold spraying
- Powder bed fusion
- Direct Metal Laser Melting
- Fused Deposition Modeling

Rapid prototyping

Rapid prototyping is a relatively new term and in its simplest form, the process of creating prototypes quickly to visually and functionally evaluate an engineering product design. A prototype is a preliminary version of the end-product and used to evaluate the design, test the technology or analyze the working principle which in turn provides product specification for a real working system. Rapid prototyping allows for the quick production of physical prototypes with the benefit of reducing the time to market. This development permits the concept conversion of a complex component into a solid replica in a matter of days, “whereas traditional prototyping systems would require an extended amount of time”[23]. Rapid prototyping is accredited by CAD data, meaning without data no creation of parts could possible. The picture below is a part design in CAD and can be directly printed as a part form the specified data.

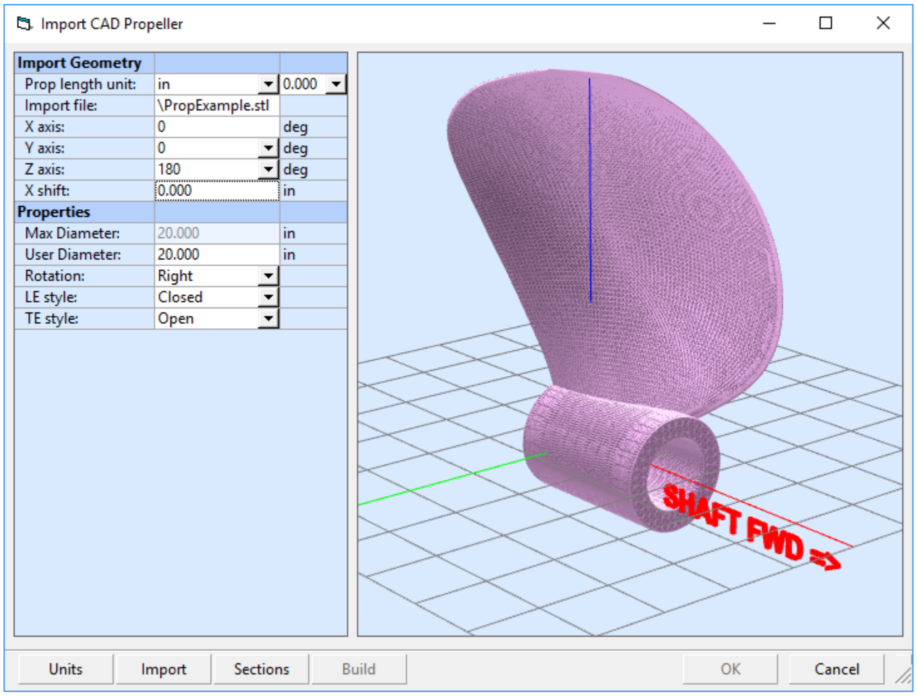

Figure 2. 3 Computer Aided Design Part [24].

All rapid prototyping techniques begin with a CAD data which is then transformed into the desired part. Whether the Model is created for data that was hardcoded into CAD or a digital scan that came from a laser or optical scan, the data must be transformed into a language that can be read by the 3D printing machine. The computer then slices the part into thin layers and feed the information on the shape and dimensions of each layer to the manufacturing system. The systems differ in the way the component is built up layer by layer. In its current state, the technology faces some difficult challenges linked with size and scalability, high material costs, narrow range of materials, limited multi-material printing capabilities, and quality consistency issues" [21]. Continuing advancements in the AM technology and material sciences will likely address these limitations and can be expected to drive AM's wider adoption. Currently, the most frequently used methods of AM or rapid prototyping turns out to be cold spraying, PBF (powder bed fusion), DMLs (direct metal laser sintering), and FDM (fused deposition modeling). The AF uses all three methods.

Cold Spray

Cold spray technology was developed in the early 1990s. While testing particle erosion, the particles were exposed to a two-phase high-velocity flow of fine powder in a wind tunnel. During this testing, scientists observed the accidental rapid formation of coatings. This coating technique was first commercialized in 1990 [25]. Cold spraying in simple terms is sending fine metal particles through a high-pressure nozzle at speeds so fast that when the fine particles collide with the stationary object they create a strong thermal bond. When working on thin pieces of metal or parts sensitive to heat, the cold spray method is ideal. The cold spray method is most used when a metal object needs to be repaired. For this reason, the military is undoubtedly interested given the diverse applications in which it can be used. The picture below is a depiction of how powder is accelerated in a high pressure nozzle at sub melting temperatures can bond to metal surfaces.

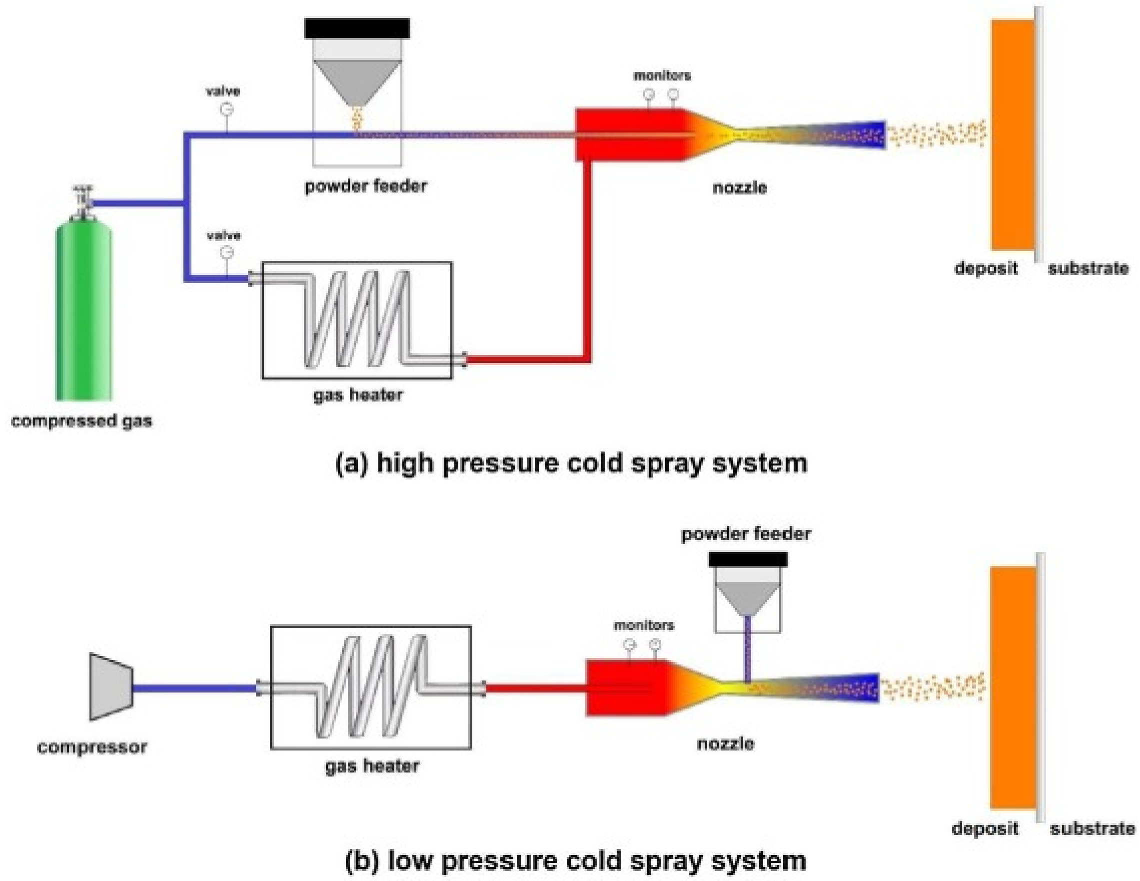

Figure 2. 4 Powder Bed Fusion Model [26].

The DoD and AF fund certain labs for the development of technology in areas they feel is important for future critical warfighter capabilities. The University of Dayton Research Institute (UDRI) remain one of those labs. A major focus at UDRI is Cold Spray technology. “Cold spray is a surface repair via supersonic particle deposition of metallic powder to worn, damaged, or corroded substrates. Its advantages include the ability to repair and reuse valuable parts, reduce repair lead times, replace hazardous methods, and deposit wear-resistant coatings”[27]. Cold spray is utilized for the dimensional restoration of parts that remain readiness critical and have long lead times for replacement. The image below is a good example of a broken part that was repaired by cold spray. Left picture: Original broken part. Center picture: Metal material added by cold spray. Right picture: Machined part after cold spray material was added.

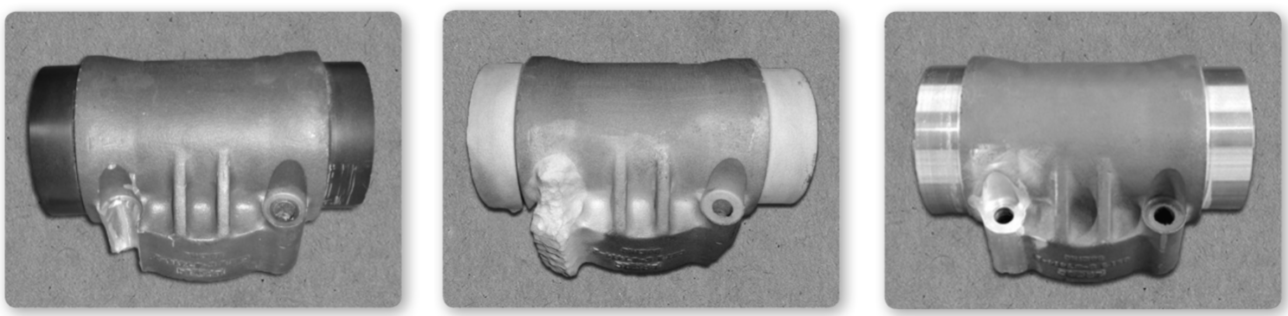

Figure 2. 5 Cold Spray Fusion [28].

The AF has 1763 legacy aircraft [29], some of which have existed for more than 50 years. When parts need to be replaced on these older aircraft, the replacement time for the parts can range for as long as 2 years. Cold spraying grants a solution to long replacement times and at a fraction of the cost. Currently in use, exist many air worthy vehicles in service with cold spray repairs. A B-1 bomber was repaired using cold spray to repair a wing back in 2009 and is still flying sorties today [28]. In Texas, the Army is saving enormously due to cold spray, “Corpus Christi Army Depot (CCAD) has over $250-million-dollars in magnesium parts removed from service due to excessive corrosion and wear. A significant cost to the DoD supply-chain will be mitigated with the introduction of the Cold Spray process” [30]. The DoD has fully embraced cold spraying as a useful method for repairing parts with long lead times and extremely expensive parts. However, with each new technology comes a few downsides.

The AF is aware of the disadvantages using cold spraying. Although composites can be sprayed, pure ceramics and some alloys (such as work-hardening alloys) cannot be processed. Cold spray requires at least limited ductility of the substrate to produce well-bonded coatings. Hence, cold-sprayed coatings over ceramic substrates show only limited bond strength [31]. As of right now high quality coating materials such as MCrAlYs (rare earth metals), Inconel (rare earth metals), etc, require helium gas to produce the velocities necessary for deposition. Those gasses do not come cheap. Cold spraying also requires a line-of-sight process which makes creates difficulties when spraying complex shapes with internal surfaces. Cold spraying has advantages which PBF does not, which takes the reader to the next section.

Powder bed fusion

Most current metal AM systems use the PBF type process of printing. In the PBF process, thin layers of powder are applied to a build plate and an energy source (a laser or electron beam) is used to fuse the powder at locations specified by the model of desired geometry. When one layer is completed, a new layer of powder is applied and the process is repeated until a 3D part is produced [32]; complex geometries can be created through this process as well as super-strong lightweight products. PBF can print in a variety of different materials such as polymers, composites, metals, hybrids, ceramics, Investment casing patterns, and sand molds. The speed in which parts can be created fills an essential role in the readiness of the military. PBF capability allow for replacement parts to be created in a matter of days. The C-5 galaxy, the largest cargo aircraft in the AF, was able to cut down on time by producing parts through AM. The C-5 was expecting some parts to take as long as 12 months to reach the base. By printing the parts organically, Dover AFB was able to have the parts in hand in under 48 hours [2]. The figure below renders a schematic overview of the select laser melt process both at the machine and powder scales.

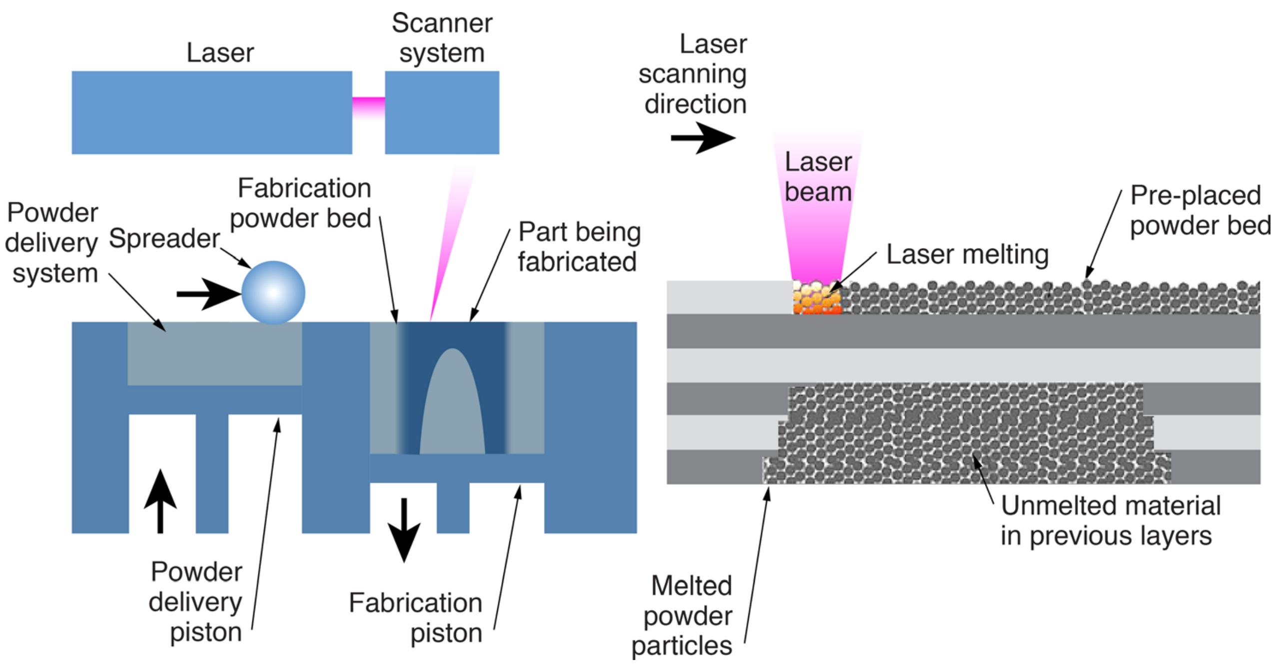

Figure 2. 6 Powder Bed Fusion Process [32]

PBF does have its challenges. A capability the military would love to capitalize on is the ability to fix parts where they break." Fixing parts at forward operating bases in deployed environments or even at sea onboard an aircraft carrier" is of huge importance to the DoD [33]. However, significant challenges create an environment where PBF printing anywhere but in a lab environment nearly impossible. The powder that is used to print parts is highly explosive as is the gas in which the powder is stored. Additionally, special respiratory masks are required to be worn at certain stages of the printing process. The mask helps to keep fine metallic particles from being inhaled by the individual operating the machine. PBF processes have a significant amount of unused powder at the end of each build. These powders have been subjected to some level of thermal history, which history may cause undesirable changes in the powder. Thus, a well-designed recycling strategy must be created. Most sources share the same view that it will be difficult to print parts in austere deployed environments until the technology matures [34]. Technology does continue to mature in laboratories through funding efforts from DoD and AF. It is the hope of the DoD to use this PBF technology on bases throughout the world[35]. The most common type of PBF used in the military's labs is DMLS. Below is a picture of a lab technician with a Respirator Face shield Assembly and Supplied Air Kit. The mask and air are to keep dangerous fine metal particles from entering the body of the technician.

Figure 2. 7 Respirator Face Shield Assembly [36].

Direct Metal Laser Sintering

Direct Metal Laser Sintering is a type of PBF which uses a laser as a beam of energy to bond thin layers of powdered metal together; this is done hundreds of times until the part is built up. Parts are built from the bottom up layer by layer. DMLS fabricates metal prototypes and tools directly from CAD data. This process is popular in rapid tooling since suitable metal powders can be used to produce metal parts and tools [37]. The properties of the required part are contingent on composition and solidification condition. DMLS usually produces strong durable parts that are metal. However, often lightweight material with no conductivity such as polymers are required. The picture below is a part being built by DMLS. The section that looks on fire is where the above attached laser is interacting with the material producing energy in the form of light.

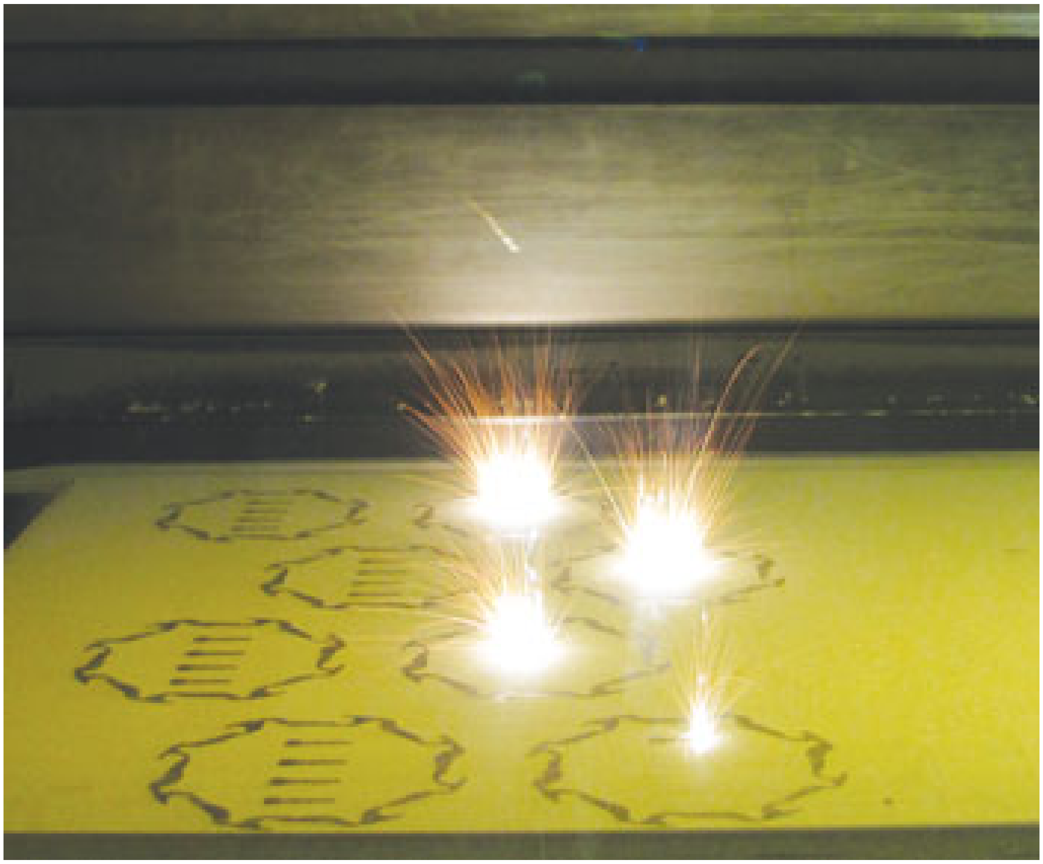

Figure 2. 8 Direct Metal Laser Sintering [38]

FDM (Fused Deposition Modeling)

Fused deposition modeling is the process of modeling CAD data by printing thin layers of polymer materials called thermoplastics to form the geometry of the part. A thread of the thermoplastic is fed through a small heated nozzle which turns the plastic into a semi liquid state. In that liquid state, the materials can bond with the part already lain down. The designed object is fabricated as a 3-D part based solely on the precise deposition of thin layers of the polymer. The deposition path and parameters for each layer are designated depending on the material used, fabrication conditions, applications of the designed part, and the preferences of the designer. The Image below is a good model of the FDM process. One can see the path the material goes through until it is finally extruded as a thin layer onto the existing part.

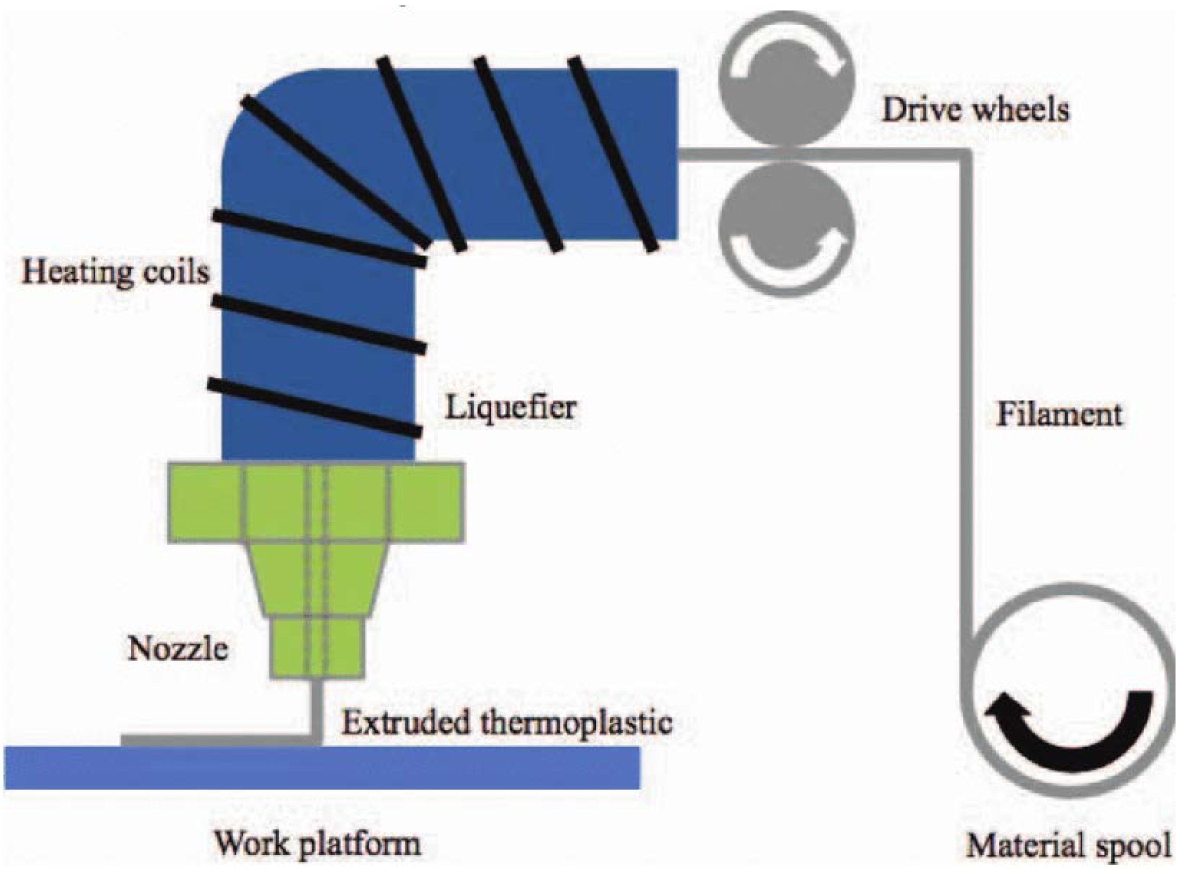

Figure 2. 9 Fused Deposition Modeling [39].

The main advantages of the FDM method are the fabrication of low cost parts and the ability to coat the surface to improve its quality [40]. The ability to create parts that can be printed in 2-6 hours gives engineering and maintainers the ability to test whether a part will fit and be compatible before creating a permanent replacement. The thermoplastics are able to withstand temperatures of up to 400 degrees Celsius [41]. FDM parts are inexpensive to build, light weight, and relatively durable. However, challenges exist when working with FDM

Conversely, the disadvantages are the poor surface quality with the grainy appearance and the poor dimensional precision. Because the plastic material must be printed in layers and has a certain thickness predefined by the nozzle, high precision prints are hard to acquire and often require a considerable amount of post-processing to acquire a professional, finished look. Another downside of the layers in FDM printing is fact that it creates an inherent weak point in the print where each layer is joined, causing prints to be less sturdy and unsuitable for certain applications [39].

The AF currently uses FDM to build air worthy parts that are on aircraft today, the C-5 being one of them. With the time and money saved, AM is a great fit or the AF and DoD alike. However, setbacks and challenges have been identified when working with AM. However, the literature reveals AM Is an extremely popular field which is growing fast [42]. The literature implies that AM yields a large benefit to the engineering and manufacturing world. AM could be a perfect fit for the AF maintenance career field.

AM Benefits in Maintenance

Maintenance in the AF is like a doctor at a hospital; they keep the planes alive and in good health. However, due to the age and small amount of specialty aircraft, finding the right parts when pieces break is often a stumbling block for the maintainers. For example, the Oklahoma City Air Logistics Complex reported lead times (time from request to receiving the part) as long as 800 days for constant speed drive castings [43]. Also, 29% of F-18's were grounded at the end of 2016 due to pending spare parts. The difficulty in acquiring replacement parts is due to the age of the aircraft. Some aircraft are over 60 years old and the companies that use to build the spare/replacement parts are no longer around. AM can fill a critical role in quickly replacing parts and getting the aircraft back in the air [21].

AM is causing a fundamental manufacturing paradigm shift that is changing how aircraft are now maintained and sustained. AF maintenance is benefited by AM, and emerged as a potential solution to reduce both lead times and inventory costs [44]. The best application for AM is in low-volume, customized, and complex components. Studies have shown that over 15% of all replacement parts could be produced using AM. Inventory costs are often overlooked when considering benefits. A spare part could sit on a shelf on in a warehouse for years and not be used. Space does cost money. Now consider the ability to print or replace parts on-demand; the military places a high degree of importance on readiness. AM has a strong potential sidestep excessive wait times [35].

Not only are wait times reduced for the maintainers, often the properties of weight and strength increase. Weight is often a limiting factor in aircraft design. An AM part can produce the same strength properties and can weigh as little as 30% of the original milled part. Mathematical systems can optimize the topology by integrating lattice structures to reduce weight without compromising performance [18].   Parts that were originally designed to have many moving parts can now be built in one piece while still retaining the mobility of the original. Replacement parts can also be built using AM.

Sustainment of aging aircraft presents unique challenges due to the lack of technical data, aged tools, and the need to rapidly respond to parts availability, which causes issues for a variety of aircraft and exchangeable end items. Having the right tools for the job can save considerable time and effort. For example, the B-1 production was conducting testing on a valve body assembly, the B-1 office tested the internal shaft by "shoving a screwdriver in the spline and manually turning to see if it moved the butterfly valve" [13]. This greatly increased the risk of damaging a good part simply because they did not have the right tool. The 76th maintenance group in Oklahoma was able to print a part by laser scanning data for $3. The expected annual saving was 125K and 750 flow days [13]. For each aerospace vehicle, hundreds of fixtures, guides, templates, and gauges can be printed with AM, reducing cost and lead time by 60–97%. An industrial supplier for composite parts has identified 79% savings in cost and 96% savings in lead time by replacing CNC machining with material extrusion to produce tooling [45].

AM or rapid prototyping was originally designed for fit check models. It is difficult for metallurgists and engineers to determine whether a part will fit correctly without truly building and tested for fit. AM allows for quick parts to be built and tested for fit. Once the part is determined to fit properly, a part can then be machined out. AM prototypes can prevent surplus time being spent on incorrect geometries or dimensional tolerances. The images below is of a prototype and final ready for use part. The black part in the back is a rough estimate that was built to test for fit. The Blue part in the front is a machined part built using test data from the first part.

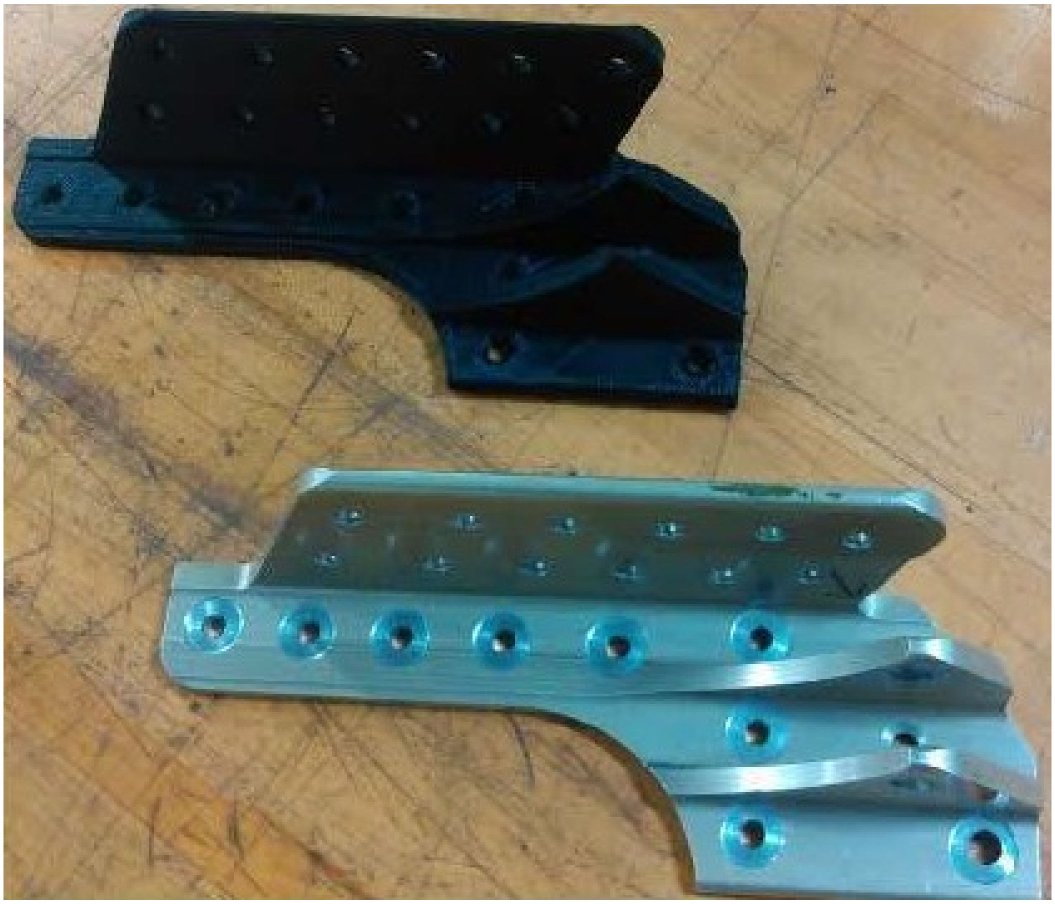

Figure 2. 10 Additive Printed Part [46].

The Best Scenario Where AM is Used

Most sources say AM is best utilized in small batch size or for complex hard to obtain parts [47], while others disagree[5]. The current problem with AM with mass production is the speed at which parts can be produced. If AM parts could be produced at four to ten times as fast as the current rate, the technology would then become competitive with anything else found on a factory floor [48]. Laser sintering, is a direct beam of energy that bonds materials together, is often the bottleneck to the process. For large parts, the cost to benefit ratio is lower than smaller parts. However, research is currently being done by ASME that has the potential to be “ten to 100 times faster” than traditional laser centering methods [49]. Current research on AM costs reveals that this technology is cost effective for manufacturing small batches with continued centralized manufacturing; however, with increased automation distributed production may be cost effective.

Some do believe that AM is capable of producing a mass amount of parts in large batch sizes and still remaining cost effective. Cost AM has continually decreased. Between 2001 and 2011; the average price decreased by 51 % after adjusting for inflation (Bureau of Labor Statistics). Approximately twelve parts of a Pratt & Whitney engine were created using AM, engines that now equip Bombardier aircraft. These are mainly fasteners, fuel collectors and injection nozzles 3D printed from nickel and titanium. 3D printing saved Pratt & Whitney around 15 months over the entire engineering design process and reduced the final weight of the part by 50% [50]. General Electric has announced they will be using 3D printing to produce more than 85,000 fuel nozzles for its leap jet engines and over 100,000 printed component parts total, and this was back in 2013 [51]. Today, as AM becomes cheaper, more companies are looking to AM as a viable option. One needs to ask does AM technology meet the needs of the AF.

The AF does look to AM with promise, but does AM meet AF standards? Air worthiness is a vital concern to the AF. Air worthiness is discussed in great detail by maintainers and designers alike. It means “one that is in safe working condition and safe to fly” (Cambridge Dictionary). Can AM produce parts that are air worthy is the question the AF is asking. The C-5 galaxy currently has 17 parts that are 3D printed in the Cabin compartment and has plans to add 20 more printed parts throughout the plane [2]. In 2018 the AF approved one third ratio of 3D printed “console pin fitting” to be installed on the F-22. Before installation each part requires a strength test and approval from the Chief Engineer [52]. Findings from literature and news sources show AM parts being installed on airworthy planes, but AM parts do have weaknesses. The image below on the left is a CAD rendering of the console pin fitting, and the image on the right is a real life 3D printed metal console pin fitting piece.

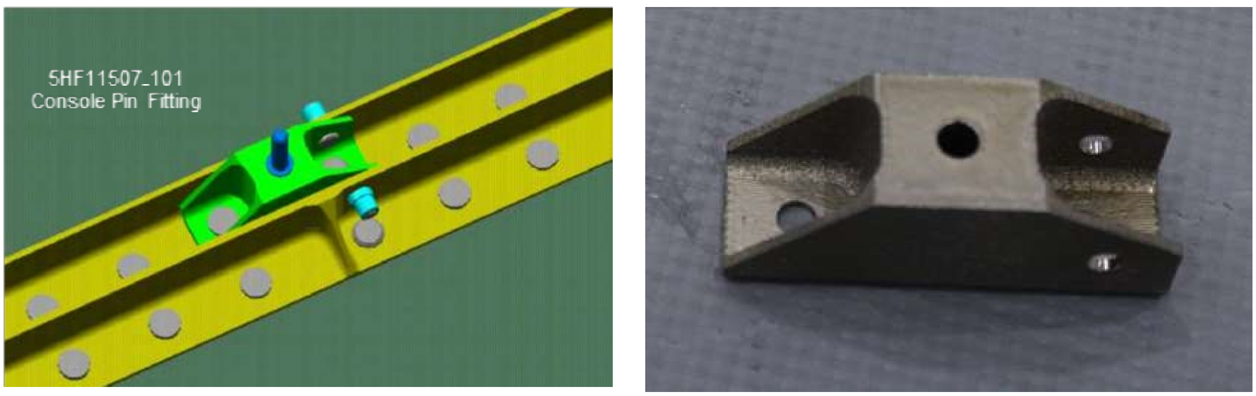

Figure 2. 11 Left: Console Pin Fitting, Right: AM Printed Console Pin Fitting [52].

Because of the process by which most AM parts are created, an internal built in stress exists in the structure. When residual stress exceeds the tensile strength of the printing material or substrate (an underlying substance or layer) defects, such as cracking in the part or warpage of the substrate, can occur. The surface roughness of the parts is often a downside to design. Additional machining and heat treatment are frequently required for end use parts [53]. The extra time required for post-treatment needs to be considered when weighing costs and benefits. Even with a small amount of Post-treatment, AM may still produce a part that meets requirements much quicker than ordering a piece which may have excessive lead times. The speed at which parts can be produced is often more important than cost to DoD and AF [54].

Mission Readiness.

The ability to mobilize quickly and deploy planes in the air is the top priority of the AF. AM is postured to play a critical role in getting damages repaired quickly and back in the fight. The quote below describes the military's need for AM capabilities.

> As early as 2013, the Army began deploying rapid prototyping labs to Afghanistan in the form of a 20-foot shipping container equipped with a 3D printer and supporting materials, enabling rapid on-site material solutions. "It's really difficult to connect the guy who is building the product to the kid who really needed it to begin with, so what we went after is to connect the scientist to the soldier," said Col. Pete Newell, then-commander of the Army's Rapid Equipping Force at Fort Belvoir, Va. "Rather than bringing the soldier home to the scientist, we have uprooted the scientist and the engineer and brought them to the soldier. [35]

The value of AM repair is impacted by factors such as inspection for defects, the ability to repair the part in the field, the speed and cost of alternative repair techniques, and the requirement to restore the part to the original form with the same mechanical properties [44]. In December 2017, Army G-4 released an executive order allowing commanders in the field to invest up to $10,000 of their operating budgets in 3D printers, software, and training. It was believed by Lt Gen Aundre Piggee that by allowing for a AM budget we were "giving them flexibility and the power to innovate" [55]. The organic capability of printing in the field allows for major time and cost savings for replacement parts. In an environment where organizational resources are at an all-time low, the AF must contribute the same or greater military capability and readiness than ever before. Still, limitations do exist which limit AM readiness in the AF.

Numerous materials which are required for AM are obtained by foreign entities which limit the DoD's ability to be self-sustaining. The lion's share of rare earth metals is attained by trade with China. 80% all rare earth metals are extracted there. By holding the largest, cheapest reserves, China could artificially limit supply and move prices as Saudi Arabia and OPEC does with oil [56]. Current events like the trade wars between China and the United States, force the DoD to consider what implications current events may play in warfighter capabilities. An in-depth look at organic in country materials may need to be taken to better understand the threat of supply cut off in an emergency. If supply chains are disrupted, lead times of part-to-customer may be prolonged.

The effect long lead time's play on the AF's ability to be mission ready is deplorable. Many sources describe excessive lead times for the military's legacy aircraft. Program offices are in charge of ordering and confirming that sure parts are delivered and installed in a timely manner. Many firsthand accounts at the AFLCMC/WISM program office reviled much frustration and road blocks when it comes to mission accomplishment due to difficulties in part procurement. John Hepner a Senior Program Manager said: "it is not uncommon for a part to take more than 6 months to delivery"[57]. The issue the AF faces is most of the legacy planes were built over 30 years ago. The oldest plane still flying within average of 53 years in service. Most companies that supported the legacy aircraft are no longer in service and the technical data required for a replacement part is no longer available. Meanwhile, the AF has grounded planes that cannot fly due to the lack of replacement parts. Many military maintainers have found success with considerably shortened part-to-customer times by manufacturing the parts themselves through AM venues.

DoD/AF funding for AM

The AF does realize AM offers a benefit to the service but needs to identify how much funding and resources should be dedicated to staying on top as the leader of innovation and technology. DoD and AF is the past have looked to the academic community, such as colleges and universities, to help research and develop modern technology. The Manhattan project, for example, was worked on at the University of Chicago and the University of California Berkley. Similar to the Manhattan project, the AF has funded several labs both inside and outside of the military working on research and development. Other directives were given to Maintainers at ALC's to develop tools as a need for work. [12]. In the following passage, the different funding efforts the AF is currently committed to will be discussed.

In 2016 American Makes (the National Additive Manufacturing Innovation Institute) received more than 50 million dollars in federal funding to "enhance national economic and military competitiveness. America Makes an AM accelerator, has helped the U.S AF set up operations to 3D print low-cost replacement parts for legacy aircraft. 10 million dollars was award by AFRL for Maturation of Advanced Manufacturing for Low-cost Sustainment (MAMLS) project, 9 million was granted for overseas funding for MAMLS, and 9,045,915 was given by congressman Tim Ryan in hopes Mahoning Valley (Youngstown, Ohio) will turn into "the Silicon Valley of additive manufacturing."[58]. American makes then Partnered with UDRI to further research.

A national leader in scientific engineering research UDRI performed over 99 million dollars in 2015 in sponsored research to help the U.S. AF integrate new or better technologies to more affordably, safely and efficiently sustain its entire fleet. In 2018 the University of Dayton performed $149.8 million in sponsored research in fiscal year 2018. Nearly 92 percent of its research revenue is from federal sources – DoD, DOE, EPA, NASA and more [59] .UDRI is ranked third in the nation among all colleges and universities for sponsored materials research, according to the National Science Foundation. Much of the research performed at UDRI is the further development of AM technologies. However, UDRI is only one of many research initiatives around the country.

Air Force Research Lab (AFRL), located at Wright Patterson AFB, has a specific department dedicated to AM. 4.4 billion dollars was the given budget in 2014 spread across 9 directorates. Information for specific funding departments in the military is difficult to acquire and will need additional approval and clearance to include such information.

Summary

We now have more detailed knowledge of what AM is and its useful applications in the DoD. An overview of the literature gives the reader a better understanding of the benefits, current status, and maturity of AM technology. The AF is currently dedicating significant amounts of funds to further develop AM [35]. A major challenge which is being faced with this type of technology is the ability to produce parts in large batch sizes, however painstaking efforts are being taken to solve this problem [17]. In depo-level maintenance AM will save considerable time on parts with excessive lead times [47] . Findings for the literature reveals progress to produce airworthy parts that are now being used on fighter air craft [52]. The research concludes that if AM is to produce replacement parts, it could cost 3-28 times more than traditional methods, However AM could reduce wait times by 6%-99%.

The following chapter provides the research design and methodology used in this study, as well as the steps necessary to answer the investigative questions presented in Chapter 1.

Chap 3 Methodology

Overview

USAF planes, systems, support equipment, vehicles, and facilities remain in use much longer than was originally anticipated by congress and the military. This creates a unique problem for the AF. Spare parts for older legacy planes are habitually difficult to procure due to the lack of technical data which was not transferred from older companies, now most shut down, and the small batch sizes of required parts[35]. By investigating AM for alternative methods of producing the needed parts, the AF stands to save considerable time and money in specific cases where parts have disproportionate lead times and, due to batch size, very expensive parts. In addition to saving money, Additive Manufacturing created parts often have better properties which last longer and prove more durable [52].

This chapter provides the rationale for selecting the qualitative research method employed in this research, and the elements that lend the study to case study design. This research used a case study approach to examine the use of AM in the DoD. This chapter also details the data used for analysis as well as how that data is processed in preparation for the study. It introduces the case study subjects as well as explains the data collection and analysis procedures.

Purpose of Study

The AF is particularly concerned with maintaining a competitive advantage when it comes to warfighter capabilities, which is why the Department of Defense (DoD) and AF fund AM efforts. The capability to fix and restore planes rapidly is of top importance to those in Washington [60]. Because US warplanes remain in use far past their expected use dates, the

DoD and AF seek creative ways to sustain the aircraft longer with a discounted budget[61]. An attempt at a sustainment solution has been prepared by funding research in the AM department [45]. In recent years, AM has shown promise in delivering capabilities desperately needed by legacy aircraft [12]. For example, the C-5 galaxy, which is a large transport aircraft, has over 20 parts installed which were created by AM processes. A few of the parts have wait times well over a year.

This study will seek to gather data from the C-130j plane, C-5, and other planes, analyze that data, and determine if specific parts associated with the plane will be good candidates for AM or whether the parts should continue production in its current avenue**.** The researcher determined by study and advice from SME's that a **"good" candidate for AM is one that cuts delivery times and cost in half**. By doing a thorough analysis of the data one will be able to determine how much time, money, and increased readiness will be saved by creating the part through AM techniques or if the part should continue being produced in the traditional (subtractive) method. The data will be actionable and will provide direction for key decision makers on the method and process of acquiring needed parts.

Theory

Since many of aircraft being used by the AF are very old, many of the parts are old and hard to obtain. The difficulty in obtaining these parts often comes in the shape of high costs and long wait times [13]. It is the belief of the research as well as many thorough the AF and DoD that changes in the process, by which select replacement parts are fabricated will save time, decrease costs, and increase the readiness throughout the DoD [61].

Traditionally, quantitative research involves measurable variables, while qualitative research is comprised of descriptive or verbal data and is typically used to answer questions about the nature of phenomena [62]. This research will focus more on introduction and information gathering in the first three chapters of the paper, and quantitative data analysis in the later chapters.

There has been a lot said by authorities and experts about how AM is beneficial and saves money in specific cases [61]. The theory of this paper is that AM will save considerable time and money, for hard to obtain and overly expensive replacement parts [12]. Not only will AM provide savings of money to those buying manufactured parts, it will increase AF readiness by quickly producing critical parts for the warfighter.

Materials, Methods, and Equipment

The most important part of this section will be to discuss the methods of gathering data. Parts with disproportional prices and lead times which can be later scrutinized for opportunities to exploit AM. The first section will discuss the case study approach used to examine AM. The next section will explore how the parts examined in the study were selected. The final section will look at a cost model to calculate the costs of producing the candidate parts. The section will also include assumptions the cost calculations are based on.

AM Use in the Air Force

The research determined to use a case study approach to inspect the use of AM in the AF. 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 [63]. Table below depicts a specific method in which to use in each case of circumstances.

Table 1. Comparison of Research Strategies [63]

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**

This study will examine how and why questions shown in later sections of the paper, will not need control over the system being examined, and is dealing with a contemporary problem or situation. The USAF will be the case that is investigated. Data was collected by a variety of different methods. Interviews were conducted with service members, subject matter experts, and engineering experts, site visits were conducted, and current publications were reviewed. During the 2019 year the researcher visited various AM sites such as Power Alloy Corp (PAC), a facility located in Cincinnati, which creates and provides much of the powdered metals used by the AF Institute of Technology (AFIT) and AFRL for 3D printing. Secondly, the researcher visited AFRL, located at Wright Patterson AFB, which has a whole department dedicated to AM. Third, the researcher visited UDRI, located in Dayton Ohio, a research lab which prints and tests the majority of AM for the AF. Next, the researcher visited Hill AFB, Located in Ogden Utah, which now prints 3D parts being installed on the f-22. Last, the researcher visited the Defense Innovation Symposium, Located at Sinclair College Ohio, which discussed major advances in innovation and technology including AM.

In order to determine the costs and savings to employ AM capabilities, the researcher gathered information from depos, contractors, end use users, and read present case studies to develop a feel for the requirements and costs for associated with AM.

Part Selection

The source of data used in this research will come from a variety of locations. The first of data obtained was the C-130 Hercules structures and engineering division at Robins AFB, who has access to a large database of all parts installed on the C-130 as well as wait times for parts and pricing. The second source of data was UDRI, who has a large lab with over 50 printing machines all dedicated to research AM technology. In 2018 UDRI accomplished 149.8 million dollars in research for the federal government [59]. The third and last source of data was a SME metallurgist working at Power Alloy Corp who has expert knowledge of the current market conditions and a knowledge of structures and methods by which AM processes are put in to practice.

To select parts for examination the research used data given by the three previously mentioned sources. The C-130 office provided a rough list of 150 parts that had been identified as feasible candidates for printing. UDRI provided over 20 parts that could be printed using AM. The B-1 structures engineering office provided two parts that have been approved for printing. The researcher narrowed down the overall list of 172 parts by eliminating parts that did not meet multiple criterions listed below. The list was further narrowed by removing parts that had no demand over the past 5 years. Though many of the parts did not have a demand, this does not mean they will have a demand in the near future. Only parts that had a cost of $1000+, lead times of 70+ days, and were of a specified material such as steel, alloys, and polymers which can be printed were considered. Parts such as wire assemblies, spacer plates, bolts, and screws were not considered because they are not good candidates for AM. These types of parts may not be the best candidates for AM because said parts are not of a complex design which loses the benefit of printing the said parts altogether. Each part, or part of the assembly, was required to fall between the build dimension volume of EOS M290 9.85 x 9.85 x 12.8 inches for metals or Stratasys Fortus 900mc 36 x 24 x 36 inches for polymers". The build chamber dimensions will be discussed later in the study. Additionally, ten parts were selected from the list for further examination. None of the parts being examined are flight safety critical due to the maintenance advisory given from the C-130 office. The engineering specifics, size and materials compositions were taken from a large database called Haystack. Haystack Gold logistics management system contains parts and sourcing data for millions of items in the U.S. Federal Supply Catalog and over 70 U.S. Army, Navy, Air Force, and related databases.

Because the data base will be analyzed, the study requires a method to analyze the data. Software such as Microsoft Excel, Microsoft word, and R will be used to analyze and filter data. The software just mentioned will be playing a crucial role in providing clear explainable cost and savings data to key decision makers. Photographs will help document and give a clear depiction of the writer's thoughts and ideas.

SMEs from differing career fields in cost analysis, manufacturing, and logistics will be needed to corroborate the data and opinions associated with the study. Experts in the above mentioned career fields will be able to provide direction on the feasibility of the data and ideas being proposed. As a reference point, the SME will help identify redundancies in work that have already been studied, aiding in higher quality research [64].

Cost Calculations

The research examined the current cost the AF pays for replacement parts and the cost of printing the parts organically. The research will further show equations to help aid the process for future replication of the study in future endeavors. The total cost of AM will be separated into several different cost categories. The first of which will be the cost of raw materials used by the machine to produce the part. The next cost is the price of the machine depreciated or amortized over the life of the machine. Eight years will be the amortization period assuming technology will be outdated or obsolete by that future date. The reason for choosing 8 years is because technology is advancing so rapidly that most technology from 8 years ago is now obsolete. The metal printer machine, an EOS-M290, costs $700,000 - including delivery, installation, training and a one-year service contract. Meanwhile, the polymer printing machine, Stratasys Fortus 900mc, costs $750,000. Both machines are being used by AFRL and UDRI.

Other costs which relate to AM are post processing, maintenance costs, and non-recurring engineering. Most parts require some post-processing after the build for which the cost needs to be considered. Locations have the option of post-processing the part in-house or sending it to a contractor for post-processing. The cost of inspection and quality assurance will be factored into total production cost. If outsourcing is the chosen option for validation one should assume it will be very costly and will drive the price of the part up significantly. Additionally, maintenance costs needs to be measured when comparing total cost of AM. The 3D printing machines are just that, machines, and as such needs to be maintained. Parts need to be replaced or serviced regularly. Finally, non-recurring engineering (NRE), the primary labor cost for using AM, should always be deliberated when factoring total costs. NRE is the reengineering required to print a part, including creating digital 3D data, and programming.

There will be costs savings through AM that are difficult to quantify. Savings in inventory storage costs and transportation costs have the likely hood of differing across parts and locations. AM offers some benefits which will not have a dollar amount associated with the part, such as a decrease in supply chain weakness. Readiness is another aspect with is hard to quantify but is of most importance to the AF. AM has great potential of decreased lead times which in turn increases readiness.

The formula used to determine the cost of producing a part with AM was adapted from a previous AFIT students work [65], which references Atzeni and Salmi in the international journal of advanced manufacturing technology [66], and AM Developmental Guidance Notification: 19-001 AM Design Rule Book [67]. Atzeni and Salmi's model estimates the cost to produce a part using selective laser sintering. This research will determine the cost for producing a part using the EOM M290 Direct Metal Laser Sintering machine, which is a similar process. Their model determines cost by adding materials cost per part, pre-processing cost per part, processing cost per part, and post processing cost per part. The equation used to calculate the cost of producing a part with AM is as follows:

$$CAM = CMAT + CPRE + CPRO + CPOS \quad (1)$$

Where

CAM = Cost of Additive Manufacturing ($)
CMAT = Materials cost ($)
CPRE = Pre-processing cost ($)
CPRO = Processing cost ($)
CPOS = Post-processing cost ($)

The materials cost is defined as:

$$CMAT = MC * (MD * MW * VP) + MC * (MD * MW * VT) \quad (2)$$

Where

CMAT = Materials cost ($)
MC = Material Cost per Kg ($/Kg)
MD = Material Density (g/mm3)
MW = Waste Material
VP = Part Volume (mm3)
VT = Test Sample Volume (mm3)

The preprocessing cost is defined as:

$$CPRE = (ET * EC) + (TS * CO) \quad (3)$$

Where

CPRE = Preprocessing cost ($)
ET = Engineering Time (Hours)
EC = Engineering Time ($/Hour)
TS = Set-up Time (Hours)
CO = Operator Cost ($/Hour)

The processing cost is defined as:

$$CPRO = [TBUILD * (CDEP/MH)] + (TBUILD * CENERGY) + [TBUILD * (CMX/MH)] \quad (4)$$

Where

CPRO = Processing cost ($)
TBUILD = Build time (Hours)
CDEP = Machine Depreciation ($/year)
MH = Machine Hours per year (Hours/year)
CENERGY = Cost of Energy ($/KwH)
CMX = Maintenance Contract Cost ($/year)

The post-processing cost is defined as:

$$CPOS = (TPOS * CO) + CTEST + CHT + CMACH \quad (5)$$

Where

CPOS = Post-processing cost ($)
TPOS = Post-Processing Time (Hours)
CO = Operator Cost ($/Hour)
CTEST = Test Cost ($)
CHT = Heat Treat Cost ($)
CMACH = Machining Cost ($)

Various components have been included in the previous AM cost calculations. Building a test sample and testing the sample, as well as cost of non-recurring engineering costs were included by the researcher. The non-recurring engineering give the impression of being a large share of overall cost for producing an AM part, though it will vary from part to part bases on shape and build complexity. One must also realize the cost, thought it may be small, of producing and testing the test sample. Additionally, after researching build time formulas, the research decided to use a simple formula created for another study which is similar to this one.

Interviews

An interview in qualitative research is a conversation where questions are asked to elicit specific information. The researcher selected interviews as a process to determine if a correlation exists between the researcher's findings and professional opinions of those working daily with AM technology. A recent study showed that interviewees who answered anonymously were 31.5% more honest than those who knew their names would be recorded and referenced [68]. For the before mentioned reason all interviewees will remain anonymous as to retain the most accurate data and responses as possible. All interviewees were told beforehand their responses would remain anonymous. Data from the interviews will strictly be used to support or reject the researcher's findings.

Interview questions were surmised from especially important topics related to AM and important issues currently plaguing the AF. Research questions were semi-structured, meaning the study had planned a series of open-ended questions focusing on different parts of the particular research issue. The research then took steps to mitigate unambiguous questions by peer-reviewing all questions from trusted colleagues and professionals. Interview questions can be seen below.

Interview Questions:

(1) What is the total cost of setting up an AM lab for a single Metal Printer (including: Labor, Equipment, supplies, and other costs not mentioned)
(2) How does having Additive Manufacturing capabilities effect Air Force readiness (professional estimate)?
(3) What additional capabilities would be available to the Air Force if further funding was provided for Additive Manufacturing?
(4) What type of problems and limitations exist within Additive Manufacturing that might be a problem to the air Force?
(5) What types of problems in regards to long lead times and expensive parts could be solved through Additive Manufacturing?
(6) How can we speed up wait times and increase warfighter capabilities through AM efforts?
(7) How much money is the air Force currently spending on AM research and development (in your department, squadron, base, or Air Force Wide?

Multi Objective Decision Analysis

Each part considered for AM is unique and should be treated as an individual cases, because a variety of factors, like weight, material, angle, quality etc., may vary depending on the part. Multi-Objective Decision Analysis (MODA) is a process for making decisions when very complex issues involving multiple criteria, in the case of this paper, correspond to AM parts. Using MODA permits the research to consider and weight factors and tradeoffs while evaluating each alternative (in this case, each routine option) [69]. Principally, the MODA tool developed for this research will help decision makers in deciding whether to use AM or traditional methods of manufacturing.

MODA breaks the attributes of a part into categories. In the case of this paper, there are nine categories lead time, price, strength of part, weight, air worthiness, readiness, quality of part, quantity of part, and expected life. Each category is assigned a weight. The SME's collectively rated each category in order of importance, and percentage of 100 divided by the 9 categories. For the purpose of this study all categories have different weights, in real operations, the weights would be changed on a part, case by case, to reflect user requirements as shown in the table below.

Table 3.1 SME's order of importance table

1	Quality of Part	21.0%
2	Lead Time	20.1%
3	Readiness	18.3%
4	Price	14.6%
5	Air Worthiness	7.3%
6	Expected Life	6.3%
7	Strength of Part	6.2%
8	Weight	4.8%
9	Quantity of Parts	1.5%

The first classification one must decide on is whether the attribute in question is Beneficial or Non Beneficial. Customers' requirements might be beneficial (higher values are desired) or non-beneficial (lower values are preferred). The beneficial or non-beneficial nature of the customers' requirements dictates the value of the corresponding improvement driver, positive values for beneficial attributes, and negative values for non-beneficial attributes.

The second classification is the required action of the part (Lead Time, Price, and Strength of part, Weight, Air Worthiness, Readiness, Quality of Part, Quantity of Part, and Expected). As mentioned previously, each part will be weighted in order of importance, parts with greater need will have a higher weight, while requirements that are of less importance will have lower weights.

The final classification one must decide on is the criterion by which the part is judged. A range allows the participant to decide which of the definitions best fits their parts criterion. For example, after the participant has decided that their part is a “Non-Beneficial”, “Price”, they must then decide, for example, if the part: is Low, med, or high, Below average, Above average, or just average. Each part will have a unique scale by which it can be accurately measured against. Additionally, the criterion is broken down further and given further ranges; for example, if the participant chose “Expected Life” and then choose the category of “Increased Expected Life,” one then must decide on a range of time to meet that category. The range would be a subcategory of Expected Life, for example, 1-5 days for below average, 5-20 days for average, and 20+ days for above average. All ranges will be decided upon before the participant interacts with the MODA tool.

Assumptions:

The cost calculation assumptions are as follows:

- Heat treatment is assumed to cost $85 per part, a 15% decrease from 2015 due to technology updates and innovation. This study will not consider Isostatic Pressing (HIP) costs
- Build time will be defined as:

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

Where:

N = Number of layers
10 secs = fixed time between layers
A = Part Area
10^{-4} *= beam velocity (1 m/s) * beam size (10^{-4} m)*

- Time for the powder to be respread after Direct energy beam contact is assumed to be 8 seconds
- The machine will be unavailable before and after the build for 6 hours during the setup, heating the chamber, cooling the chamber and removal of the part
- Machine energy usage is assumed to be constant at 3.2 kW throughout the build. The assumed price for energy per kWh will be $.0133, Which was the average cost per kWh for the united states as of Oct 2019 [70].
- An internal flaws inspection known as a volumetric inspection will not be conducted during this study.
- After each build a tensile strength test will be conducted at room temperature of 68-72F for consistence. The GF-9 Wedge Grips required for test cost $1061.
- The researcher assumes the cost to pay a machinists for set up and post-processing is $21.9 per hour, ($45,536/year the national average for a machinist)/[(52weeks)*(40 hours)] [71]. The time for machine set up is expected to be 2 hours, while post-processing is expected to be 1 hour
- The cost to maintain a single AM machines used for metal printing is expected to be 26,810.86. (Service Agreement M290 Expert plus, price 2nd - 4th year) [72].
- Part demand over the past 5 years will be used as a measure for the volume of parts with are assumed to be needed in the coming 5 years. Parts with zero demand in the past 5 years will
- The cost of metal powder is assumed to be $65/lb.

Build time is an important factor to consider when printing due to operator, power, and material costs. The height, density, angle, and time between build have a large impact on the time as well as the success of the build. To calculate part build time, the study determined the logical part build orientation, which determined the build height. This decision was made by consulting with experts in the AFRL AM department. Additionally, the study calculated the area normal to the build direction of the part, again taking into account the fill area of the part.

Two assumptions are made to determine the cost calculation: manufacturing a single item and maximizing the number of parts printable on a single build platform. One can surmise that the more parts which are built at a time the more economical the individual cost of said part will be. Grouping parts together in one build, even when they are different parts, saves considerable time with set up and post processing costs.

Direct Observations.

The researcher conducted initial site visits to UDRI and Rapid Development Integration Facility (RDIF) in May 2019 to gain exposure to depot maintenance. During this visit the researcher gathered information through informal discussions, conducted a shop walk through, prepared for interviews, and conducted research on AM and its practical applications. During the shop walk throughs, the researcher was able to see how an object is scanned into CAD or point cloud software and sent to an AM machine to be manufactured into a 3-D object. The researcher saw first-hand 3-D objects that had been printed to gain familiarity with the technology. Additionally, the researcher was able to observe AM parts installed on a C-130j.

Summary

In summary the AF will produce much higher quality parts at a margin of the cost using AM techniques [10]. The delivery of these spare parts will be increased tremendously due to the speed at which the spare can be produced. Because the printed parts are stronger in most cases planes will experience less maintenance related issues, thus spending more time on station helping the troops thus increasing readiness [73]. A detailed analysis of the collected data will be provided in Chapter 4. This analysis will rely on pattern matching guided by the theoretical propositions identified in the literature review.

Chapter 4 Cost Analysis and Benefits

Overview

This chapter discusses the results from the cost analysis and cost benefit of metal printing, SME interviews, and feasibility of printing the selected parts. First, the cost analysis will be discussed, figures and charts will be provided. Secondly, the interviews from SME's will be discussed in detail and investigated. Additionally, the feasibility of printing each part will be expounded on. Finally, a Multi Objective Decision Analysis tool will be discussed.

Parameters and Cost for Fielding AM

While AM sounds very attractive and seems by many to be the way of the future, one must consider costs not immediately thought of when deliberating the technology. The type of printer required for instance will demand support equipment, a special environment, and post processing facilities. In addition to the physical equipment and real-estate, AM requires training to be facilitated, personnel to operate the equipment, and an energy source to be provided. It is important to note that different machines require different levels of support. In this chapter the research strictly focuses on metal printing. A metal printing machine is more expensive and requires more support equipment than polymer or desk top printers, but it also has the ability to print end use-air-craft items while the polymer and desktop printers do not. Post processing is usually required when printing with metal, which is both expensive and often dangerous. AM metal printing will be the only material discussed throughout this chapter.

Metal Printing and its associated costs

One of the biggest hurdles to overcome when setting up a metal printing facility is safety. Due to the extremely explosive nature of the products used in the printing process steps need to be taken to mitigate risks. Extreme care need to be taken when operating machinery and storing the powdered metals. Class D fire extinguishers need to be on hand in the case of a site fire. Not only is the powder explosive, but it is hazardous as well. The metal powder poses a threat to Airmen and Operators alike. If the powder is inhaled or touches the skin of the subject, gastrointestinal problems, Alzheimer's, and pulmonary diseases have been linked to exposure [74]. Due to these health risks, operators are required to wear specific personal protective equipment while interacting with machine. A respirator and protective gloves are included in the safety gear. This gear can cost up words of $8,500. Additionally, metal printing requires nitrogen gas or argon gas which can cause health risk to the recipients exposed to gasses. When the gas is cleared and the build has been complete, unused metal powder is present. To dispose of the metal, wet vacuums are be used and the metal is marked HAZMAT.

Real-estate or facilities are an important consideration which needs to be thoroughly thought out. Difficulties arise when trying to find a facility that meets all requirements of AM. An EOS M290 Weighs 2846 lbs. and has the dimensions of 8.2 x 4.26 x 7.18 ft. The recommended floor space dictated by EOS is 15.75 x 11.83 x 9.5 ft. In addition to taking up a fair amount of space, the printer needs to be placed in a structure with level floors that can support its weight and the weight of anyone operating the machine. Operating the machine on any floor other than ground level may prove difficult. Space also needs to be set aside for all equipment such as nitrogen and argon bottles, powdered metal, and protective equipment.

Ventilation is again important for the safety of those operating equipment, which may require hardware to be added to the structure or renovation work done, which could prove costly. The building which the machines are stored in must be properly designed to operate machinery. For example, the temperature of the room which the machine is stored in must remain between 50-104 degrees Fahrenheit, with humidity no less than 20% and no more than 80%. When the machine is printing temperature will not drop below 68 and will not exceed 86 Degrees Fahrenheit. The electrical plugs in the walls must be designed to handle the amperage required of the printers. Typical requirements for power taken from the 2019 fact sheet located on the EOS website states a typical requirement of 3.2kW with a maximum requirement of 8.5kW [75]. Most buildings are equipped to handle such amperage pull from the grid; however, in a deployed environment, such energy usage may prove difficult, even more so if a build is 200+ hours. For the purpose of this study, consider only state-side facilities were considered.

The majority of metal builds are performed by AFRL, UDRI, and a few select maintenance facilities scattered around the US, all of which use EOS M290s. The EOS machines require support equipment transformers, air-water laser cooling systems, fine and course filter systems, wet separator vacuums, and antistatic mats. One cannot successfully print quality end-use parts without the presence of these machines. The machine and support equipment cost about $1,105,000. Maintenance on the EOS machine for the first year is roughly $18,500. For years 2-4, the maintenance cost climbs to $26,810.26. Prices listed are priced for a single machine. Many facilities have multiple machines.

After visiting UDRI, AFRL, and other facilities the study concluded each facility and staff agreed upon one thing, the EOC metal printers should be configured to print one type of metal if striving for efficacy. It is not cost effective to own a single metal printer and switch between varying types of metal powders. For example, a single machine should be configured to print aluminum and not vary form that specific type of aluminum, nickel, or other types of metals. Costs are associated with testing the ideal humidity, grain size, heat, gas ratio, distance to hold the energy beam above build plate, paying personnel to perform tests, and other not mentioned costs. The research gathered information from multiple SME's, and each concurred with the numbers listed. It will take 6+ months for testing and research to get the machine properly configured with the aim of printing the desired quality. During that 6 months, 30+ tests are required to ensure quality and performance of the new metal. Labor alone will cost $25k+, heat treatment $25K+, machining time $40k, and an additional $20k in materials. Testing costs can easily climb to $150,000+ to discover the right configuration a specific material will need to perform as desired[76].

Pre Build Costs

As mentioned in previous chapters, before a part can be printed, data needs to be collected and transferred to a computer which is then transformed in to the desired part. Different ways exist in which this data can be collected. One of the most popular methods of collecting this data is a coordinate measurement machine. The machine is able to precisely collect data points by tracing the desired part with a small probe and then records the movement path. Coordinate measurement machines cost between $30k and $1million. The AF typically uses a machine which has a price tag of $200,000+. 3D laser scanning is another method used to collect data for the build. A 3D scanner uses a laser to scan the exterior of the part and then computer aided design (CAD) is used to build tolerances and the internal architecture of the part. The 960 LR Laser probe most commonly used by the AF for higher capacity AM has a cost of $130K+. The Romer Arm 700 handy scanner (a smaller hand held scanner) cots $70K with $20k cost for software associated with the machine. CAD Licenses are often needed which have a cost of $7,500+. Product lifecycle management software will be needed to sustain parts and costs approximately $80,000. Additionally, resource planning software costs approximately $20k which is needed to operate and keep track of parts [77]. Finally, a lab in-house will be required to test the quality of the powder or contracted out. Quality testing of powder will require $10k+ per year. Once prep work is complete the build process is ready to begin.

Build Costs

Special gasses are necessary to produce the preferred results when printing with metals. Oxygen has varying degrees of humidity which will cause problems with corrosion and build quality, not to mention that it is explosive in nature. In the world of rapid prototyping and production of metal components, it is imperative to have the proper gas atmosphere to produce quality parts. The cost gas during build is negligible. Gas is supplied through a high-pressure manifold which regulates the flow of gas. The manifold costs approximately $3,500. Other sensors required for safety cost $1,500. Finally, materials or consumables used during the build range from $500-$1,000 per build. Once build is complete finish work can commence

Finish costs

As a result of printing parts from metal powder, often the surface of the build is rough and will require a machining or polishing process called “finish work.” Because the print is literally welded to the printing stage the part will need to be removed. This is usually done by an Electrical Discharge Machine (EMD), in which a current is run through a wire that heats up which easily cuts through metal. EDM machines cost approximately $160,000, much more than using a band saw to remove part from stage. After removal of part, excess material needs to be removed. Most parts need to be polished or smoothed according to user requirement; this polishing required labor by skilled workers and machinery.

As mentioned in previous paragraphs, all metal prints need to be heat treated. The heat treatment application consists of gas, pressure, and high temperatures. This is done to relieve internal tension and pressure inherently built into the print. Every end-use-item will need to be heat treated to increase hardness, eliminate possible cracking, and release internal tension throughout the structure. A heat treatment furnace is need on site, and they can be costly. A special heat treatment furnace for one specific type of metal costs approximately $26,000 each. For example, if a printing lab desires to have the capability of printing three separate types of metals, they will need to have three special furnaces one for each type of metal. In addition to specialty AM tools, an AM lab will require common use machines

Metal working labs will usually have a basic set of standard tools that run consistent across all labs/manufacturing facilities which may decrease the price of setting up a lab because needed machines are already on hand. A 4-Asix CNC, arguably one of the most important pieces of support equipment, is used to bring the part closer to the finished product. The CNC makes possible the reuse of build stages/plates. After a build is complete and the part is cut from the plate the CNC refinished the surface for reuse. Also, sand blasters are an essential tools needed when parts with rough surfaces are required to be smooth. The sand blaster is able to forcibly propel a stream of abrasive material against a surface under high pressure to smooth a rough surface, roughen a smooth surface, shape a surface or remove surface contaminants. Sand blasters that meet AF requirements standards cost between $8,500 and $16,800 Furthermore, belts and sanders will be heavily used during the finishing process. Belt Sanders create a great deal of metal shavings, small in size, which can float in air if not handled properly. A down draft table will mitigate the risk of floating particles and keep clutter to a minimum. High grade belt sanders cost $10,000+, with down draft tables costing $5,000+. Finally, hand tools can be used throughout the lab for a variety of tasks before, during, and after the build. Specific requirements exist when using specific metals like titanium and unique alloys; buying tools for these specific parts would undoubtedly cost more. For the purpose of this study a set of hand tools which cost $7,500 will suffice. In closing, when setting up an AM lab, one may reasonably surmise that the lab is going to be supported in a warehouse/facility which is already supported by manufacturing efforts which could be used to also support the AM effort. So the equipment costs listed in this paragraph may be dismissible and can be left out of a cost analysis if support equipment is already available. The table below lists the costs associated with setting up an AM lab for a single AM machine printing one type of metal.

Amortization

Each machine which is discussed in the study is assumed to be amortized over an 8 year period. The reason for choosing 8 years is because of the extremely high rate at which technology is maturing. At 8 years technology that was once cutting edge is not obsolete and outdated and of no use to the AF. The first year of the machines life will depreciate 30%, and 10% per year after that until the value on the books is zero. Depreciation needs to be considered when compiling the costs of an AM shop.

Table 4. 1 AM Lab Equipment Costs (UDRI, and USAF AFMC 76 CM)

Equipment	Quantity Needed	Approximate Cost
EOS M290	1	$1,105,000
EOS M290 Maintenance	1	$26,810.26 per year
Sand Blaster	1 (1 per Alloy Family)	$12,500
High Pressure Argon 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
Wire Electrical Discharge Machine (EDM)	1	$160,000
4-Axis CNC Mill	1	$110,000
Oxygen Sensor	1 (1 per AM machine)	$1,250
Belt Sander	1	$10,000
Down Draft Table	1	$5,000
Coordinate Measurement Machine	1	$200,000
Small Hand Held Laser Scanner	1	$70,000
Laser Scanner Software	1	$20,000 per license
AM Design Software	1	$20,000 per license
AM support logistic Software	1	$80,000 per license
Computer Aided Design Software (CAD)	1	$7,500 per year
Personal Protective Equipment	1 set	$8,500
Enterprise Resource Planning Software	1	$20,000
Hand Tools	1 Set	$7,500
Consumable Powder (Ti-6Al-4V)	300 LB per year	$54,000
Total		$1,943,060.26

SME interviews

To better answer the questions proposed at the beginning of this paper the study surveyed leading professionals in selected career fields and asked those questions on related topics. The researcher chose to keep the names of the surveyed individuals confidential to give them the freedom to answer honestly and without conflicts of interest. Yes an IRB Package was submitted for human subject research. Below are the given questions and a summary of responses.

First question: "What is the total cost of setting up an AM lab for a single Metal Printer (including: Labor, Equipment, supplies, and other costs not mentioned)"

- The general consensus was \$2M-\$3M for a larger capacity powder base printer. This cost includes the facility floor space, the structure needed to hold the printer up, and other associated costs.

Second question: "How does having Additive Manufacturing capabilities effect Air Force readiness (professional estimate)"?

Readiness Capabilities are reduces due to maintenance downtime as, for AM qualified parts, units will no longer have to wait for long lead items or go through difficult local manufacturing procedures. Complex and low demand parts can be produced in a manner of day instead of months or years. Networks are also become more secure so files are not as high at risk of corruption. Additionally Polymers are ready for the Field, while Metals are not. Working with a SPO or management office would prove most useful to the AF

Third question: "What additional capabilities would be available to the Air Force if further funding was provided for Additive Manufacturing"?

Available printing sites could be expanded, allowing for faster turn-around on field requests. **ARCM, DED, and ATLAS** style machines that help with, intricate designs, heat exchange, and build volume could be expanded upon. Additionally, more training could be made available to qualify printer operators and spread knowledge and expertise about AM. AM materials research could also use more funding to provide a broader database of material properties and give better confidence when using AM for flight critical applications.

Fourth question: “What type of problems and limitations exist within Additive Manufacturing that might be a problem to the Air Force”?

The first issue that arises is the lack of trust and support for AM printed Flight critical parts. Like anything new to the Air Force change is often slow coming until buyin occurs. Multipole SME’s mentioned that AM is where Composites were 30 years ago. More research would help with this problem. Additionally, machines and difficult to obtain metals severely limit the progress. Finally, the airworthiness process is challenging and difficult

Fifth question: “What types of problems in regards to long lead times and expensive parts could be solved through Additive Manufacturing”?

- Most agreed upon answer was mostly every can be fixed using some form of AM. The supply chain would cut costs by buying smaller batch sizes, less material would be used, speed of delivery increases, and overall value rises. In the short run the AF has a part delivered much faster than long contractor lead times, and in the long run the AF saves money. Once the AF has the data files for the part the said part can be printed anywhere a facility with proper capabilities exists.

Sixth question: “How can we speed up wait times and increase warfighter capabilities through AM efforts”?

- Building an integrated support network of printers throughout the country would provide much faster replacement times and possibly an easier approval method. By networking the AF will reduced the amount of reverse engineering which is often done and not shared with other units thus causing the same project to be done twice. Often the longest time in the AM process is the reverse engineering of the part often reaching 150+ hours.

Seventh Question: "How much money is the air Force currently spending on AM research and development (in your department, squadron, base, or Air Force Wide"?

- (SME1-3) Unable to provide Answer for this question

  All responses were similar stating they did not know, nor did they know where to find an appropriate response for a number

Almost everything the SMEs said was in line with results and research already conducted. The results of what they said support the findings of the researcher's results. The area where none of the SME's could answer was the financial situation of the AF. The research proved greatly difficult in finding a definitive answer on how much money is being spent by the Federal US government on AM military efforts. The next section will discuss the cost comparison of selected parts.

Comparing Parts

To determine the potential benefit AM can provide to key decision makers, the examiner chose 10 printable air craft parts to analyze for costs and benefits. This comparison rests on the assumption that 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 the selected parts are capable of being produced using AM processes. To determine the cost of each part, the examiner looked at raw materials, machine time used, labor, and any post processing that may be required. The price of parts being scrutinized were found using Haystack Gold, a large logistics database used by the AF. All prices used are current. This price could be paid to the original equipment manufacturer, a contractor, third party, or be produced by USAF personnel.

The study selected ten parts from a list of potential AM parts sent by various AF organizations to conduct a cost analysis. Each part is listed by its National Stock Number (NSN) in order. The information included below involves NSN number, size dimensions, material, price per part, demand in past 5 years, weapon system, Back Order Days (BOD), and administrative lead time (ALT).

Table 4. 2 Part Characteristics Data

NSN	x000313455	x002534792	x002935263	x003350110	x006528879
Part Name	Beam Assembly Support	Support Seat Frame	Conveyor roller Gurage	fitting Assembly Tr	Parachute rack
Source Of Supply	DLA	N/A	DLA	DLA	N/A
Price (USD)	$6,484.25	$3,010.43	$1,766.13	$1,102.34	$1,030.14
Back order (days)	120+	120+	294	591	120+
Material	Steel	Aluminum	Aluminum	Steel Comp 4140	Aluminum
Average need past 5 years	1	2	13	67	1
Weapon system	C-130/AC-130	KC-130/C-130	KC-130/C-130	KC-130/C-130	C-130
Length	6.2 in	N/A	8 in	1.63 in	6 in
width	0.164 in	N/A	4 in	1.16 in	2 in
thickness/Height	10.81 in	N/A	10 in	0.204 in	0.75 in
Diameter	1.81 in	N/A	2 in	0.26 in	N/A

Table 4.2 (continued) Part Characteristics Data

NSN	x006721817	x013655833	x1560016535565	x1680014692740	x1730016327236
Part Name	Bracket Mounting	Electrical Adapter	Air Craft Engine Cover	Beam Assembly Troop	Support Troop Seat
Source Of Supply	DLA	DLA	H	DLA	DLA
Price (USD)	$1,032.97	$1,062.87	$1,697.30	$4,472.38	$2,931.39
Back order (days)	71	120+	120+	120+	120+
Material	Titanium	Steel	Aluminum	Steel	Aluminum
Average need past 5 years	14	1	1	1	6
Weapon system	C-130	KC-130	C-130	SOF C-130 variants	C-130
Length	6 in	N/A	24 in	8 in	9.125 in
width	1.78 in	N/A	24 in	1.25 in	4 in
thickness/Height	1 in	N/A	3 in	9.25 in	5 in
Diameter	N/A	N/A	24 in	2.61 in	2.51 in

Of the ten parts which the study selected only 6 parts will be analyzed. Upon speaking with engineers at UDRI the examiner concluded that only 6 of the 10 parts are eligible candidates for AM.

Table 4. 3 Single build costs

Part Name	Beam Assembly Support	Support Seat Frame	Parachute rack	Bracket Mounting	Beam Assembly Troop	Support Troop Seat
NSN	x000313455	x002534792	x006528879	x006721817	x1680014692740	x1730016327236
Material Cost per part ($)	604.5	416	540.87	378.3	436.15	695.37
Pre-processing Cost ($)	71.1	105.3	79.065	78.795	149.85	69.3
Processing Cost($)	1104	2374.8	1486.8	1186.8	1075.2	1729.2
Maintenance Cost ($)	672.65	1227.6	308	126.5	264	679.25
Energy Cost ($)	20.25	44.15	24.07	34.76	22.95	47.93
Post-Processing($)	357.35	580.5	459	328.5	202.5	687.15
Build Time ($)	37.5	93.75	44.5	68.87	44.5	88.75
Cost per part (AM)($)	2867.35	4842.10	2942.30	2202.53	2195.15	3996.95
Number of Parts(	1	1	1	1	1	1
Current Price DLA ($)	6,484.25	3010.43	1,030.14	1,032.97	4,472.38	2,931.39
Cost Change with AM ($)	-3,616.91	1,831.67	-1,912.16	1,169.56	-2,277.23	1,065.56
Current Lead Time	120+	120+	120+	71	120+	120+
5-year Demand	1	2	1	14	1	6

The next table looks at only the parts which have a geometry allowing multiple pieces to fit on a single build plate. These parts will intuitively cost less because they are made in tandem with each other.

Table 4. 4 Maximum Parts per Build Cost

Part Name	Parachute rack	Bracket Mounting
NSN	x006528879	x006721817
Material Cost per part($)	410.865	313.3
Pre-processing Cost($)	146.57	170.3295
Processing Cost ($)	1966.8	1546.8
Maintenance Cost($)	418	236.5
Energy Cost ($)	31.36	40.7025
Post-Processing	594	463.5
Build Time	56.25	75.625
Cost per part AM($)	1811.92	1423.37
Number of Parts	2	3
Current Price DLA($)	1,030.14	1,032.97
Cost Change with AM ($)	781.78	390.41
Current Lead Time	120+	71
5-year Demand	1	14

Table 6 shows the average costs across the seven parts and a breakdown of the total costs.

Table 4. 5 Single Part Cost Breakdown

Build components	Average	Percentage
Processing Cost	$ 1,492.80	47.98%
Maintenance Cost	$ 546.33	17.56%
Material Cost	$ 511.86	16.45%
Post-Processing	$ 435.83	14.01%
Pre-processing Cost	$ 92.24	2.96%
Energy Cost	$ 32.35	1.04%
Build time	62.98	N/A
Cost per Part	$ 3,174.39	N/A

The figure 1 below is a graphical depiction of approximate average breakdown for single part**.**

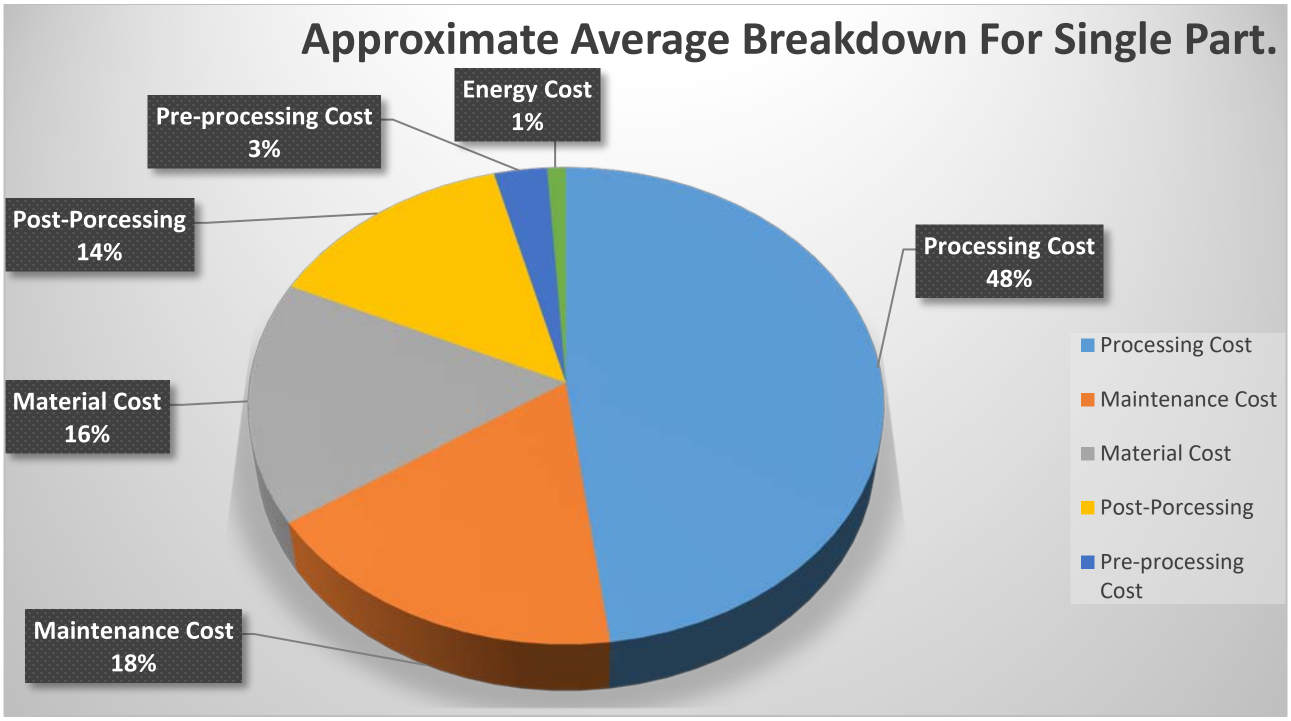

Figure 4. 1 Approximate Average Breakdown for a Single Part

Table 4. 6 depicts the average cost breakdown for the maximum number of parts per build.

Build components	Average	Percentage
Processing Cost($)	1756.8	49.75%
Maintenance Cost($)	327.25	9.27%
Material Cost($)	724.165	20.51%
Post-Processing($)	528.75	14.97%
Pre-processing Cost($)	158.4473	4.49%
Energy Cost($)	36.0315	1.02%
Build time	65.9375	N/A
Cost per Part($)	3531.444	N/A

The figure 2 below is a graphical depiction of approximate average breakdown for a maximum number of parts

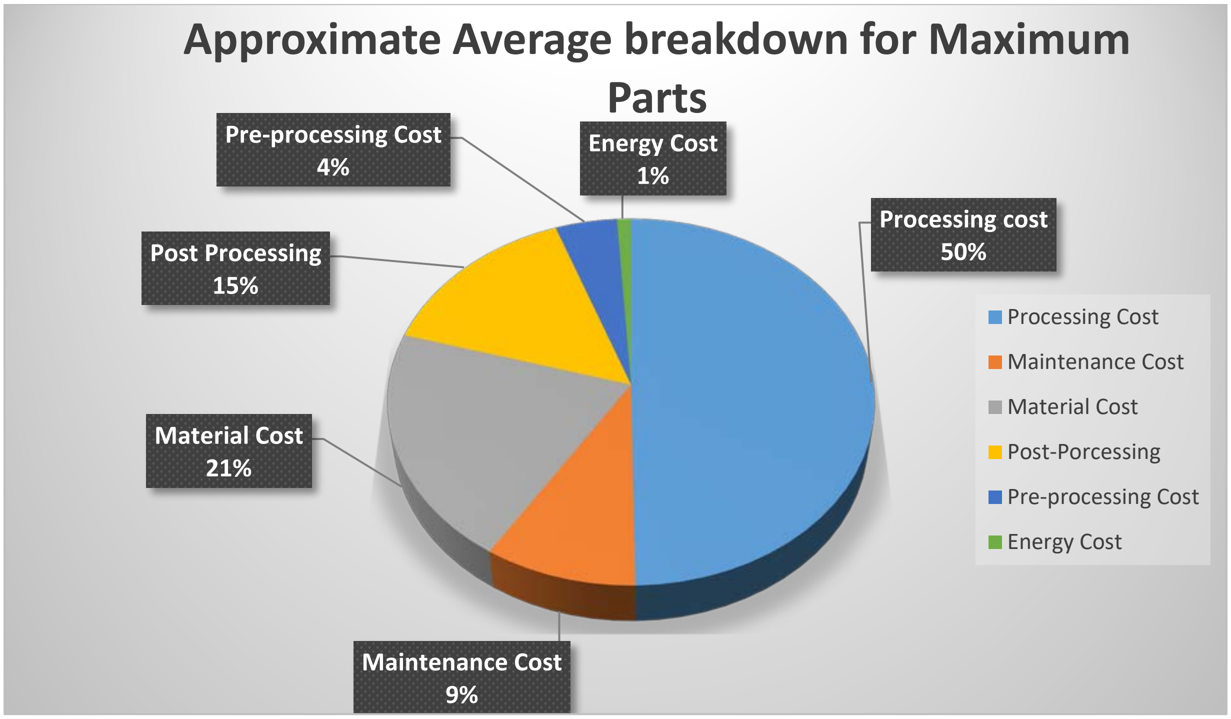

Figure 4. 1 Approximate Average Breakdown for maximum number of parts

Of the six parts analyzed only three of the six parts cost less to produce one part at a time with AM than the current cost of acquisition. As hypothesized earlier in this paper, the more parts which are built using AM at a time is directly correlated to a decrease in maintenance, material, and post processing costs. As seen above one can observe a 33% savings when two parachute racks are printed using AM in the same batch, and a 35% savings when three bracket mounts are printed in the same batch using AM. Prints using AM technology is still more expensive specifically from a cost perspective.

To purchase a mission critical part from DLA frequently take an excessive amount of time to receive, but is on average still less expensive than metal printing the parts on average.

When comparing the total cost of the six parts produced by DLA divided by the number of parts, one arrives at an average of $2,486.83 per part. Then look at the total cost of the six parts produced using AM divided by the number of parts, one arrives at $3,174.96 per part. Producing the chosen part using AM is on average 27.6% more expensive than traditional DLA methods. However reediness and time are important factors to consider when choosing the method.

The figure 3 below gives a graphical depiction of the time to receive a part from vendor using DLA and AM.

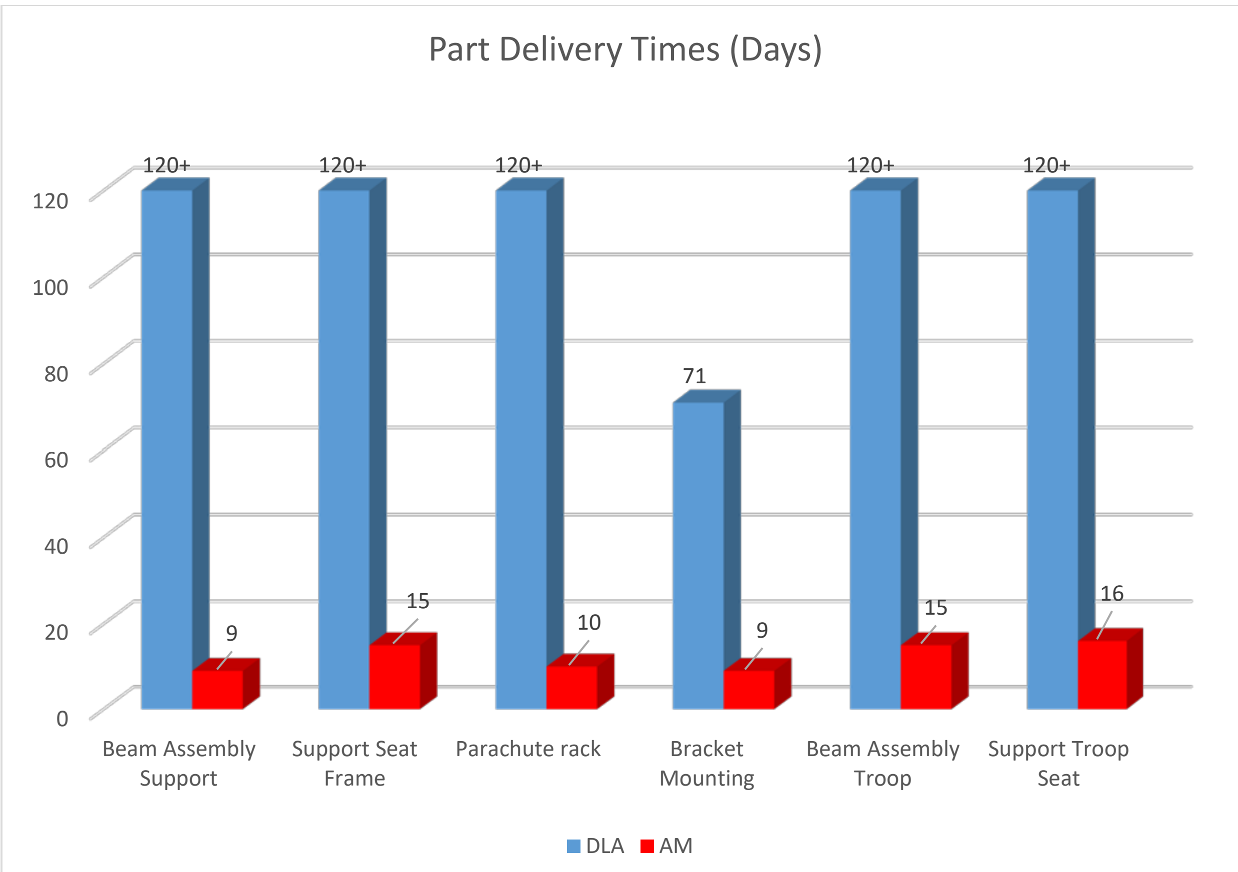

Figure 4. 2 Part deliver times from DLA and AM acquisition

Data for the chart above was gathered using Haystack Gold, an online logistics database, and subject matter experts. The parts which have times of 120+ days reflect an assumption of how long the acquisition of that part would take at a conservative minimum. Parts created by AM have much shorter lead times to delivery. With a conservative approximation it will take 88.9% longer to receive the DLA named parts than it would to create the named part by AM.

Multi-Objective Decision Analysis tool

The objective of this paper is to provide tools and information to help key decision makers decide if AM Operations are feasible within their organizations. The Multi Objective Decision Analysis (MODA) tool allows interested parties to quickly analyze a few of their tools. If the tools analyzed score between 60-85%, the interested parties can then read the whole of this paper for finer details. If the part's score is between 86-100%, the part is an extremely good candidate for AM. If the part's score is below 60%, traditional methods should be considered. The criterion score are below in the "Criterion Explain" section.

Table 4. 7 is a Multi Objective Decision Analysis tool which aids decision makers in provide a quick analysis of AM feasibility of a selected part.

Figure 4. Multi Objective Decision Analysis Tool

Multi-Decision Analysis Model				
Model Component	**Component Classification**	**SME Recommended Weighting**	**Customer Input**	**Score**
Part Quality	Beneficial	21.00%	Exceeds Industry Standards	10
Lead Time	Non Beneficial	20.10%	1-15 Days	10
Readiness	Beneficial	18.30%	Must Be Printed Within 100 Hours	10
Price	Non Beneficial	14.60%	Equal to or Less than 89% Average Cost	10
Air Worthiness	Non Beneficial	7.30%	Does Not Effect Air Worthiness	10
Expected Life	Beneficial	6.30%	Life Expectancy is Extended	10
Part Strength	Beneficial	6.20%	Exceeds Strength Requirement	10
Weight	Non Beneficial	4.80%	Lighter than 85% Original Design Weight	10
Part Quantity	Non Beneficial	1.50%	1-2 Parts Needed	10
			Raw score	10.01
			Final Adjusted Composite Score	**100.1**

Table 4.8 Criterion Explained:

Lead time	**Very short**(10)= 1-15 days, **Short**(8)**=** 16-30 days, **Medium**(6)= 31-45 days, **Long**(4)= 46-65, **very long**(0)**=** 65+ days
Price	**Below**(10)= 11% or less than average, **Average**(5)= 10% above or below average price, **Above** (0)= more than 11% above price
Strength of part	**Below**(0) = weaker and more likely to break thank original part, **Average**(6)= meets the same requirements as the original specification, **Above**(10)= stronger and more durable than original specification
Weight	**Light**(10)=more than 15% lighter than original design, **Normal**(7)= within 14% lighter to 14% heavier than original design, **Heavy**(0)= more than 15% heavier than original design
Air worthy	**No**(10)= Part does not affect air worthiness, **Marginally**(6)= part marginally effects Air worthiness, **Yes**(0)= Part DOES effect Air worthiness
readiness	**Very important** (10)= needs to be able to be printed immediately within 100 hours, **Important**(8)= means can be printed within 500 hours, **marginally important**(5) = needs to be printed within 2 months, **Not important**(0) = printed within 6 months
Quality of part	**Low**(2)= can be printed fast and does not have a requirement standard, **Average**(7)= meets the Industry standard , **High**(10)= Exceeds industry standards
quantity of parts needed	**Low**(10)= 1 to 2 parts, **Medium**(6)=3-20 parts, **high**(2) = 20+ parts
Expected Life	**Decreases**(0)= expected life decreases, **Stays**(7)= No change in Life, **Increases**(10)= Life is extended

Assumptions:

- Beneficial means the higher the points on the scale the more benefit gained

- Non Beneficial means the higher the more negative the outcome

- All weights of importance are bases off current needs of the AF and DoD according to SME'S opinions and are subject to change due to Economic stability, availability of raw materials, and many other factors

Data Conversion Costs

Transforming the part drawings in to digital data requires a great deal of time and money. These costs can be considered one time only costs because after the data is loaded it is saved and does not need to be repeated. For a part to be produced with AM there needs to be an accurate 3D model that can be loaded into the machine to produce the part. The cost will come down to what material is the part made of, how complex the part is, and what type of mechanical properties are required. An estimate from AFLCMC said it costs $1,000,000 on the high end to redesign a part and optimize it for AM. The AM department at Tinker said it only takes 50 hours to reverse engineer a part which is not going to cost more than $10,000. The benefits of optimizing a part for AM is increased durability and strength.

Chapter 5. Conclusion and Recommendations

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 3 and 4. Then this chapter will discuss the potential for related follow-up research. Finally, recommendations based on the findings of this research will be provided.

Results of Research

The results found in this study were consistent with findings from alike studies done by the AF and DoD alike [1] Which is to say that AM has a bright future in the military as a tool for increasing readiness capabilities and in some cases reducing costs. Challenges exist and research is ongoing to make parts that are airworthy, very few AM parts as of now are airworthy and require extensive testing and approval before being deemed fit for flight. Over all half of the AM parts in this study which were compared against traditionally manufactured parts proved greater cost savings than the traditional method. Additionally, in all cases tested AM proved to have significantly faster delivery times than that of traditional manufacturing.

Research question answered

(1)What additional capabilities would be available to the Air Force if further funding was provided?

As mentioned previously, readiness is key component of military strategy and can have crippling effects if hindered. AM provides the capability of producing high quality, light weight, and super strong parts that can be immediately used for spares and in some cases outperform milled parts. Imagine a plane breaks down in the Middle East and the part in question will take 5 months to deliver if expedited. In many cases the part in question can readily be made through AM and could reasonably be delivered in a matter of days. Additionally, AM is extremely applicable in prototype and form-to-fit applications as is being recognized by AFRL , AFMC, and many Depos [52].

(2)What type of problems and limitations exist within Additive Manufacturing that might be a problem to the AF?

A great deal of moving parts are required to make AM successful, even if one component of the process is slightly miss-calibrated the whole process may fail, now combine those components with a high stress high speed environment and it is easy to make mistakes. Furthermore, extensive training is required to use and operate AM machines and as of now there is not enough trained professional inside the AF to operate organically. Another issue to consider is the fact that the military wholly relies on industry partners to provide am support, which may or may not be a large issue considering the military relies heavily on industry partners for a large majority of military might and support. Lastly, materials required for AM are often limited in supply and given the current political climate obtaining specific materials which are heavily imported from foreign countries may potentially become an issue.

(3) What types of problems in regards to long lead times and expensive parts could be solved through Additive Manufacturing?

As the AF continues to use planes well past their intended-use time frames part suppliers for these air craft are diminishing, causing a short in the supply chain for replacement and spare parts, and thus increasing the time to deliver and cost of parts. Of the 10 parts analyzed in this study 5 were shown to have cost savings when compared to traditionally manufactured parts. On average the delivered part is in hand 100 days sooner than buying the same part from industry. With the savings from AM parts whose funds could be used for training, research, or given to another departments in need. Additionally, the days saved by early part delivery means planes that are grounded are once again made valuable assets to the warfighting machine increasing readiness and response time.

(4)How can wait times and increase warfighter capabilities be increased through AM efforts?

The added benefit of AM is hard to measure when considering warfighter capabilities, if the government places a high demand on lower wait times then the added benefit would be considerable. The Capability to fix not only broken, but complex broken parts is a skill that derives more attention. In fact, research have proven that the government and DoD alike are contributing greatly to increase these capabilities. AM cuts lead times in some cases by 90%, this decrease in wait time could potentially take a wing of 50 fighter jets with only 30 fighters that are flight worthy, due to maintenance, and increase that number to 35 or 40 due to ability to start printing the broken part the very day the break occurs.

(5) How much money is the Air Force currently spending on AM research and development?

It is difficult to come up with one definitive answer on how much the military or even the AF is spending on AM efforts because each unit has some discretion on where resources are allocated, however initiatives in the "DoD service AM implementation plan" are dedicating to fund industry partners for reach and development of AM technologies. In 2018 the University of Dayton performed $149.8 million in sponsored research in fiscal year 2018 most of which was for AM efforts. The University of Dayton Research Institute is in partnership with American makes and is the largest funded source of AM research in the AF. Although each Service has its own unique ecosystem of AM research, all the services are members of the National Manufacturing Institutes, more recently renamed "Manufacturing USA". As of 2018, the federal government committed over $1 billion, which has been matched by more than $2 billion in investment by industry, academia, and state and local governments [1].

Limitations of the research

The use of 3D printing spare parts that are end use items or temporary replacements is a fairly new endeavor by the military which causes data to be scarce. The researcher was given a list of potential AM parts for the C-130 and variants, however the said list was a conglomeration of parts which have little to no data, some of which had not been order in 10+

years. Subject matter experts, Logistics software, and calculated assumptions were heavily relied upon for conclusions.

Future Research

The research that was accomplished in this paper gives evidence that further research is important in the understanding of limitations and applications of AM and investigation into additional elements of AM are needed. The study will discuss below the areas of research which could be explored by future aspirants.

United State Special Operations Command (USSOCOM) is reportedly using AM. Researching the applications and cutting edge technology in which the USSOCOM is currently using could be a remarkable experience for all parties involved. AFIT does have access to many supplies as well as the close proximity to UDRI making this research a feasible option as long as consent is given and proper clearances are secured.

The research discovered throughout this study proves that the process by which AM/3D printed parts are deemed to be air worthy and installed on fully functional planes is a challenging process which takes much time and many approvals. A potential for streamlining a more simple process by which all AM/3D parts are approved could prove useful to the AF and DoD alike.

The study's interaction with many subject matter experts over the course of the study helped to identify many issues which are of great importance. An engineer at Warner Robins AFB explained in detail how a lack of engineers at AM labs are limiting the ability to produce a successful product. Not only Warner Robins, but Hill and Moody AFB has a problem with getting enough properly trained engineers to run the lab properly. A framework or standardization of training and recruiting processes would be helpful for those offices seeking employment

Recommendations

While there is great potential for time and costs savings with metal AM on a small scale, it is not currently feasible to use AM technology to produce aircraft replacement parts on a full scale do to the maturity level of the technology. While the research does not recommend full scale AM operations at this time, the time is not far off where mass production of 3D printed plane parts is become ever more possible. Companies in industry are producing parts for production Aircraft through AM on mass scale, and the AF is not far behind.

A great potential exists in AM for savings and significantly reduced wait times. As of now 3D printing is best used in prototyping and special use cases were the specific replacement part has significant wait time.

List of Acronyms:

- **3D**: has 3 dimensions, an x, y, and z plane
- **AM:** Additive Manufacturing
- **AF:** Air Force
- **AFB:** Air Force Base
- **AFIT:** Air Force Institute of Technology
- **AFMC** (Air Force Material Command: AFMC delivers war-winning expeditionary capabilities to the warfighter through development and transition of technology, professional acquisition management, exacting test and evaluation, and world-class sustainment of all AF weapon systems (AFMC official website).
- **AFLCMC** (Air Force Life Cycle Command): Mission is to Acquire and Support War-Winning Capabilities.
- **AFRL**: Air Force Research Labs
- **ARCM** manufactures electron beam melting (EBM) systems for use in additive manufacturing
- **ALT**: administrative lead time
- **ATLAS** Atlas designs, repairs, and remanufactures complex equipment and components for industry and municipalities
- **BOD**: Back Order Days
- **CAD** (Computer-Aided Design): an advanced computer design software.
- **CAGR**: Compound annual growth rate
- **CCAD:** Corpus Christi Army Depot

- **DMLM:** Direct metal laser melting
- **DED** Directed Energy Deposition is a category of metal additive manufacturing (AM) that utilizes robotic welding processes to print at high deposition rates but with relatively low resolution
- **EDM:** Electrical Discharge Machine
- **FDM**: Fused Deposition Modeling
- **Laser sintering:** An additive manufacturing technique that uses a laser as the power source to sinter powdered material, aiming the laser automatically at points in space defined by a 3D model, binding the material together to create a solid structure
- **MAMLS**: Maturation of Advanced Manufacturing for Low-cost Sustainment
- **MAMLS**: Maturation of Advanced Manufacturing for Low-cost Sustainment
- **MODA**: Multi Objective Decision Analysis
- **NSN**: National Stock Number
- **OSD**: Office of the Secretary of Defense
- **PBF**: Powder Bed Fusion
- **PAC**: Powder Alloy Corp
- **Subtractive Engineering**: involves cutting away from a solid block of metal. "Manufacturing processes based on controlled removal of undesired materials through cutting, drilling or milling to achieve the desired forms" [9].
- **SME**: Subject Matter Expert
- **Substrates**: Surface of the material

- **Topology**: the study of geometric properties and spatial relations unaffected by the continuous change of shape or size of figures
- **UDRI**: University Of Dayton Research Institute
- **USSOCOM**: United State Special Operations Command

Appendix 1

Power Alloy Corp Site Visit
The AFIT Strategic Topics and Innovation Class had the fantastic opportunity and privilege of attending a site visit to the Power Alloy Corp's (PAC) Manufacturing Plant. This visit was coordinated and organized by AFIT students, who are working with PAC to develop thesis topics which will identify logistical processes to reduce the power metal procurement costs for the United States Air Force. The tour of the site was guided by Mr. Lewis Temples, Vice President of Manufacturing and Engineering, and Mr. Scott Ostholthoff, Chief Executive of Sales and Operations. Mr. Lewis has been working for PAC for over 20 years has in-depth knowledge of Metallurgy, Chemistry, and Engineering. The tour covered the entire process of turning metals into fine powder to be used in 3D printing. There are many different types of metal, quality, size, and weight all of which need to be considered when meeting each customer's unique needs. Customers of PAC include General Electric, Pratt and Whitney, Rolles Royse, CFM international, and several other well know large corporations. Some of the many parts created through PAC's additive process include turbine blade housings, parts for the F-22 wings, and many other tools. Tools produced by PAC are known to reach torque strengths in excess of 7,000 lbs, while others can be made in only 30 minutes through powder forming. Overall this site visit was not only enjoyable but also an eye-opening experience to see how innovative and cutting edge their processes are. The Air Force has always been a leader in cutting edge technology and will continue to do so as it embraces Additive engineering techniques and applies them to the warfighters arsenal.

Appendix 2

Questions Answered by SME's

First questions: "What is the total cost of setting up an AM lab for a single Metal Printer (including: Labor, Equipment, supplies, and other costs not mentioned)"

- The general consensus was $2M-$3M for a larger capacity powder base printer. This cost includes the facility floor space, the structure needed to hold the printer up, and other associated costs.

Second question: "How does having Additive Manufacturing capabilities effect Air Force readiness (professional estimate)"?

- (SME#2) Reduces maintenance downtime as, for AM qualified parts, units will no longer have to wait for long lead items or go through difficult local manufacturing procedures. Complex and low demand parts can instead be procured in a matter of a few days once the AM integrated support network is fully realized.
- (SME #1) For Polymer; the technology is mature enough for field units to own a polymer FDM style printer. They will be able to download print files from a secure source and print locally. This will shorten the supply chain for those parts to possibly hours instead of days or weeks. I believe that in a couple of years, the units will be printing knobs, panels and covers regularly.
  For metal, this the areas with the most potential to improve readiness. The idea of quickly printing off flight worthy parts is the end goal. Obviously, lots of hurdles to surmount before we can do that. The AM enterprise along with the SPO and Supply Chain partners needs to continue to figure out the airworthiness and configuration control issues before we can truly impact AF readiness with metal parts.

Third question: "What additional capabilities would be available to the Air force if further funding was provided for Additive Manufacturing"?

- (SME#3) Tough question. There are three capabilities that I know for sure that we are looking into but it would be in the FY24-25 range or later. One, Electron Beam. ARCAM and other makes an EBM style machine that is capable of making very intricate designs from a powder bed. Fan blades and some conformal style Heat Exchangers come to mind with this. Two, our propulsion side is investigated a Wire fed DED style machine with a machining attachment for fan disk and housing repairs. I have seen the results and it is an amazing machine. Finally, GE has a large scale powder based single head laser machine called the ATLAS. Nearly 4ft by 4ft by 5ft build volume. That would help with engine fan cases and complete housing replacements when we can't get castings.

- (SME#2) Currently, the only qualified printing sites include the ATTCs in Dayton, OH and Warner Robins, GA as well as Travis AFB. With additional funding, the network of available printing sites could be expanded, allowing for faster turn-around on field requests. Additionally, more training could be made available to qualify printer operators and spread knowledge and expertise about AM. AM materials research could also use more funding to provide a broader database of material properties and give better confidence when using AM for flight critical applications.

Fourth question: "What type of problems and limitations exist within Additive Manufacturing that might be a problem to the Air Force"?

- (SME#2) One main difficulty I have seen with getting AM parts on aircraft is the lack of trust or understanding from engineers regarding the reliability of AM for flight critical parts. At this stage, however, these concerns are justifiable because there is so much variability in material properties with AM. Through building stronger database of B-basis material properties and improving our knowledge of 3D printing, I believe these concerns could be better addressed, opening the door for more critical applications in the near future.
- (SME#1) There are many that we, the AM enterprise, are currently working on. I think today's AM is where composites was 25 to 30 years ago. At that point, not many people were familiar or comfortable with composites and now it is used in almost every new aircraft. Some of the problems and limitations: Engineers are risk averse, lack of knowledge about AM, scared of AM part failure, limited metals and machines in the AF, Airworthiness process, convincing the Change Evaluation Teams and Configuration Control Boards of AM's value.

Fifth question: "What types of problems in regards to long lead times and expensive parts could be solved through Additive Manufacturing"?

- (SME#1) The answer is almost everything. Polymers could be used to replace thermoformed panels that crack and age badly. It could also be used to replace the knobs and switches that break in the flight decks. The supply chain is forced to buy too many parts because of the manufacture lot quantities or some suppliers just refuse to sell to the government. For metal, casting houses are shutting down and manufacturing in general is not as popular as in the past. AM, once the build file is complete, eliminates a lot of the contractor lead time. On a price per part basis, AM tends to be more expensive but its "value" is in the speed of production. For example, if you needed 10 parts for your aircraft fleet, would you rather pay $10 per part for a 1000 parts from a manufacturer with a lead time of 180 days or $500 per part for 10 parts with a lead time of 2 weeks. Option one is the better net cost per part while option two gives to the most value per part.

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Sixth question: "How can we speed up wait times and increase warfighter capabilities through AM efforts"?

- (SME#1) By building up an integrated support network of printing sites throughout the country, we will be able to provide replacements for approved parts in a matter of a few days rather than trying to locally machine complex parts or accept excessive lead times for low demand parts.
- (SME#2) This touches on an issue that is rarely discussed, Reverse Engineering. AM, from a production stand point, is relatively fast. Everyone thinks of it as simply hitting print and then in a couple of days, I have a part. While that is somewhat true, we forget that most of the parts that the AF wants to print will require a reverse engineering effort. The legacy parts were designed differently than AM parts. Therefore, REACT does the reverse engineering to make AM versions of the legacy parts. A simple reverse engineering project for this AM transformation takes between 100 and 150 engineering hours. If you want to speed up wait times and increase warfighter capabilities in the future then you need to invest in reverse engineering now.

Seventh Question: "How much money is the Air Force currently spending on AM research and development (in your department, squadron, base, or Air Force Wide"?

- (SME1-3) Unable to provide Answer for this question

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14. ABSTRACT

Extremely long lead times for legacy aircraft replacement parts often exceed 120 days and cost 3 to 4 times the original price drives a search for alternative manufacturing methods such as additive manufacturing. Currently, the method to procuring a legacy replacement for aircraft such as the C-130 is daunting and at times, impossible. Through a comprehensive knowledge collection of organizational data the Air Force body of knowledge increases and provides actionable data to decision makers which has the potential of dramatically decreasing part wait times and procurement. The proposed, intuitive decision analysis framework mapped out in this research provides relevant direction for potential candidates considering additive manufacturing alternatives within their organizations. As result of this study, interested parties now have an abridged guide to costs, expenses, and challenges of setting up an Additive Manufacturing facility within their establishments.

15. SUBJECT TERMS

Additive Manufacturing, 3D Printing, Logistics, Cost Analysis, Legacy Air Craft

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