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JUST DO IT…YOURSELF:

Implementing 3D Printing in a Deployed Environment

by

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ABSTRACT

With increased budget cuts and an aging aircraft fleet, the Air Force is looking for innovative ways to reduce procurement, transportation, and inventory costs of tools, parts and supplies. In particular, traditional manufacturing, taking inventory, and transporting aircraft parts and supplies can be slow, costly, hazardous to personnel, and dangerous for the environment. The new manufacturing technology called "3D printing," also known as "Additive Manufacturing" has been held out as a possible way to reduce repair time, costs of procurement, transportation, and inventory costs, while also being safer, less labor intensive, and more environmentally sound than traditional manufactured replacement parts.

The problem/solution methodology is used to examine the extent to which, if at all, Additive Manufacturing (AM) can benefit the Air Force and what is currently being done to implement its use. This paper provides an overview of the costs, operational failures, and environmental impact of the Air Force's current supply chain, and how AM is being utilized by military units to help reduce these problems. While steps are being made to implement three-dimensional (3D) printing at the base and depot levels, the Air Force has not provided clear direction for its implementation or fully capitalized on its benefits. Consequently, the paper recommends the Air Force develop deployable 3D printing packages, provide 3D printing training, more guidance on the circumstances under which 3D printers should be purchased, what parts should be printed, and establish a formal approval process for certifying 3D printed aircraft parts.

Introduction

Brief description of the problem:

Transportation of Air Force materiel between contractors' plants and military logistics centers absorbs tremendous resources; such field activities exceeded $5.6 billion in 2013.[1] This is in part because the average cost per flight hour of a C-5 Galaxy, carrying much of the material, is $100,941, and this does not account for repairs and maintenance of the aircraft.[2] Consequently, more parts are needed as an operation's tempo increases.[3] Additionally, the more distant the conflict, the greater the transportation cost becomes.

War planners attempt to estimate war reserves and spares for the freedom of logistical support the military has grown accustomed too, but their estimates are often over or under actual demand. For example, in 2012, the Air Force spent $486.1 million for the delivery of 16 C-27A Spartan cargo planes, which included $60.5 million in spare parts, to the Afghan Air Force.[4] Of the 16 aircraft, six had to be "cannibalized" for spare parts so the other ten aircraft could continue operating.[5] Cannibalization is the removal of a currently functioning serviceable part from a weapon system for the repair of an aircraft that needs the part to make it fully mission capable.[6] The C-27A Spartan program was ultimately deemed unsustainable because the Air Force determined an additional $200 million in spare parts were needed to properly maintain the aircraft.[7]

To address the tremendous costs and shortfalls related to similar problems, the Army, Navy, NASA, DoD vendors, and other organizations are increasingly turning to a new technology called "3D printing," also known as "Additive Manufacturing." This technology enables them to create parts and supplies in-house, thus reducing their supply chain and transportation costs. Unfortunately, the Air Force is only now starting to explore the benefits of three-dimensional (3D) printing. Consequently, this paper explores the following question: What would be the merits, if any, of the Air Force implementing 3D printing in deployed locations?

The Air Force's deployment of 3D printers and related raw materials to deployed locations may allow for the rapid customization of aircraft parts, reduce hazardous waste, and cut inventory holding and transportation costs. More importantly, it could improve warfighting capabilities by giving units the ability to manufacture tools, parts, and supplies on-site as needed.

Additive Manufacturing (AM) is the process of making 3D objects by adding (printing) layer by layer of a material (usually plastic or metal) until the object is created. In contrast, subtractive (traditional) manufacturing removes material until the desired object remains. AM allows for the customization of parts and on-site production with minimal training requirements.

3D printing often uses reverse engineering to recreate, and potentially, improve an existing part with the help of 3D scanners. Much as magnetic resonance imaging (MRI) uses a magnetic field and radio waves to create detailed images of the organs and tissues inside the human body, a 3D scanner creates a digital replication of the desired part. This 3D model data can be stored for future manufacturing or manipulated, using software, to improve the parts' design.[8] 3D manufactured parts can be printed with hollow or honeycombed attributes which can make them lighter and better capable of withstanding heat stresses. AM allows for designs to be developed and tested in a virtual environment, very quickly, and before manufacturing has commenced. Additionally, these 3D designs can be electronically sent to operators in deployed locations.

3D printing in a deployed environment will require the initial transportation of large printers, raw materials, and peripheral supporting equipment. However, it could reduce transportation and inventory costs in several ways. First, raw materials can be packaged or palletized to allow more material per cubic inch than the parts themselves. This condensing of material could allow for greater utilization of aircraft load, and thus fewer resupply missions. Second, excess powder based raw materials can be recycled back into the AM process at least 14 times. Additionally, raw materials often retain their monetary value, or appreciate in value. Thus, excess raw materials could be sold in the private sector with minimal security concerns.

Manufacturing parts and supplies at deployed locations could help reduce the transportation costs. Additionally, some spare parts for our aging aircraft fleet are no longer being manufactured and getting harder to find. 3D printing could reduce maintenance costs and offer an opportunity for the Air Force to extend the useful life of its fleet by manufacturing these parts in-house. Time spent locating and transporting rare parts could be reduced, thus increasing sortie rates (flying hours related to missions and training).

The Air Force's recent acquisitions of 3D printers for state-side facilities and the early implementation of 3D printing by the Army and Navy may suggest that AM offers financial benefits. AM allows for the production of parts on an as-needed basis, which could reduce material storage footprints, eliminate the holding cost of parts, and enhance operational capabilities with less downtime.

This research paper will use a problem/solution methodology to examine how the Air Force can benefit by deploying 3D printers to forward operating bases to produce aircraft parts, tools, and supplies. This paper will begin with a brief description of 3D printers and AM and provide some examples of their use. Additionally, a brief summary of the Air Force's supply chain will be presented. Following this summary will be a thorough description of the problems and challenges the Air Force faces when deploying aircraft parts and supplies, along with environmental issues and operational impacts. The next section will outline potential ways 3D printers can be deployed to a combat environment. Quantitative data will be used in each section of this paper to support all claims and recommendations regarding expenditures, savings, inventory levels, and manufacturing output. Lastly, a recommendation for the implementation of 3D printers will be presented based on research findings, followed by the conclusion.

Background

The next section provides a more thorough description of AM, along with some current and potential future applications of this technology. Additionally, a brief overview of the Air Force's current supply chain may help identify some potential cost savings that AM can offer. Understanding these two topics will help with the analysis and recommendations to follow.

Brief Description of Additive Manufacturing

Once an interesting hobby for technologically advanced enthusiasts, 3D printing has now turned into a multidisciplinary and multibillion dollar industry, with far reaching possibilities. According to the 2016 Wohlers Report, more than 278,000 desktop 3D printers (under $5,000) were sold worldwide last year and amounted to over $5 billion.[9] Advancements in 3D printing technology and materials are reducing hardware and software costs, making the technology more accessible and relevant.

3D printing is reducing manufacturing costs with the help of computer-aided design (CAD) programs that create 3D digital representations of objects. These digital 3D files can be saved to removable media and carried to deployed locations or stored in a cloud based server, which allows them to be retrieved from anywhere with an internet connection. 3D printers can then transform intangible data to physical objects. Imagine an aircraft maintainer deploying with all their hand tools and parts on an encrypted flash drive.

Many 3D printers use spools of material which are fed into the machine (similar to how a welder uses flux core wire to weld a seam). The 3D printer simultaneously moves and melts the material, which applies successive layers of material until the object is complete. The list of materials used in AM is growing everyday but includes metals such as stainless steel, bronze, gold, nickel steel, aluminum, and titanium; carbon fiber and nanotubes; stem cells; ceramics; and food.[10] Furthermore, more advanced 3D printers are capable of blending materials, which can be used to print integrated circuits onto irregular shaped surfaces.

AM allows for the duplication of existing objects, or their reverse engineering, using a 3D scanner. 3D scanners are devices that takes distance measurements of real world objects, using a variety of techniques, and digitally recreates the object to a specified scale. Alternatively, 3D modeling software can be used to create new or prototype digital objects.

From an aeronautical perspective, in December 2016, engineers from the Army Research Laboratory flight tested a 3D printed unmanned aircraft that exceeds 55 miles per hour, performs surveillance, is equipped with small arm weapons, and can be printed in less than 24 hours.[11] The 3D printer is designed to be forward-deployed and capable of customizing drones to support a wide variety of missions. Additionally, the Navy recently announced a Marine MV-22 Osprey made the first successful sea services' flight with a "flight critical" component built by a 3D printer, and plans to 3D print five additional flight critical components in 2017.[12]

While the Army and Navy have embraced the implementation of AM, the Air Force is only now considering how to capitalize on this innovative technology. Consequently, AM may offer the best hope for designing a reusable hypersonic weapon. Traditional manufacturing techniques are unable to produce parts capable of withstanding the higher temperature friction of Mach-5-plus speed.[13] AM allows for the design and production of parts with elaborate and efficient cooling channels. Additionally, hypersonic weapons require large structures made from exotic metals.[14] Consequently, it is believed the next generation of 3D printers will be large enough to manufacture structures that conform to hypersonic weapon designs.

Overview of Air Force's Supply Chain

The Air Force manages one of the largest and most complex supply chains in the world.[15] Its primary focus is mission sustainment which includes the acquisition, transportation, maintenance, repair, supply, and product life cycle management of parts, supplies, and weapons systems. Entire industries have been created to support each phase of the supply chain, but they all work together to provide war fighters with the tools they need to defend United States' national interests. Consequently, the total ownership cost of these parts and supplies increases as they pass through their life cycles.

Acquisition is the beginning and perhaps the most important phase of the supply chain. This is where the demands of the Air Force get translated into supply. "The acquisition process encompasses the design, engineering, construction, testing, deployment, sustainment, and disposal of weapons or related items purchased from a contractor."[16] As such, it must not only account for the initial development and manufacturing cost of parts and supplies, it must anticipate future maintenance and repair costs. Depending on the complexity of the part or weapon system, the acquisition process can take years. Additionally, the average acquisition cost of a weapon system with a 30-year life cycle can amount to 20-35 percent of its total life cycle cost. Unfortunately, "DoD acquisition programs have seen budget cuts up to 10 percent, changes in acquisition schedule, reduction in the number of systems purchased, and an increased scrutiny over cost estimates."[17] With the acquisition process facing a great deal of turmoil, innovative and improved methods of reducing costs are needed.

Once parts and supplies have been purchased, they must be transported from the vendor to a warehouse or end user. While the Defense Logistics Agency (DLA) manages the acquisition and initial transportation costs, further transportation of parts and supplies is managed by the United States Transportation Command (USTRANSCOM). USTRANSCOM is capable of moving cargo by air, sea, or land. Consequently, air transportation is the responsibility of the Air Forces' Air Mobility Command (AMC), sea transportation is managed by the Navy's Military Sealift Command, and land transportations are managed by the Army's Military Surface Deployment and Distribution Command (SDDC).

Transportation costs and delivery times vary between these modes of travel. Land and sea transportation are understandably slower and less expensive. However, with today's rapidly changing political environment, speed of logistics is paramount. Hence, combatant commanders are relying on airlift support more than ever. This reliance on agile airlift support comes at a price. For example, suppose a flying squadron at Bagram Airfield, Afghanistan requires all their aircraft to perform a combat mission and one of the aircraft is grounded due to a broken pneumatic valve. They up-channel this request as a Mission Impaired Capability Awaiting Parts (MICAP) condition. The part is found and shipped on an AMC Special Assignment Airlift Mission (SAAM). The SAAM is assigned to a C-5 crew at Dover, Air Force Base who will fly to Ramstein, Air Base, Germany, then to Bagram, and return to Dover using the same route. This total flight is estimated to take 28.6 hours. The C-5 flying hour rate for fiscal year 2017 is

$32,087 (see Figure 1). Thus, the total cost to transport the pneumatic valve is $917,688 (28.6 hours x $32,087 flight hour rate). While this example is simplified for the sake of discussion, it is an accurate cost analysis of a C-5 mission from the United States to Afghanistan. It is worth noting, several of these missions are being performed each day.

AIRCRAFT	SAAM/JETP/ CONTINGENCY FLYING HOUR RATE	MINIMUM ACTIVITY RATE
C-5	$32,087	$64,174
C-130E/H	$7,657	$15,314
C-130J	$11,414	$22,828
C-17	$15,702	$31,404
KC-10	$17,527	$35,054
KC-46	TBD	TBD
KC-135	$13,592	$27,184

Figure 1: FY17 Charter Hourly Rates and Minimum Activity Rates for Aircraft on TWCF Missions[18]

As the previous example suggests, maintenance and repair of Air Force weapons systems are a necessary evil, but a common occurrence given its aging fleet of aircraft. In fact, "the last B-52 Stratofortress rolled off the assembly line in 1962; the A-10 Thunderbolt II, F-15 and F-16 Fighting Falcon first flew in the 1970s, and the B-1 Lancer in the 1980s."[19] The Air Force Sustainment Center (AFSC), headquartered at Tinker AFB, Oklahoma, is the focal point for the sustainment of these and other legacy Air Force weapon systems. The AFSC consists of Oklahoma Air Logistics Complex (Tinker AFB), the Ogden Air Logistics Complex (Hill AFB), and the Warner Robins Air Logistics Complex (Robins AFB). Currently, these three aircraft maintenance depots are battling to locate hard-to-find parts that few vendors want to produce. To make matters worse, the cancellation of the F-22 program and reduction in F-35 orders means the retirement of legacy aircraft will be delayed.[20]

General maintenance of any aircraft based on flight hours is expected. However, most repairs are done at the base level. These maintenance duties include installing replacement parts or even fabricating replacement parts from scratch. The more repairs and maintenance that can be accomplished at the base level, the sooner aircraft can get back into the air increasing sortie rates.

With the number of parts the Air Force has on-hand, it may be surprising they have to manufacture anything. The DLA "supplies nearly 86 percent of the military's spare parts."[21] Additionally, they support 2,300 weapon systems, provide $34 billion in goods and services, and manage nearly, 5.1 million different supply items.[22] However, their current strategy is to create warehouses of supplies wherever the war fighters are located. This strategy makes sense when there is an abundance of time to transport large quantity of goods to the front line, but time and money are running short.

In recent years, the Air Force has made several attempts at improving its supply chain and reducing costs by "utilizing outsourcing, global sourcing, supply-base rationalization, single sourcing, just-in-time deliveries, and lean inventories."[23] Although these practices offer many benefits in efficiency and effectiveness, they can also make supply chains more brittle and increase the risks of supply disruptions.[24] Leaner supply chains only work when there are assurances the parts will be there to meet current requirements. Consequently, many logisticians are now noticing unintended supply chain risks such as the loss of control over products once they have been outsourced.

Problem Analysis

Armed with an understanding of AM and the Air Force's supply chain, this section addresses some of the financial, operational, and environmental challenges the current supply chain faces. Following this is a discussion of some steps the Air Force is currently taking to adopt AM and additional implementation steps to be consider.

Increasing Procurement, Transportation, and Inventory Costs of Parts and Supplies

The Air Force is spending an exorbitant amount of funds to purchase and maintain aircraft parts and supplies. For example, a 2014 Department of Defense (DoD), Inspector General (IG) report found the Air Force awarded vendors $1.6 billion in contracts for F-22 Raptor engine sustainment, including engine spare parts, without validating actual unit costs.[25] Additionally, a 2015 IG report stated, “DoD overspent approximately $154.9 million more than fair and reasonable prices for numerous spare parts.”[26] Other evidence suggests that DoD’s spending on parts and supplies is excessive. For instance, Tracy Rycroft, a mechanical engineering technician with the 573rd Commodities Maintenance Squadron, Robins AFB, Georgia, estimated the government was spending $10,000 to $15,000 on each F-15 Eagle seal plate.[27] However, Mr. Rycroft manufactured them with a 3D printer for $20 each, in about six hours.[28] These examples demonstrate how an over-reliance on defense contractors to design and manufacture weapon systems can lead to excessive procurement expenditures. Thus, the Air Force needs to play a more active role in the supply chain, which will reduce manufacturing costs of parts and supplies.

DoD guidance 4140.1-R, describes supply chain management risk as “stock outages, stockpile drawdowns, shelf-life expiration, supplier financial problems, long repair-cycle times, long order and shipping times, underestimation of the true maintenance replacement rate.”[29] These risks are of great concern to the Air Force because the lack of spare parts or delays in their delivery has a direct and negative impact on mission readiness and national defense. As Retired Navy Cmdr. Chris Harmer stated, when there are delays in the procurement of weapon systems or aircraft are awaiting parts, “the less [pilots] fly, the less training missions they get, the less training the aviation maintenance personnel get…the higher the mishap rate will be if everything else is held constant."[30] Thus, military supply chain risk management does more than focus on procurement and sustainment objectives. Its primary focus is on providing war fighters with the parts and supplies they need in a timely manner so they can defend the United States and its allies.

Frequent design changes during the acquisition and manufacturing process increases the time it takes to field weapon systems. In 2016, the Government Accounting Office (GAO) reported that the 18 major Air Force weapon systems they evaluated had average schedule delays of approximately 18 months.[31] Some may think these delays are understandable given that these weapon systems are being integrated with sophisticated technology. However, many of these delays are simply caused by the failure of subcontractors to deliver parts on time. When this happens in private industry, many manufactures forego outsourcing and begin manufacturing the parts themselves.[32] This form of supply chain risk management does have an initial startup cost but can result in long-term cost reductions because it places the manufacturing control back into the hands of the interested party. The Air Force has done this on a smaller scale by integrating aircraft part manufacturing at their sustainment depots, but the Air Force needs to expand this initiative at the base level and at deployed locations.

A major component of weapon systems procurement costs is the storing of inventories by defense contractors and the Air Force. Inventory carrying costs include such costs as opportunity costs, construction, maintenance, and utilities for warehouses, inventory handling costs, and value of alternative defense expenditures that must be given up to maintain spare parts in obsolescence, damages, or pilferage of inventory.[33] Opportunity cost in this case is the benefit or

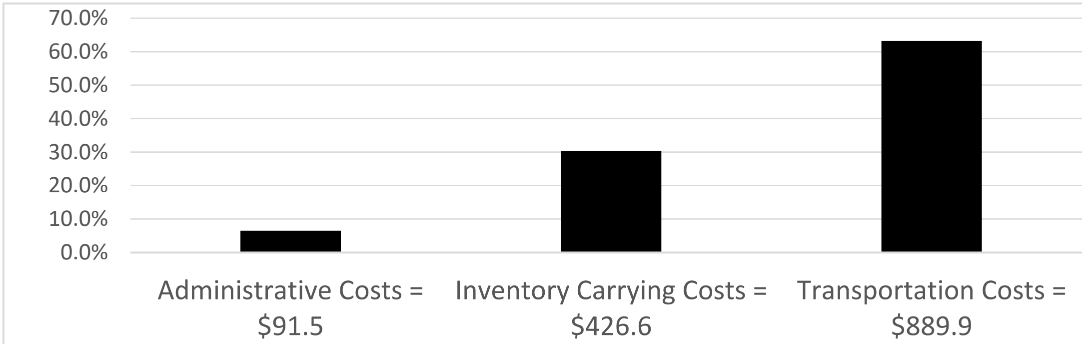

Figure 2: Total Cost of U.S. Logistics in 2015 (in Billions)[34]

inventory. Figure 2 demonstrates that the total cost of U.S. inventories in 2015 is estimated to be $426.6 billion and accounts for 30.3 percent of total logistics expenditures.[35] Thus, even a small reduction in the Air Force's inventory of spare parts and supplies can reduce expenditures or free up resources for other needed assets. Excess inventories of parts and supplies results in a holding cost and subsequent financial liability. However, the lack of access to spare parts in a deployed environment can impact the mission by reducing sortie rates and combat support. Thus, the ability to maintain a constant supply of spare parts directly affects war fighting capabilities.

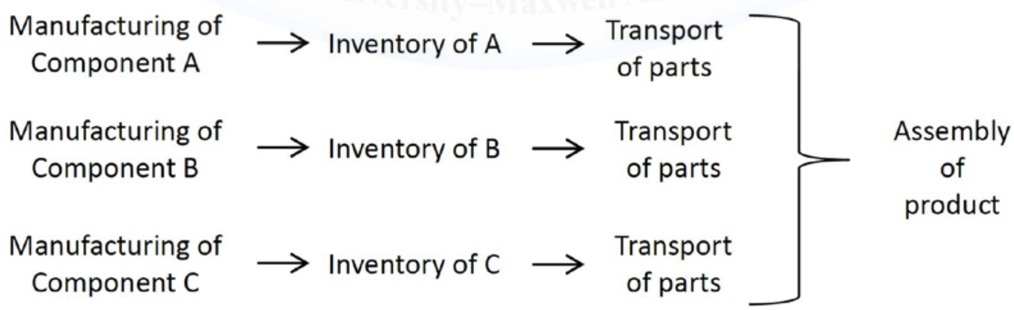

Figure 3: Example of Traditional Manufacturing Flow[36]

The most expensive component of weapon systems procurement is the transportation of parts and supplies during the manufacturing process. Figure 3 demonstrates how the transportation of parts and supplies using traditional manufacturing increases as more subcontractors are used. This example demonstrates the logistics involved when a handful of subcontractors provide a defense contractor parts for the assembly of a weapons system. With that in mind, more than 1,400 manufactures store and transport over 300,000 individual parts to Lockheed Martin's factory in Fort Worth, Texas to assemble one F-35 Lightning II.[37] Even then, final assembly and checkout is performed at facilities in Cameri, Italy and Nagoya, Japan.[38] The burden of these additional transportation costs is ultimately borne by the taxpayers because they are incorporated into the acquisition cost of weapon systems.

The previous example demonstrates the importance of reducing transportation costs of parts and supplies during the acquisition phase of a weapon system. However, a major concern of the Air Forces at this time is the cost and availability of aircraft parts during the sustainment phase of weapon systems' lifecycle. As stated by Brian Rice, Division Head for the University of Dayton Research Institute's Multi-Scale Composites & Polymers Division, "One of the biggest hurdles to maintaining legacy aircraft is securing out-of-production spare parts. In some cases, suppliers have gone out of business, or they will no longer support the production of spare parts for older aircraft. It's just not profitable for them."[39] Consequently, 3D printing may provide an inexpensive and expeditious way to obtain hard to find aircraft parts.

While these legacy aircraft parts are in demand, the Air Force is not yet ready to manufacture flight critical parts using 3D printers. The Air Force is currently restricting the use of 3D printers to the manufacturing of objects that will not endanger personnel if they fail, such as tools, fixtures, prototypes, and nonflight critical parts, until they can gain more confidence in the material science behind printed materials, including faults and tolerances.[40] As Lt. Gen. Lee K. Levy II, commander of the Air Force Sustainment Center, stated, "Sometimes the Air Force and the Department of Defense can't get out of [their] own way when it comes to inserting new technologies…we're very conservative."[41] Aside from overcoming the learning curve of 3D technology, "there are also legal considerations to be made, such as whether warranties on expensive equipment would be voided if a part is replaced with a 3-D printed piece, or if intellectual property rights of the original manufacturers would be infringed upon if [Airmen] create virtual model of those parts."[42] These are some of the issues the Air Force Research Laboratory (AFRL) is currently trying to resolve before they start using 3D printed flight critical parts.

Operational Failure from Lack of Access to Parts and Supplies

In addition to the escalating cost of procurement, transportation, and inventories, a lack of spare parts and supplies can negatively impact aircraft readiness, pilot flight hours, as well as workforce morale and retention. For instance, at the end of 2016, the Marine Corps had 1,065 aircraft on flight lines around the world, but only 439 were considered ready to fly.[43] The remaining aircraft were awaiting maintenance, in-service repair or supply, meaning they are lacking the parts they need to be operational.[44] As high as 64 percent of Marine Corps' C-130 Hercules aircraft were considered temporarily non-mission capable.[45]

The challenges of maintaining aircraft is not limited to the Marine Corps. It was reported last year that of the 20 B-1 bombers assigned to Ellsworth AFB, South Dakota, only nine were airworthy due to missing parts.[46] Additionally, out of the 79 F-16 fighter jets assigned to Shaw ARB, South Carolina, only 42 percent were mission ready.[47] Furthermore, the F-16s that were able to deploy to the Middle East experienced serious maintenance issues resulting from a shortage of 41 parts, despite bringing along an extra F-16 just to cannibalize.[48]

The military's challenges with maintaining their weapon systems due to a lack of spare parts has reached international attention. It was reported last year that both the Marines and the Air Force have been scavenging air museums around the country to obtain spare parts from static aircraft displays to use on operational aircraft.[49] House Armed Services Committee Chairman

Mac Thornberry reported, “I have heard firsthand from service members who have looked me in the eye and told of trying to cannibalize parts from a museum aircraft…getting aircraft that were sent to the boneyard in Arizona back and ready to fly missions, [and] pilots flying well below the minimum number of hours required for minimal proficiency.”[50] Negative publicity such as this could damage the public’s confidence in the armed forces ability to defend them and embolden enemy combatants.

A lack of flying hours due to spare part shortages impacts Air Force pilot’s ability to train for potential future conflicts against advanced weapons and technologically equipped nations, such as Russia and China. Regrettably, pilots are reportedly flying fewer training hours than the adversaries they are being sent to meet.[51] Some critics say the lack of flying hours is also contributing to the large number of pilots who are abandoning the Air Force in favor of flying for commercial airlines.[52] For the last few years, the Air Force has been trying to figure out how to deal with “a looming pilot shortage that many predicted would be severe enough to cripple the service and harm national defense.”[53] The Air Force is trying to increase fighter pilot retention by offering adjustments to their Special Salary Rates (SSR), Aviation Retention Pay (ARP-Pilot Bonus), and Retention/Recruitment/Relocation (3R) incentive streamlining.[54] However, despite these financial incentives, less than 35 percent of active duty pilots have agreed to stay on for an additional nine-year commitment. [55] Thus, it does not appear the Air Force is addressing the possibility that pilots are leaving the Air Force because they feel they are unable to obtain an adequate number of flying hours.

The lack of access to aircraft spare parts not only affects pilots’ flight hours, it can have a negative impact on aircraft maintenance personnel as well. For instance, it is a common occurrence for maintenance personnel to cannibalize serviceable parts off one aircraft to repair and maintain another.[56] Cannibalization creates more work for maintenance personnel, degrades morale, and can impact employee retention. For example, the GAO reported to Congress that in "fiscal years 1996 through 2000, the Navy and the Air Force reported about 850,000 cannibalizations, requiring over 5 million maintenance hours. These numbers, however, did not include the Army's cannibalizations, and the Navy reportedly understates its data by as much as 50 percent."[57] Additionally, the GAO reported in February of this year that Air Force officials expect maintenance depot workload hours to increase in the future as depots begin repairs on new systems, such as the F-35 and KC-46.[58] Consequently, Air Force Materiel Command Instructions 65-101 states that the added workload and overtime created by cannibalization and spare part shortages "tends to hamper the normal flow of work and causes gaps in production such that follow-on work absorbs higher than planned overhead and causes depot maintenance losses."[59] Therefore, the Air Force needs to find a viable alternatives to cannibalizing aircraft.

Some may argue the shortage of spare parts and supplies is due to the extended military operations in Iraq and Afghanistan and the unexpected demands these operations have placed on the military's aging weapon systems. This explanation can be only partially correct because mission impairment from the lack of spare parts also has been observed in newer weapon systems as well. For example, the F-35 fighter is the military's latest (fifth generation) and most expensive weapon system to anticipate a shortage of spare parts. Lieutenant General Jon Davis, the top U.S. Marine in charge of aviation, has been quoted as saying, "I know we're going to need more [spare parts] than we have. I think there's risk there, and I wanted to lay out exactly what that risk is."[60] It is reasonable to assume aircraft parts will become unserviceable over time but when and how often they will break is unknown. Furthermore, throwing money at the problem does not always work because parts can take two to three years to purchase, depending on their complexity and the reliability of the procurement process.[61] Thus, the Air Force needs to find a way to expedite the delivery of spare parts without storing large stockpiles of them.

Environmental Impact of Traditional Manufacturing

Aside from the monetary outlay, traditional manufacturing processes produce excess waste. Parts are traditionally manufactured using a subtractive manufacturing technique or by forming them with cast moldings. Subtractive manufacturing essentially takes a block of raw material and removes unwanted parts that results in a finished product. Cast molding manufacturing starts with a wax mold covered with a ceramic shell. The metal is melted and poured into the mold, melting/pushing the wax out of the mold and leaving the part to cool. Both processes are dangerous, labor intensive, produce hazardous waste, and consume large quantities of energy and natural resources. The U.S. Environmental Protection Agency (EPA) reported in 2014, for example, that manufactures paid over $9.7 billion in pollution cleanup costs.[62]

One leading cause of pollution in traditional manufacturing is the use of water for cleaning at various stages of the manufacturing process. This results in water waste, hazardous materials and messy residues.[63] For example, the Ward Transformer Company, which manufactured electronic transformers, recently agreed to pay a $5.5 million settlement to the EPA and costs associated with cleaning up polychlorinated biphenyls (PCBs) contamination in areas surrounding their manufacturing plant in Raleigh, North Carolina.[64] The Ward Transformer Company admitted to contaminating the soil at its 11-acre manufacturing facility, neighboring properties and a nearby lake.[65] Additionally, as the world population grows, more agricultural water is used, and the amount of fresh water is reduced.[66] Thus, clean manufacturing techniques need to be explored that will reduce or eliminate the use of water in the production process.

In another case, Selmet Inc, a manufacturer of titanium parts for the Boeing 737, Airbus A320, and the F-35 Joint Strike Fighter, is currently managing a cleanup site at its manufacturing plant in Albany, Oregon.[67] [68] Selmet, Inc. dumped processed wastewater into an unlined surface impoundment some time before 1991.[69] The Oregon Department of Environmental Quality has discovered a list of solvents and chlorides in the adjacent soil and groundwater.[70] Aside from the chemical pollutants, manufacturing titanium parts with traditional methods consumes massive amounts of energy. Titanium melts at 3,038 degrees Fahrenheit, making it one of the more heat-resistant elements on the periodic table.[71] Consequently, the cast molding process of traditional manufacturing requires a vacuum arc furnace which uses over 1,200 kilowatts of electricity to melt the titanium alloy.[72] This energy intensive manufacturing process is significant to the Air Force because of the large volume of titanium used in military aircraft (see Figure 4).

	Titanium buy weight	
Aircraft/engine(a)	kg	lb
A-10/(2) TF-34	1,814	4,000
F-5E/(1) J85	635	1,400
F-5G/(1) F404	1,089	2,400
F-14/(2) TF-30	24,630	54,300
F-15/(2) F-100	29,030	64,000
F-16/(1) F-100	3,085	6,800
F-18/(2) F-404	7,620	16,800
C-130/(4) T-56	499	1,100
C-5B/(4) TF-39	24,812	54,700
B-1B/(4)F101-GE-102	90,402	199,300
KG-10/CF-6-50	32,206	71,000
CH-53E/(3) T-64	8,800	19,400
CH-60/(2) T-700	2,041	4,500
S-76/(2) A11.250	544	1,200
AH-64/(2) T-700	635	1,400

Figure 4: Military Aircraft (Including Engines) with Titanium Requirements[73]

Several companies have implemented just-in-time or lean manufacturing principles to help reduce waste. However, these initiatives focus on reducing inventories or product defects. They do not reduce waste for the products produced. While the EPA has historically held manufacturing companies financially accountable for their poor handling of toxic chemicals, it is often only after the environmental damage has occurred. Thus, the Air Force needs to consider the environmental impact of traditional manufacturing in its supply chain.

Another drawback to traditional manufacturing is the length of time it takes to design new prototypes. In many cases, the part is designed and manufactured several times before it meets the specifications of the project. This trial-and-error approach to manufacturing wastes raw materials and is labor intensive.

Steps the Air Force is Currently Taking to Adopt Additive Manufacturing

Air Force Instruction 1-1 directs Air Force members "to develop a sustained passion for the continuous improvement and innovation that will propel the Air Force into a long-term, upward vector of accomplishment and performance."[74] In light of this direction, Air Force personnel are implementing AM at bases and maintenance depots, in varying degrees, to reduce costs and improve operational capabilities. However, while 3D printers are being used at various Air Force locations, there has been little guidance from Headquarters Air Force (HAF) on their implementation and use. Consequently, Air Force units are acquiring a variety of 3D printers with diverse production capabilities and without the knowledge to fully utilize this innovative technology.[75]

In an effort to provide more AM resources to Air Force units, the AFRL has signed a five-year Cooperative Agreement (CA) with America Makes, the National AM Innovation Institute, to developing AM technologies for Air Force sustainment applications.[76] This cost-reimbursement/cost-sharing agreement has a value of up to $75 million and provides an opportunity for Air Force units to partner with America Makes and address their AM and 3D printing needs.[77]

The 910th Maintenance Group (910 MXG), stationed at Youngstown ARS, Ohio, has taken advantage of this agreement and is currently working with America Makes to manufacture several parts using 3D printers. The 910th Air Wing's mission provides DoD's "only large area fixed-wing aerial spray capability to control disease-carrying insects, pest insects, undesirable vegetation and to disperse oil spills in large bodies of water."[78] The aerial spray delivery systems, which the 910 MXG maintains, are over 30 years old and many of the parts are either nonexistent or cost prohibitive to manufacture with traditional methods.[79] Furthermore, many of these parts need to be periodically replaced because the chemicals that are transferred through them are corrosive.

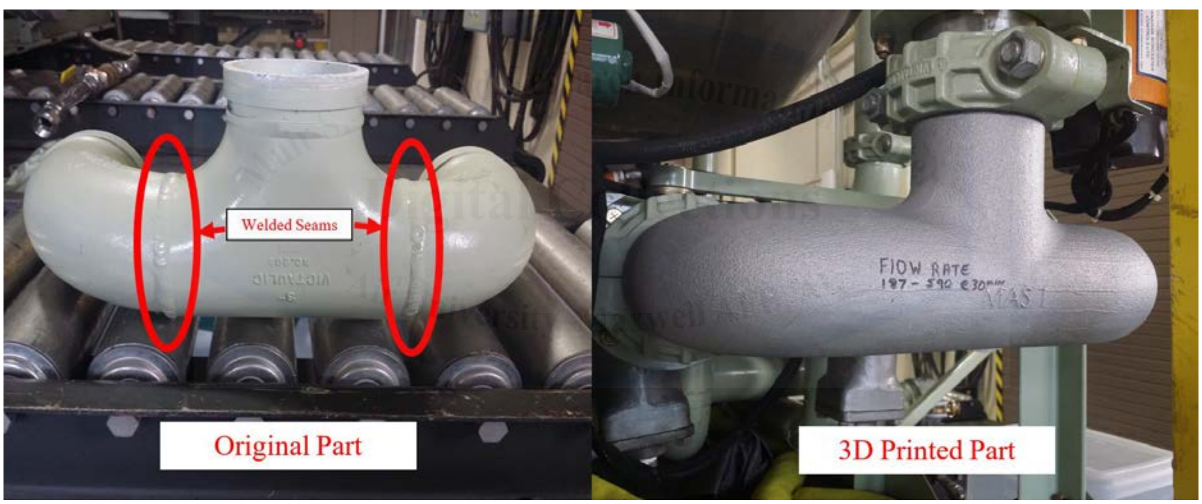

Figure 5: Aerial Spray Delivery Systems Tee Flow Branch[80]

To help with this issue, the 910 MXG is working with America Makes to manufacture these parts. Figure 5 shows an example of a tee flow branch that was manufactured using AM. This part was scanned, while still attached to the spray delivery system, using a handheld scanner and the sand cast mold was 3D printed by Humtown Products, a local additive manufacturer.[81] Note, the original part was manufactured in three sections and welded together while the 3D printed part was manufactured as one piece. By eliminating the welded seams, the part is stronger because it now has two less points of failure. Additionally, fabrication time and labor hours are drastically reduced because the 3D printed part does not require welding or adjustments. The scanning process of the original part ensures the 3D printed part will fit.[82]

While the agreement between AFRL and American Makes is currently covering the cost of the 910 MXG's 3D printed parts, they expect the AM process will reduce future expenditures and mission interruption. For example, now that the casting mold has been 3D printed, the part can be manufactured on an as-needed basis with minimal down time and labor. The original part would have taken six days to manufacture but the 3D printed part can be manufactured in just one day.[83] Additionally, the exercise of producing this part has helped the 910 MXG and America Makes streamline the AM process for the manufacturing of additional spray delivery system parts. As a result, several other parts, such as plastic knobs for aerospace ground equipment (AGE) and C-130 throttle covers, are being designed to reduce procurement costs and improve designs.[84] Thus, the 910 MXG will be able to 3D print these plastic knobs and covers using a LulzBot TAZ 5 3D plastic printer they purchased from the internet for less than $2,000.

For another example, the 911th Maintenance Squadron (911 MXS), stationed at Pittsburgh ARS, Pennsylvania, recently purchased a Fortus 360mc 3D printer which manufactures highly durable plastic parts.[85] The raw material for this printer costs approximately three dollars per cubic inch and has a tensile strength of about 5,000 pounds per square inch. According to Technical Sergeant Joseph Davis, the printer is a valuable time saving device because the printer can manufacture parts while they focus on other maintenance activities. For example, the 911 MXS recently scanned and printed a part (see Figure 6) that cost them about $45 to manufacture, but would have cost them about $200 to purchase. Thus, AM is saving the 911 MXS time and money.

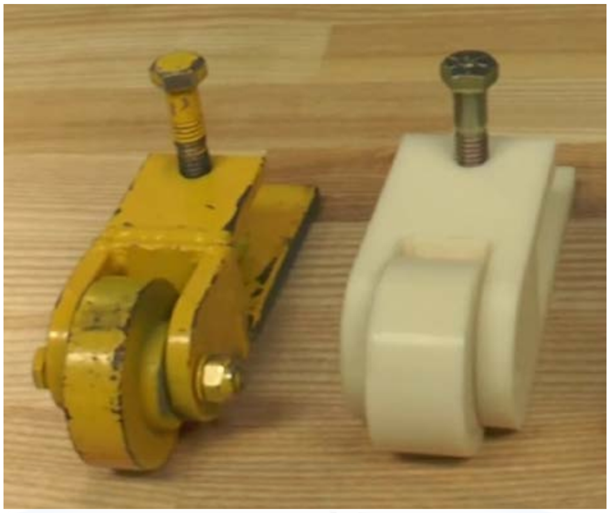

Figure 6: Original Versus 3D Printed Part[86]

In another example, Capt Carl Densford from the 3rd Operations Support Squadron (3 OSS), stationed at Joint Base Elmendorf-Richardson (JBER), Alaska, described how they are using the first 3D printer in the Pacific Air Force (PACAF) to helped increase their production by 17 percent and accuracy by 20 percent.[87] Additionally, the Makerbot 3D printer was used to manufacture the first F-22 infrared counter-measure brackets, negating a seven-month mission impaired capability due to awaiting parts (MICAP). They are also using the 3D printer to manufacture jigs and various prefabricated parts. Moreover, since JBER is outside the continental United States (OCONUS) and susceptible to extreme weather, it is more difficult and costly for them to acquire parts. Consequently, this example demonstrates how 3D printing at a deployed or forward operating base can benefit Air Force operations.

The three previous examples demonstrate that Air Force units are using AM in a variety of ways and utilizing different 3D printers. In some cases, units are working with universities or members within the AM industry to gain a better understanding of this emerging technology.[88] Nevertheless, the Air Force has not yet provided clear guidance on what 3D printers should be purchased, what parts should be manufactured, or what formal training should be obtained.[89] However, the agreement between AFRL and American Makes is a step in that direction. America Makes is reaching out to Air Force units, and other DoD organizations, to educate service members on what AM can provide and what resources they have in their area.[90]

Besides assisting Air Force units with AM education and resources, America Makes is conducting independent research to provide AFLR and DLA with advanced AM solutions for a variety of projects.[91] For example, Rodrigo Enriquez Gutierrez, Factory Engineer with Making America, is using a ProX DMP 320 3D printer (see Figure 7 on next page) to manufacture and redesign military parts.[92] This 3D printer is a metal powder bed fusion (PBF) printer that can use a variety of metals to manufacture intricately designed parts that traditional forge or mold pour manufacturing cannot produce (see Figure 7).

Figure 7: ProX DMP 320 3D Printer[93] and Aircraft Brackets[94]

Two benefits of the PBF 3D printer are the ability to recycle the metal powders raw material and its portability. Mr. Gutierrez stated, “the industry standard allows the same powder to be recycled 14 times, but I have tested this standard and found I could reuse the powder at least 20 times without a noticeable difference in the quality of the parts.”[95] Additionally, Mr. Gutierrez stated, “it would be easier to deploy this PBF 3D printer than traditional metal working machines because it is more compact and only needs metal powder and argon gas for raw materials.” Thus, it may be economically and operationally feasible to deploy PBF 3D printers to forward operating bases.

Mr. Gutierrez’s research is part of AFRL’s agreement with America Makes and extends to industry, academia, and government partners for the sole purpose of providing Maturation of Advanced Manufacturing for Low-cost Sustainment (MAMLS) options to the Air Force.[96] Consequently, Youngstown State University, Ohio (YSU), has been tasked with developing ways to integrate AM into traditional manufacturing. To help facilitate this, YSU purchased one of the first hybrid manufacturing machines last month, a HAAS VF-3, that combines both 3D printing and computer numerical control (CNC) machining (subtractive manufacturing).[97] With this machine, they hope to demonstrate to the Air Force that aircraft parts can be repaired, rather than replaced.[98] Additionally, it will help aircraft maintenance technicians transition from traditional manufacturing to AM by incorporating techniques they are comfortable with.

The goal of this research is for YSU to working directly with Air Force officials and the three aircraft maintenance depots to “enhance and improve Air Force sustainment operations through the development, demonstration, and transition of AM and related advanced manufacturing technologies.”[99] Thus, AFRL and program managers hope to improve maintenance efficiencies at Air Force bases and depots for rapid part replacement for legacy and other aircraft.[100]

Further Steps Needed

One of the benefits of AM is the ability for a user to quickly and efficiently create virtual prototypes of parts. Parts which may have taken weeks to design can now be designed in minutes or hours with the help of computer aided designing software. However, AM can also be used to duplicate or reverse engineer parts. This capability calls into question the legality of parts being manufactured under intellectual property laws governing copyrights, patents, trademarks, and trade secrets.[101] The specifics of these various laws are outside the scope of this paper. However, they should be addressed during the planning phase of any acquisition. Ideally, contracts should be written so that the Air Force is given legal authority to replicate any part or weapon system it procures. Furthermore, the Air Force should include an indemnification or limitation of liability clause in all contracts for the purchase of parts, supplies, or weapon systems from a defense contractor that utilizes AM. This clause should be included in the contract to protect the Air Force in the event a third party accuses the defense contractor of violating an intellectual property law.

Besides the risk of violating intellectual property laws, many question the cyber security of 3D data files which could potentially be sent over the internet or stolen by means of a cyber-attack. However, cyber security is not a new concept for the military. In fact, “the fiscal 2017 DoD budget calls for spending $6.7 billion for cyber operations, which represents an increase of about $900 million over fiscal 2016 enacted levels for the Pentagon's defensive and offensive cyberspace operations capabilities and cyber strategy.”[102] It is uncertain how much of the $6.7 billion will be earmarked for the security of 3D technology but both software and

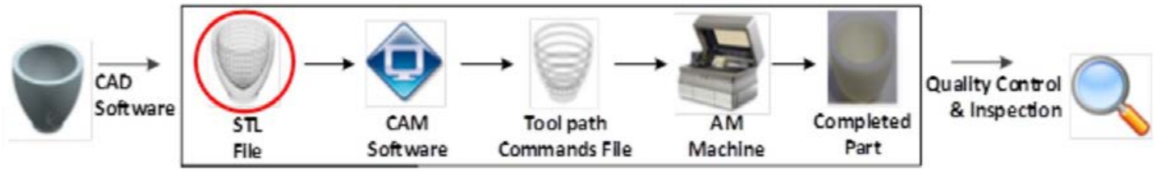

Figure 8: Additive Manufacturing Process Chain[103]

hardware vulnerabilities should be considered. For example, Figure 8 shows four phases of the AM process that are susceptible to a cyber-attack, the CAD model, the .STL file, the toolpath file, and the physical machine itself. The .STL file is considered the most vulnerable to a cyber-attack because it is easily edited and can create unsafe parts if not properly inspected.

Currently, 3D printers are not designed for the mass production of parts. This causes some to question if 3D printers will be able to produce parts and supplies in the volume the military demands. This concern is justified for the majority of supplies currently procured by the military. Traditional manufacturing is capable of producing mass quantities of products at a lower price per part (economy of scale). However, AM is ideal for high cost low volume production, such as aircraft parts or to meet demands at a deployed location.

Others question if 3D printers are capable of printing large parts. While 3D printers have historically manufactured small objects, and this continues to be the mainstay of the industry, many 3D printer manufactures have large scale printers capable of printing houses, car frames, furniture, and plane parts.[104] The key variable when evaluating the size of 3D printed parts is the printing material. For example, there is no theoretical size constraints for a concrete or plastic printer because some printers are designed to move as they print.[105] On the other hand, some printing materials, such as titanium alloy, must be printed in a vacuum. Thus, their build dimensions are constrained by the manufacturing environment. However, Sciaky, Inc., a company based in Chicago, Illinoi, manufactures the EBAM 300 printer, which can 3D print titanium aircraft parts and structures up to 19 ft. x 4 ft. x 4 ft., in 48 hours at a rate of approximately 15 lbs. of metal per hour.[106] Consequently, the size limits of 3D printed aircraft parts will be less of a concern as AM technology progresses.

While this and previous examples demonstrate that aircraft parts can be 3D printed, there are concerns over how Air Force flight critical aircraft parts, manufactured with 3D printers, will be inspected and certified safe. This is a valid concern with no easy answer. Even non-flight critical aircraft parts are required to have smoke and toxicity level ratings.[107] However, there is currently no universal DoD approving authority for the certification of 3D printed flight critical parts.[108] Each airframe has its own System Program Office (SPO) that approves specific modifications to their respective aircraft. While the approval process for 3D printed flight critical parts is outside the scope of this paper, more information on this topic can be obtained from Air Force Sustainment Center Instruction 61-101, *Technology Development And Insertion Process*.

3D Printing Suitability Analysis

While concerns over intellectual property rights, cyber security of data files, and certification of flight critical parts must still be addressed, the following section discusses some potential benefits the implementation of AM may have on the Air Force's supply chain. Following this is a discussion of some environmental benefits AM may provide.

3D Printing and the Air Force's Supply Chain

AM has the potential to substantially reduce procurement, transportation, and inventory costs of tools, parts and supplies. Additionally, AM has the potential to increase combat readiness by extending the useful life of weapon systems.

Imagine a combat environment where instead of transporting mass quantities of finished goods, the Air Force transports 3D printers, data files, and raw materials. The ability to produce tools, parts, and supplies on demand in austere locations could increase agile support by reducing the amount of time it takes to set up sustainment operations and begin mission objectives. Furthermore, the reduction of spare parts on-hand would give units the ability to quickly relocate if mission requirements change or retrograde operations after the conflict has concluded.

The idea of deploying 3D printers is not a new concept. The U.S. Army's Rapid Equipping Force (REF) has been deploying 3D printers to Afghanistan since 2014 to assists Soldiers with rapid solutions to part and equipment issues.[109] Thus, there are examples and resources the Air Force can use to implement its own deployed 3D printing processes and procedures.

While there are potential cost savings and operational benefits to 3D printing in a deployed environment, previous examples given in this paper suggest that stateside Air Force units would also benefit from the ability to manufacture their own tools, parts and supplies. AM requires less labor hours and expenditures then traditional manufacturing because it can produce designs that combine multiple parts, reducing assembly time and post-machining, and requires less retooling then traditional machines.[110] Thus, excess time spent purchasing the plethora of items needed to maintain aircraft and equipment could be used for career specific training or other ancillary duties. Additionally, the potential cost savings AM offers could help reduce Air Force expenditures or better use funds for new weapons systems.

3D Printing and the Environment

Unlike traditional manufacturing, AM uses minimal raw materials to produce the part, thus reducing scrap material and waste. Conventional machining can produce a scrap rate as high as 80–90 percent of the original material.[111] On the other hand, AM can bring the scrap rate down to 10–20 percent, depending on the type of raw material used to print the part.[112]

Additionally, AM can further reduce the cost of parts by using unique designs that use less raw material, but without compromising their mechanical properties.[113]

In addition to reducing scrap material and waste, AM does not use water or dangerous chemicals found in traditional manufacturing processes. This helps to prevent damage to the environment and reduce cleanup costs associated with hazardous water waste.

Furthermore, AM uses only a fraction of the energy compared to traditional manufacturing. Whereas the titanium alloy cast molding process, in traditional manufacturing, uses over 1,200 kilowatts of electricity, AM uses argon gas to generate the heat needed to melt the titanium alloy. Consequently, a 3D printer only uses between 17-31 kilowatts of electricity when manufacturing titanium alloy parts.[114]

Recommendation

Given the potential benefits AM can provide with supply chain cost reductions, operational improvements, and decreased environmental impact, the Air Force should expand and accelerate its implementation of 3D printing technology. The Air Force has taken the first step in implementing AM by contracting with America Makes to help provide more resources to Air Force units. However, it could expedite the integration process in the following five ways:

<u>1. Implement 3D Printing in Deployed Locations.</u> The Army REF's use of 3D printers in Afghanistan and the Navy's use of 3D printers aboard its ships have demonstrated some of the benefits 3D printing can provide war fighters downrange. Thus, the Air Force should consider establishing 3D printing deployment packages for civil engineering, aircraft and vehicle maintenance units. Deployment packages could be standardized to accommodate the unique mission requirements of these units. Additionally, by standardizing these 3D printing packages,

they can be deployed independent of the units and Airmen will have a working knowledge of their capabilities.

2. Incorporate Training. The Air Force should incorporate a 3D printing curriculum into technical training courses. Civil engineering, aircraft and vehicle maintenance are a few examples of career fields that stand to benefit the most from this new technology. Consequently, there are several companies that provide specialized 3D printing curricula, lesson plans, videos, and materials designed to help teachers and educate students.[115] Furthermore, many of these educational resources are free because they are produced by manufactures of 3D printers to promote their products. Regardless, the Air Force should seek the assistance of America Makes to contract with a company that can provide tailored 3D printing education to Air Force pipeline students or Quality Assurance (QA) personnel. There may be some catch-up involved in 3D printing education, but that is not expected to change since this technology continues to advance at a rapid rate.[116]

3. 3D Printer Purchases. The Air Force should provide more guidance on the circumstances under which 3D printers should be purchased. Currently, units are left to conduct their own research for and procurement of 3D printers. As such, Air Force members are spending valuable time trying to decide what 3D printer to purchase, when they could be focusing on their mission. Additionally, Air Force members may mistakenly purchase a 3D printer that is incompatible with their requirements. Thus, wasting time and financial resources. Lastly, by identifying the specific 3D printers to be purchased, the Air Force may be able to negotiate a lower price per-unit with the manufactures for 3D printers and raw materials.

4. What to Print. Once Air Force units have acquired a 3D printer and the necessary training, they will need assistance determining what tools, parts, and supplies to print. Thus, the

Air Force should conduct a cost benefit analysis to determine what items should be printed versus purchasing through traditional supply chain channels. This analysis should consider the economic and operational benefits of printing specific items. Additionally, the Air Force should consider establishing an AM working group/community and creating an AM SharePoint cite to facilitate collaboration in determining the best parts to print. These collaborations could be used to share 3D designs, knowledge, and best practices.

<u>5. Certifying Flight Critical Aircraft Parts.</u> While there may be substantial benefits to 3D printing non-flight critical parts, the Air Force has expressed an interest in 3D printing hard-to-find or obsolete flight critical aircraft parts. Therefore, the Air Force should establish a formal approval process for certifying 3D printed flight critical aircraft parts. It is understandable that the SPO's for each airframe should approve specific modifications to their respective aircraft given the complexity and variety of the Air Forces fleet. However, there should be a formal approval process for SPO's to approve flight critical aircraft parts that ensures universal safety measures are being addressed and followed.

Implementation of these recommendations would provide Air Force personnel with innovative ways to reduce expenditures, clarify 3D printing standard operating procedures (SOPs), and improve operations. The Air Force has always prided itself on innovation. 3D printing can help "propel the Air Force into a long-term, upward vector of accomplishment and performance."[117]

Conclusion

With increased budget cuts and an aging aircraft fleet, the Air Force is looking for innovative ways to reduce procurement, transportation, and inventory costs of tools, parts and supplies. Nevertheless, the Air Force's supply chain costs are increasing and there is an ongoing shortage of parts and supplies. The lack of aircraft spare parts can negatively impact aircraft readiness, pilot flight hours, as well as workforce morale and retention.

Aside from increasing costs and operational failures, the traditional manufacturing process of parts is dangerous, labor intensive, produces hazardous waste, and consumes enormous quantities of energy and natural resources. Thus, the Air Force is looking for ways to minimize the environmental impact its supply chain has on the environment.

To address these concerns, the Air Force is working with the AM industry and universities to implement 3D printing at bases and maintenance depots. While the Army and Navy have been using 3D printers for some time now, several Air Force units have started using them with positive results. 3D printing gives Air Force units the ability to reduce repair time, costs of procurement, transportation, and inventory costs, while also being safer, less labor intensive, and more environmentally sound than traditional manufactured replacement parts.

Despite the apparent benefits of 3D printing, concerns over intellectual property rights, cyber security of data files, and certification of flight critical parts must still be addressed. However, if the Air Force wants to remain at the forefront of technology, it should provide 3D printing training to its members, more guidance on the circumstances under which 3D printers should be purchased, what parts should be printed, establish a formal approval process for certifying 3D printed aircraft parts, and develop deployable 3D printing packages.

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