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Navigating Department of Defense Additive Manufacturing Acquisition Practices

December 2021

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Acquisition Research Program

Naval Postgraduate School

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Prepared for the Naval Postgraduate School, Monterey, CA 93943.

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ABSTRACT

The purpose of this research is to examine acquisition practices related to the increased adoption of additive manufacturing (AM) in the Department of Defense (DoD). We explore policies, processes, organizational alignment, and data management to assess AM acquisition in the Air Force. We use a Government Accountability Office (GAO) framework to systematically assess the state of AM acquisitions. Our research includes a DoD spend analysis of AM, policy and guidance analysis, and stakeholder interviews with multiple agencies throughout the Air Force AM ecosystem. We consolidate our findings to develop recommendations that DoD customers can use when seeking 3D-printed requirements. Our conclusion highlights strengths and weaknesses of current acquisitions processes and provides recommendations for further research. While Air Force-centric, our research findings can be adopted to fit acquisition needs specific to all DoD services seeking to meet the call for improved contracting processes outlined in the Department of Defense Additive Manufacturing Strategy.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	3-Dimensional
AFBIT	Air Force Business Intelligence Tool
AFICC	Air Force Installation Contracting Center
AFIT	Air Force Institute of Technology
AFLCMC	Air Force Life Cycle Management Center
AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratory
AFTIM	Air Force Technical Interchange Meeting
AM	Additive Manufacturing
AMSIP	Additive Manufacturing Strategic Implementation Plan
ASTM	American Society for Testing Materials
ATTC	Air Force Advanced Technology & Training Center
CAD	Computer-Aided Design
CAGE	Commercial and Government Entity
CM	Category Management
CONUS	Continental United States
CSIS	Center for Strategic and International Studies
DLA	Defense Logistics Agency
DMLM	Direct Metal Laser Melting
DoD	Department of Defense
DoDIG	Department of Defense Office of Inspector General
EZP	Product Support Engineering Division
FAA	Federal Aviation Administration
FDM	Fused Deposition Modeling
FPDS-NG	Federal Procurement Data System – Next Generation
FY	Fiscal Year
GAO	Government Accountability Office
GE	General Electric
GPC	Government Purchase Card

GSA	General Services Administration
IP	Intellectual Property
JAMSG	Joint Additive Manufacturing Steering Group
JAMWG	Joint Additive Manufacturing Working Group
JDMC	Joint Defense Manufacturing Council
MCP	Materials Characterization Process
MII	Manufacturing Innovation Institute
MT	Metal Technology
MTO	Metals Technology Office
NAMTI	Naval Additive Manufacturing Technology Interchange
NAVSEA	Naval Sea Systems Command
NCMS	National Center for Manufacturing Sciences
NDI	Non-destructive Inspection
NPS	Naval Postgraduate School
OSD ManTech	Office of the Secretary of Defense for Manufacturing Technology
OUSD (R&E)	Office of the Undersecretary of Defense for Research and Engineering
PDP	Product Development Process
PPE	Personal Protective Equipment
PSC	Product Service Code
SLA	Stereolithography
STL	Standard Triangle Language
TCO	Total Cost of Ownership
TDP	Technical Data Package
TM	Traditional Manufacturing
UDRI	University of Dayton Research Institute
USAF	United States Air Force
USALIA	US Army Logistics Innovation Agency

I. INTRODUCTION

Additive manufacturing (AM) continues to increase in market adoption across a number of industry sectors. It's expanding application is due to maturing technology that allows AM to complement most traditional manufacturing processes, or to replace them entirely. While three-dimensional (3D) printing has historically been used by engineers for rapid prototyping efforts, it has grown in popularity among hobbyists and professionals involved in countless fields (Hunter, 2021). Today, AM is used in many industries, including medical (e.g., fabricating tissues and organs and producing personal protective equipment [PPE], customized prosthetics, and implants), construction (e.g., 3D printing homes), aerospace (e.g., producing aircraft parts and rocket engine injectors), and tool and die (e.g., constructing parts, molds, machinery and casts) industries, to name a few.

The Department of Defense (DoD) also uses AM for the various requirements specific to each service. The Navy, for example, applies AM aboard ships to quickly address operational issues that can be resolved by 3D printing tools and spare parts instead of docking to wait for replacements and maintenance. The Air Force uses AM to provide spare parts for legacy aircraft that are expensive to procure commercially. Finally, the Marines and the Army have proven AM capabilities for frontline use—printing bridges, hulls for vehicles (e.g., the Army's new Joint Light Tactical Vehicle), barracks, and bunkers (Cottingham, 2021). AM application in the DoD is constantly expanding in scope due to increased research and development (R&D) efforts and collaboration with public–private partnerships such as America Makes and MITRE.

AM has recently garnered significant press and attention due to its use during the COVID-19 pandemic response and other innovative applications. Many companies across the nation shifted production lines to 3D print PPE for their workforce and to help alleviate shortages nationwide. Innovation hubs throughout the DoD used 3D printers to make plastic shields, swabs, and N95 components that were used throughout the services. These efforts displayed the value that AM offers when solutions are needed to tackle supply chain or crisis response issues. The speed and flexibility of 3D printing PPE is just one of the recent success stories that highlights this emerging field.

Construction technology companies like ICON have set the bar for AM application in the construction industry. Firms partnering with ICON use 3D printing technology to build more homes better and faster, with the goal to support the global social housing sector. For example, in 2019, ICON and local partner Échale used AM to build an entire 50-home community in Tabasco, Mexico. Each 500-square-foot house was 3D printed within 24 hours and then donated to local indigenous families living in extreme poverty. The Vulcan II printer provided the durability to operate in rural areas, printing all of these homes with designs that met specific needs of the community. 3D home building in the United States is also starting to gain momentum. Along with ICON, Mighty Buildings and SQ4D are using AM to build homes in a much more affordable and environmentally friendly way than traditional methods (Lynn, 2021). This technology may help alleviate America's shortage of affordable housing—making it possible to quickly build housing developments for homeless populations. The global housing nonprofit, Habitat for Humanity, is also using AM to help mitigate shortages in labor, lumber, and other construction materials for their builds (Walsh, 2021).

The estimated value of the 3D printing market in 2020 was $12.6 billion, with a forecast to more than double by 2026 (Roberts, 2021). Fortune Business Insights (2021) attributed the heightened AM demand to increased digitalization and adoption of advanced technologies like robotics, smart factories, and machine learning services (Hunter, 2021). However, compared to the total U.S. manufacturing activity of $13.8 trillion, AM would need continued technological breakthroughs and market adoption to significantly reshape the domestic manufacturing landscape (Hunter, 2021). AM has the potential to strengthen domestic supply chains while decreasing dependence on foreign sources for raw materials and manufacturing. AM can directly contribute to the call for strengthening the U.S. defense industrial base as highlighted in Executive Order No. 14017 (2021), "America's Supply Chains."

A. PROBLEM STATEMENT

In 2014, the Senate Armed Services Committee directed the DoD to submit a briefing or report on AM that describes "potential benefits and constraints; potential contributions to DoD mission; and transition of the technologies of the National Additive Manufacturing Innovation Institute (America Makes, a public–private partnership established to accelerate additive manufacturing) for DoD use" (Government Accountability Office [GAO], 2015, p. 2). In 2015, the GAO published a report that found the DoD has taken steps toward utilizing AM

> to make existing product supply chains more efficient by enabling on-demand production, which could reduce the need to maintain large product inventories and spare parts; and enabling the production of parts and products closer to the location of their consumers, thereby helping DoD to achieve its missions. (GAO, 2015, p. 3)

However, the "DoD does not systematically track and disseminate the results of additive manufacturing efforts department-wide, nor has it designated a lead to coordinate these efforts" (GAO, 2015, p. 1). This creates a huge gap in maximizing AM's potential in creating long-term solutions, acquisition and logistic process efficiencies, and cost savings.

The most recent audit of the DoD's use of AM states that thousands of sustainment parts and tools are 3D printed to support all services (Department of Defense Office of Inspector General [DoDIG], 2019). These were historically procured via costly acquisition methods, since they are obsolete parts that are not easily procurable through traditional manufacturing sources. AM solved that problem. The Air Force, for example, 3D prints noncritical C-17/C-10 legacy aircraft parts that are low-quantity and high-cost for manufacturers to produce (Naguy, 2016b). According to the DoDIG report, areas for improvement still exist in AM adoption and standardization across the DoD. We seek to build on an important Inspector General recommendation that addresses that issue: uncovering a standardized DoD approach that incorporates best business practices and acquisition strategies in order to increase AM adoption.

Created in October 2016, the Air Force Additive Manufacturing Strategic Implementation Plan (AMSIP) set the stage for AM's adoption and implementation within the Air Force via a "deliberate, enterprise approach" (Naguy, 2016a, p. 2). Nearly 5 years later, the DoD as whole released its own *Department of Defense Additive Manufacturing Strategy*, further solidifying AM as the frontrunner in addressing many of the DoD's operational and industrial supply chain issues, impacting the world of engineering and acquisitions as well as maintenance and sustainment functions (OUSD[R&E], 2021b). However, while experts within industry and the DoD agree about the many benefits of AM, the Air Force still lacks a clearly structured decision framework that contracting, and acquisition professionals can utilize to assess and adapt to the various contractual and acquisition implications of AM technology. A deeper synthesis is needed regarding which business models and contractual approaches are necessary in order to effectively scale and incentivize the use of AM parts throughout the Air Force.

There is consensus within the field that AM possesses immense potential in improving Air Force sustainment efforts, as it is a solution to the long lead times, scarcity, and unavailability present in sourcing replacement parts for the Air Force's legacy aircraft and weapons systems (Naguy, 2016b). Our main goal is to utilize or adapt business models that could lead to better AM procurement practices. Our research problem is fueled by an apparent gap in policy and guidance on how the Air Force plans to procure such technology from an enterprise standpoint. Ultimately, our research can benefit the DoD's current effort to publish its *Additive Manufacturing Contracting Guidebook—Phase II* (National Center for Manufacturing Sciences [NCMS], n.d.). We hope our research can inform Air Force inputs that will be incorporated into the guidebook for continuous improvement in AM acquisitions.

B. RESEARCH QUESTIONS

The DoD is aware of the benefits that AM offers and has shown interest in leveraging its capability across many applications. The DoD will have to adapt its acquisition practices to stay on pace with commercial and technological advances that continue to unfold (OUSD [R&E], 2021). Doing so will posture the Services to acquire AM effectively and efficiently, which will become increasingly important as mass adoption of AM takes place.

However, the state of DoD AM acquisition policies and processes, organizational alignment, and data and intelligence management is unknown. Gauging the strengths and weaknesses of each of these cornerstones may lead to improved practices for acquiring AM (GAO, 2005). Our study is designed to explore the intent of AM acquisition practices across the DoD. This research begins the investigation with the Air Force and seeks to uncover the state of AM acquisitions while highlighting best practices. Ultimately, we seek to provide higher level insight for the Airforce, and a starting point for better understanding AM acquisitions at the DoD level. We pose three research questions:

Primary Research Questions

1. How well do Air Force AM acquisition practices meet the GAO (2005) *Framework for Assessing the Acquisition Function at Federal Agencies*? What are the strengths and weaknesses of Air Force's AM acquisition practices?

Secondary Research Questions

2. How is the Air Force purchasing AM compared to other DoD agencies? Is the DoD meeting the intent of the acquisition Goals 1 and 2 of the Department of Defense Additive Manufacturing Strategy (OUSD[R&E], 2021b)?

*Goal 1: Integrate AM into the DoD and the defense industrial base (*OUSD [R&E], 2021, p. 8)

*Goal 2: Align AM activities across the DoD and external partners (*OUSD [R&E], 2021, p.10)

3. What are the best acquisition practices within the Air Force's additive manufacturing landscape?

The goal of this research is to recommend improvements to acquisition and contracting practices for defense personnel seeking AM solutions. We use a GAO (2005) framework for assessing acquisition functions combined with a government AM spend analysis to answer our research questions. Concurrently, we seek to uncover the Air Force's effectiveness in acquiring AM products and services, and the challenges that must be overcome to better procure AM.

C. CHAPTER SUMMARIES

Chapter II includes a background describing what AM is, its advantages and disadvantages, and how it plays a role in the DoD. It begins with a problem statement motivated by various federal strategies and reports that highlight the need for improved acquisition practices to better leverage AM. This chapter also introduces key stakeholders that are integral to the AM landscape in which the DoD operates, including federal organizations and public–private partnerships like MITRE and America Makes. The background chapter concludes with a brief overview of the key organizations and policies that govern current AM processes throughout the DoD. For the purposes of this thesis, the terms *3D printing* and *additive manufacturing (AM)* are used interchangeably.

Chapter III includes a literature review of AM-related topics that bring readers up to date with recent academic research. This chapter sets the stage for where our research fits into the larger body of knowledge regarding AM and government acquisitions. It includes a review of supply chain implications, category management, cost benefit analysis, and literature that compares the benefits between traditional and AM processes. Chapter III begins with a discussion about DoD policies for AM and concludes with an examination of private and public business models that are used to develop our own framework specific to AM acquisitions.

Chapter IV includes the methodology. It begins with an overview of our main criteria used to assess AM acquisition functions. We introduce the GAO *Framework for Assessing the Acquisition Function at Federal Agencies* (2005) and explain what portions are adapted to create our own methodology to assess Air Force AM stakeholder interviews and DoD policy. Our final framework is supplemented with and category management elements adapted from previous research by Dacanay et al. (2020). We provide a detailed description of each framework element and critical success factor that is used in our analysis section. Our interview subjects and questions are also listed in this chapter along with the protocol used to conduct interviews with various AM subject matter experts (SMEs) throughout federal and commercial sectors. The chapter provides an account of why DoD spend analysis is used in our research and how the findings were analyzed to address our research questions. Chapter III concludes with limitations of the methodology.

Chapter V includes an Air Force spend analysis of AM procurement compared to Navy and Army spend, along with our assessment of Air Force acquisition practices using the adapted GAO (2005) framework. The results from the framework assessment and spend analysis inform answers to our research questions and lead us to our final recommendations. We synthesize our findings and present positive areas, caution areas, and best practices for AM acquisitions in the Air Force. While our study is focused primarily on the Air Force, select findings and recommendations are suitable to inform AM acquisition practices at the DoD level.

Chapter VI concludes the paper with answers to the research questions, final recommendations, and areas of future research.

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II. BACKGROUND

A. WHAT IS ADDITIVE MANUFACTURING?

AM is changing the way people think about industrial production. The American Society for Testing Materials (ASTM) International, a governing body responsible for setting global standards within the manufacturing industry, defines AM (also known as [3D] printing) as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (Vitale et al., 2016, p. 7). This process of adding materials “layer upon layer” contrasts sharply with the list of long-established traditional manufacturing techniques typically found within the industry, whereby material is removed or “subtracted” via machining, drilling, or grinding techniques to create a desired finished product (Bikas et al., 2016). While slight variances may exist, the AM process customarily starts with the constructing or identification of a 3D model by utilizing computer-aided design (CAD) software. The CAD-based 3D model is then saved as a Standard Triangle Language (STL) file, and printed as individual layers on compatible AM devices or 3D printers (Vitale et al., 2016). Depending on the complexity of the requirement and material utilized, secondary and finishing activities may still be required after this process is completed. Figure 1 provides a basic-level step-by-step visual of this process (Vitale et al., 2016).

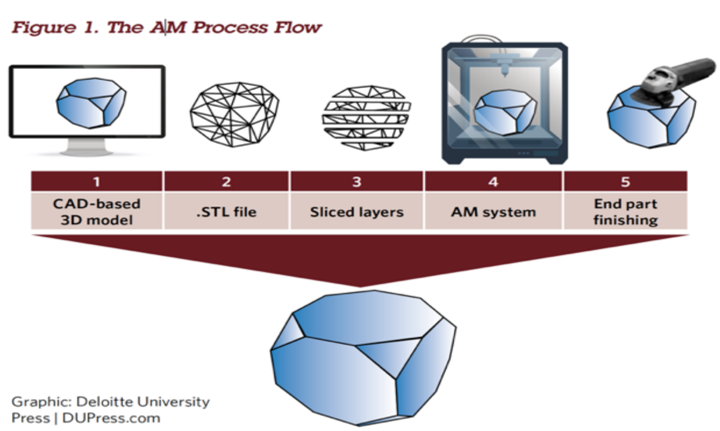

Figure 1. AM Process Visual Source: Vitale et al. (2016).

This revolutionary process and its respective industry first commenced in the early 1980s with Charles Hall’s invention of stereolithography (SLA) and the first rapid prototyping system. The process has continued to grow in market size (Ponsford & Glass, 2014). For example, between 1989 and 2014, the AM industry's average annual growth rate resided at 25.4% (Bikas et al., 2016). More recent data conveys a similar upward trend as well. According to a 2019 Wohlers Report, between 2017 and 2018, the AM industry, including all AM products and services worldwide, grew by 21% to $7.336 billion, with expected revenue forecasts to reach $35.6 billion in 2024 (McCue, 2019). Moreover, a Price Waterhouse Coopers and Manufacturing Institute report cited 71.1% of manufacturers having adopted 3D printing in some fashion (Price Waterhouse Coopers, 2016). This high adoption rate is partially due to the overall increasing number of AM processes available on the market, with a total of seven industry-recognized types of AM in existence today, each combining traditional raw materials like polymers, metals, and ceramics with energy in slightly different ways (OUSD[R&E], 2021b). Figure 2 provides a visual display of these seven industry-recognized types of AM with a brief definition for each approach.

Figure 2. AM Processes Source: OUSD[R&E], (2021).

AM technology is widely leveraged across industry sectors due to technical advancements in the processes available. Figure 3 conveys just how wide-ranging this reach is, with AM impacting the production of automotive, aerospace, medical goods and many consumer products (Bikas et al., 2016).

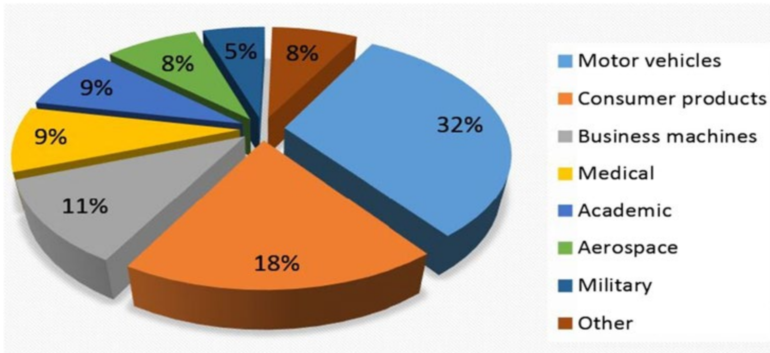

Figure 3. AM Industry Breakdown. Source: Bikas et al. (2016).

Most importantly, advancements in AM have allowed for many improvements in the repair and production of varied DoD material requirements. Examples across Services include: the Marine Corps 3D-printing a reinforced concrete bridge during an AM exercise held at Camp Pendleton, CA; the Army printing a low-cost cap to protect a tank lens; and the Air Force using AM technology to replace obsolete parts for the C-5 aircraft at 5% of the cost of traditional manufacturing (OUSD[R&E], 2021b). These are just a few of many key applications and impacts AM technology is having across the DoD. Overall, AM technology offers a plethora of advantages for how the DoD creates and acquires products for its mission and end users, including the following areas identified in the recently developed *Additive Manufacturing (AM) Contracting Guidebook—Phase II* (NCMS, n.d.):

- Time-saving
- Improved delivery timeline
- Manufacture without tool set-up
- Product development through rapid prototyping
- Weight-saving
- Topology-optimized design: stronger/lighter
- Cost-saving, less waste
- Reduced "buy to fly"
- Less "milling and drilling"
- Freedom of design

- Simplified designs
- Previously impossible geometries
- Complexity is free

This list of advantages closely resembles data found in a 2019 State of 3D Printing survey conducted by 3D Printing company Sculpteo. In this survey, 1300 respondents (3D Printing users) were asked to list the top benefits they believe AM technology has to offer. Figure 4 shows the results of this survey, with each bar graph indicating the percentage of respondents that consider a particular capability as one of the top 3 benefits that 3D printing has to offer (Leonard, 2019).

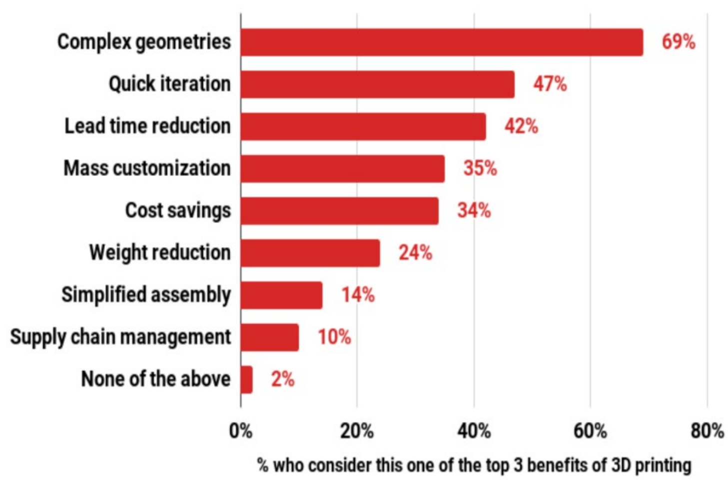

Figure 4. Sculpteo State of 3D Printing Survey. Source: Leonard (2019).

Companies around the world are positively reaping from AM's time-saving benefits such as reduced delivery timelines, manufacturing without tool set-up, and product development via rapid prototyping. Automobile manufacturer Audi's recent utilization of AM technology for the prototyping of its tail-light covers is a great example (Business Wire, 2018). The main challenge in creating products such as tail-light covers is that they are multi-colored, meaning that each individual-colored part must be created separately and cannot be produced as a single unit via conventional manufacturing techniques (Business Wire, 2018). This limitation of conventional manufacturing results in a "multi-step process" for Audi, increasing "lead times for design verification and delaying the time-to-market" for its tail covers (Business Wire, 2018, para. 3). However, Audi leveraged AM processes to overcome these limitations, enabling the "production of an entirely transparent, multi-colored tail-light cover in a single print" (Business Wire, 2018, para. 4). By leveraging this new process, Audi "expects significant reductions in prototyping lead times for tail covers, with turnaround times decreasing up to 50% in comparison to conventional methods" (Business Wire, 2018, para. 1).

As also noted in the AM contracting guidebook and Sculpteo survey, AM allows for the creation of complex geometries with optimized weight symmetries through a process called topology optimization. Topology optimization is defined as "a shape optimization method that uses algorithmic models to optimize material layout within a user-defined space for a given set of loads, conditions, and constraints" (Formlabs, n.d., para. 3). Most conventional manufacturing design processes involve applying loads to an already manufactured part and then evaluating where that part weakens. Based upon such findings, engineers then work to alter the design until it meets structural requirements. However, with topology optimization "the mechanical loads represent input data that allow the software to propose a new geometry for the part," resulting in fewer iterations being made to the design of the part (Michelle, 2020, para. 2). Topology optimization "maximizes the performance and efficiency of the design by removing redundant material from areas that do not need to carry significant loads," providing many structural benefits to the designed build (Formlabs, n.d., para. 3). This method is available through AM and is helping many aerospace suppliers deal with the significant "price pressures and increasing demand for lightweight components" (Schulz, 2019, para. 1).

Lastly, AM can save on many of the material costs produced by traditional (subtractive) manufacturing processes via its unique ability to reduce both the "buy-to-fly" ratio of parts and the amount of milling and drilling the process requires. The term "buy-to-fly" signifies the "ratio of the mass of the starting billet of material to the mass of the final finished part" (Watson & Tamniger, 2019, p. 1316). Aerospace engineers typically utilize this ratio to help them determine the total amount of waste involved in the process of making aircraft parts. The ideal buy-to-fly ratio is of course 1:1, which means that no amount of material is lost during the manufacturing process (Schulz, 2019, para. 4). However, a 10:1 buy-to-fly ratio is what is commonly found in most aerospace applications that involve subtractive manufacturing processes (Kobryn et al., 2006). Many companies are beginning to leverage AM technology to reduce such costly buy-to-fly ratios. German aircraft manufacturer Aircraft Philipp is one example, as they have recently decided to invest in Gefertec's arc605 fixe-axis metal 3D Printer to help reduce the number of materials they need to create finished products. Through the arc welding technology provided by Gerfertec's 3D Printer, Aircraft Philipp was able to achieve a buy-to-fly ratio of 2, meaning that creating a five-kilogram part with this technology now only required 10 kilograms of raw material (Schulz, 2020, para. 14).

B. KEY ADDITIVE MANUFACTURING POLICIES AND LEAD ORGANIZATIONS

Over the past few decades, AM's use has been primarily observed in a segmented, erratic manner across DoD organizations, with its rapid and excitingly disruptive nature sometimes blurring the ability for its backers to separate its hype from reality (Avdellas et al., 2016). However, AM's status in the DoD is on its way up the "slope of enlightenment" (Schrand, 2019). According to Gartner's hype cycle shown in Figure 5, there is always an innovation trigger followed by high amounts of inflated expectations when trying to implement a new, innovative technology like AM. This results in the formation of a trough of disillusionment regarding the technology's desired versus actual capabilities. However, experts in the field are claiming that AM is beginning to depart from the realm of inflated expectations and disillusionment regarding both its use and impact and is beginning to approach more realistic levels of productivity (Schrand, 2019).

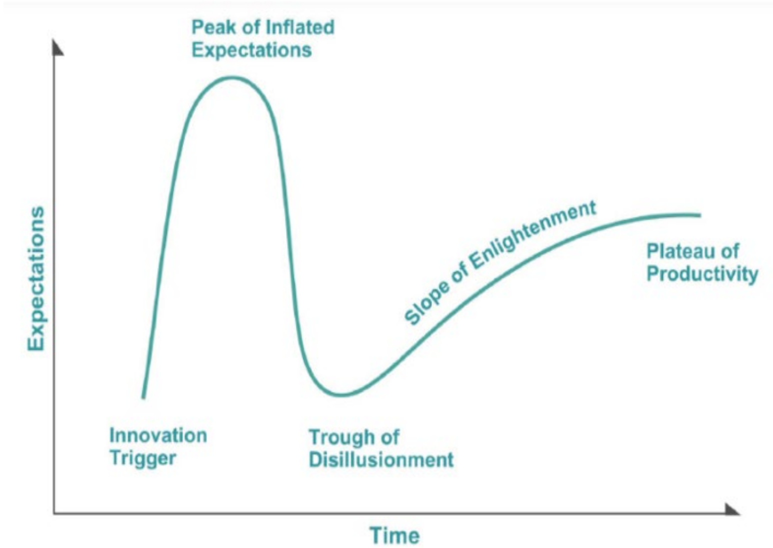

Figure 5. Gartner's Hype Cycle. Source: Schrand (2019).

One reason for this transition is the recent development of AM implementation plans. In 2016, the first DoD-wide AM roadmap was created. This guiding document emphasized the four focus areas of "design, material, process, and value chain" and aimed to identify commonalities between the military service and Defense Logistics Agency roadmaps, which are constantly being updated to ensure current technology advancements and information of service-level plans remain incorporated (Fielding et al., 2016, p. 10). 2016). Within the same year, the Army, Navy, Defense Logistics Agency, and Air Force all created individual AM roadmaps tailored to incorporate their respective visions, branch-specific requirements, and various assessments of technology gaps regarding AM implementation (DoDIG, 2019).

For the Air Force, Headquarters Air Force Materiel Command (HQ AFMC/CC) appointed the Air Force Life Cycle Management Center (AFLCMC) Product Support Engineering Division (EZP) as the lead for such enterprise-level implementation, ultimately creating the Air Force's AMSIP in October 2016. The EZP based this plan upon a crawl, walk, run strategy described in now, near, and long-term goals of reaching a successful Air Force–wide implementation of AM (Naguy, 2016a). Regarding the entire DoD, the Office of the Secretary of Defense for Manufacturing Technology (OSD ManTech) Program Office in the OUSD (R&E) oversees AM implementation. As recently as January 2021, this office assembled the first-ever Department of Defense

Additive Manufacturing Strategy (OUSD[R&E], 2021b). This strategy document further solidified the vision and support of AM technology, as it provided a “shared set of guiding principles and a framework for AM technology development” for the DoD, military services, and agencies as a whole (OUSD[R&E], 2021b, p. 7).

To ensure that the goals of the Department of Defense Additive Manufacturing Strategy are properly conveyed and structured to fit within the requirements of each Service branch, the OSD(R&E) established the Joint Defense Manufacturing Council (JDMC) to act as a focal point for cross-collaboration between DoD leaders, promoting the “sharing of information to maximize the value of manufacturing to maintain DoD’s strategic competitive advantage” (OUSD[R&E], 2021b, p. 10). The JDMC spearheaded the Joint Additive Manufacturing Steering Group (JAMSG), which is composed of senior leaders appointed by each respective Service or agency and is ultimately responsible for defining and achieving goals toward maximizing the benefits of AM (Defense Innovation Marketplace, 2017). The JAMSG accomplishes this task via the Joint Additive Manufacturing Working Group (JAMWG), which consists of action officers from each relevant organization within the JAMSG, who jointly coordinate and execute strategic and operational activities regarding AM (Defense Innovation Marketplace, 2017). Finally, Stakeholder Councils, which are subgroups of SMEs that comprise the JAMWG, meet to define, monitor, and track AM activities initiated by the JAMWG (Defense Innovation Marketplace, 2017). These initiatives then trickle down to the individual communities of practice (Army, Navy, Marines, Air Force) via communication forums designed for each respective Service branch, such as the Naval AM Technology Interchange (NAMTI), the Air Force Technical Interchange Meeting (AFTIM), and the Army Community of Practice (OUSD[R&E], 2021b). Such forums generate healthy communication over current developments in the AM field, bringing together the various voices of government and industry experts to tackle AM challenges (OUSD[R&E], 2021b). For example, AFTIM includes representation from Air Force Acquisition, Technology, and Logistics; the AFLCMC; and the Air Force Research Laboratory (AFRL; Defense Innovation Marketplace, 2017). A detailed visual of this collaborative process is broken down clearly in Figure 6, while Figure 7 provides additional information regarding the numerous representatives that comprise the various joint AM groups for each Service/agency displayed in Figure 6.

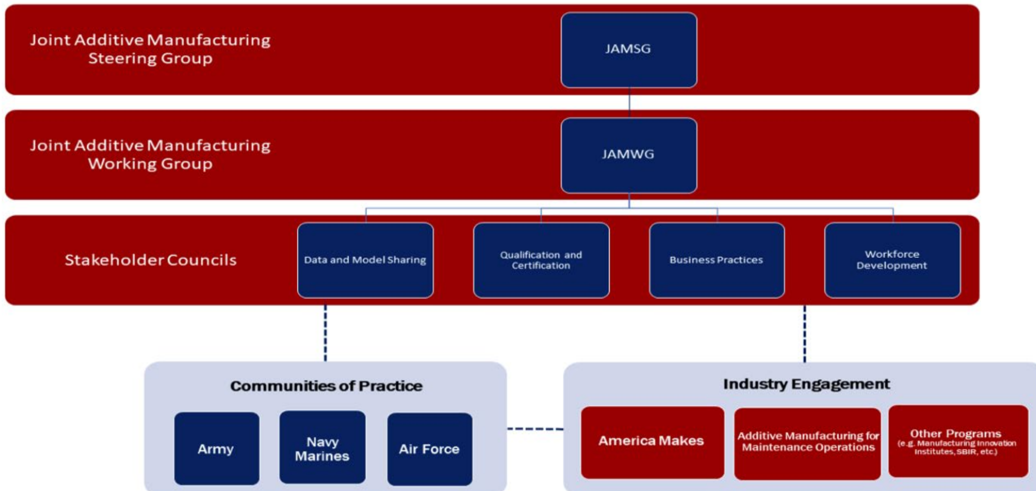

Figure 6. DoD Joint AM Organizations. Source: Defense Innovation Marketplace (2017).

AIR FORCE

- Air Force Acquisition, Technology, and Logistics
- Air Force Life Cycle Management Center
- Air Force Research Laboratory

ARMY

- Office of the Deputy Assistant Secretary of the Army for Strategy and Acquisition Reform
- Army Logistics
- Army Research Laboratory
- Army Materiel Command

LOGISTICS

- Joint Staff Logistics
- Defense Logistics Agency Information Operations
- Defense Logistics Agency Logistics Operations

NAVY And MARINE

- Office of the Assistant Secretary of the Navy Research, Development, and Acquisition
- Naval Operations for Fleet Readiness and Logistics
- Office of Naval Research
- Marine Corps Installation and Logistics

OUSD(A&S)

- OUSD(A&S) Materiel Readiness
- OUSD(A&S) Logistics
- OUSD(A&S) Industrial Policy

OUSD(R&E)

- Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E))
- Strategic Technology Protection and Exploitation
- OUSD(R&E) Systems Engineering

MDA

- Missile Defense Agency (MDA) Component and Materials Engineering Division

DCMA

- Defense Contract Management Agency (DCMA) Headquarters Technical Directorate

Figure 7. Service-Specific AM Representatives

Last, the DoD Joint AM Organization also prioritizes an engagement with industry to better inform AM decision-making and processes. In order to do this, the DoD formed a partnership with the national Manufacturing Innovation Institutes (MIIs), also known as Manufacturing USA. A total of 14 MIIs have been established, five for the Department of Energy, one for the Department of Commerce, and eight MIIs specifically for the DoD. Figure 8 provides a map regarding the location of each of these MIIs within the United States.

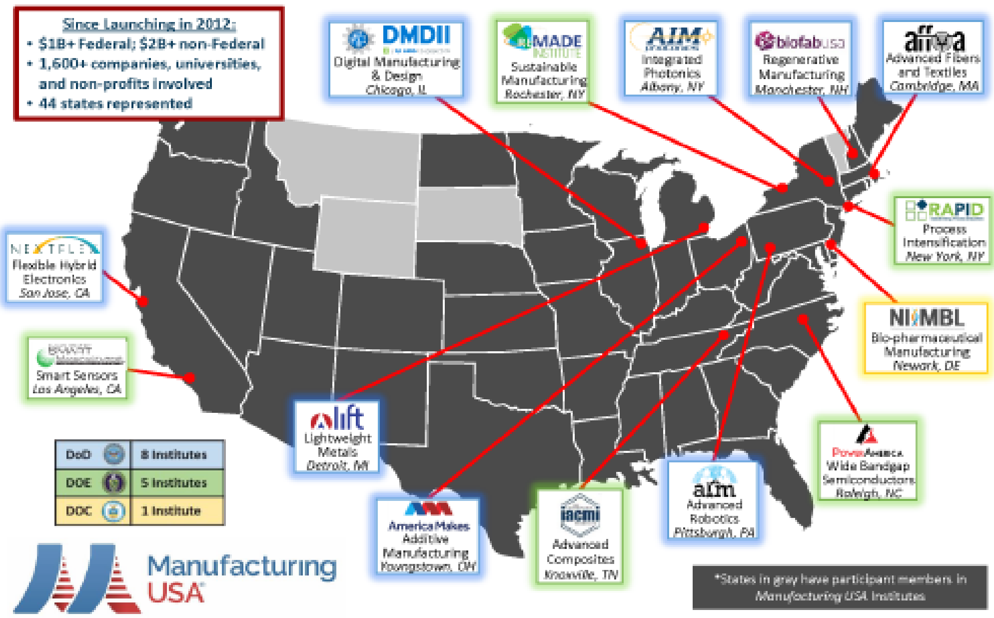

Figure 8. Manufacturing USA Map. Source: Schrand (2019).

These MIIs are public–private partnerships comprised of industry, academia, and government partners working together to advance U.S. manufacturing competitiveness. They also play a vital role in the advancement of AM within the military and receive federal funds from multiple sources, some of which include the OSD, the Air Force Office of Scientific Research, the Commander's Research and Development Fund for basic and applied research, and the Small Business Innovative Research Program (Schrand, 2019). Since its conception in 2012, Manufacturing USA has received over $1 billion in federal funds and $2 billion in non-federal investments by industry, academia, and local governments alone, establishing partnerships and workshops with over 1,600 companies and universities across a total of 44 states (Schrand, 2019).

America Makes, in collaboration with the National Center for Defense Manufacturing and Machining (NCDMM), is the primary MII that works to advance AM adoption. Since 2012, America Makes has funded over 60 manufacturing projects and is the entity responsible for helping each DoD service generate an AM roadmap (Schrand, 2019). In cooperation with the American National Standards Institute, America Makes is also responsible for the coordination and publication of a national roadmap for standards and specifications, starting a "digital storefront" that represents live AM roadmap and index project data (Schrand, 2019). NextFlex is another MII that is key to the development of AM across the DoD. Located in San Jose, CA, NextFlex works to "combine digital printing with traditional electronics manufacturing services tools in order to create a prototyping and low-volume manufacturing capability for FHE devices" (Schrand, 2019, para. 12). Ultimately, each of these MIIs that comprise Manufacturing USA possess unique technological concentrations and jointly work toward accelerating U.S. advanced manufacturing as whole.

C. CONCLUSION

This chapter covered important background information on AM and the many key organizations and policies that guide its use within the DoD. The information provided in this section provides the reader with a general understanding of what AM is, how it may be used and its many benefits, as well as an overview of the key organizations involved in its implementation across the DoD. The next chapter will involve a literature review.

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III. LITERATURE REVIEW

This chapter begins with a discussion of DoD and Department of the Air Force policies on AM. We also review procedures established to implement said policies. As we develop a framework for the acquisition of AM within the DAF and the DoD, it is important to know and understand the existing policies and procedures to ensure that our framework complies with those guidelines.

Next, this chapter includes a discussion on the difference between traditional manufacturing (TM) and AM. The discussion focuses primarily on supply chain and acquisition processes. By examining and understanding the differences between the two types of manufacturing, we can appropriately incorporate the benefits and challenges in our framework. We also examine different models that were useful in developing our framework. We look at basic acquisition models as well as AM business models used by the Navy and private companies.

Finally, this chapter concludes with a discussion of the different issues and challenges with AM application. It is important to study these issues and challenges and use them as considerations in developing our framework.

A. POLICIES AND PROCEDURES

The DoD's vision for implementing AM is to "enable a more agile, adaptable and aligned defense supply base to outpace adversarial threats" (OUSD[R&E], 2021b, p. 7). While AM has been around for decades, the drive for its use within the DoD and the DAF started only a few years ago. There are few policies and procedures within the DoD and the Air Force that are focused on AM.

In January 2021, the DoD released its AM strategy with the purpose of providing "a shared set of guiding principles and a framework for AM technology development and transition to support modernization and Warfighter readiness within DoD, Military Services, and Agencies" (OUSD[R&E], 2021b, p. 6). The strategy outlined five areas that must be addressed to maximize the full potential of implementing AM within the DoD. These areas, or "goals," (OUSD[R&E], 2021b) as referred to in the strategy are:

- rapid and standardized approaches for qualification of materials and processes, and certification of AM parts,
- new business models for contracting and acquisition of AM digital technical data,
- logistics model for production of AM parts at forward operating locations,
- standard AM technical data content, and
- an interoperable secure AM digital thread for connectivity and data management. (OUSD[R&E], 2021b, p. 6)

The strategy also shows that the DoD recognizes the different issues and challenges when it comes to the acquisition of AM-related products and services. To meet the first and second goals outlined in the strategy, the DoD "is developing responsive AM-related business practices and contracting guidance that consider Intellectual Property considerations with other legal and liability implications" (OUSD[R&E], 2021b, p. 9). As of this writing, the AM acquisition guide has not been published.

In 2019, to "maximize Additive Manufacturing (AM) awareness and efficiencies across the Air Force enterprise" (Keller, 2019), the AFLCMC Metals Technology Office (MTO) released 12 notifications outlining plans, processes, facility requirements, and more. The following is a list of the notifications and a summary of their purposes:

Table 1. MTO Notifications Summary

Notification Title	Purpose
19-001 AM Design Rule Book	Provides necessary information, best practices, standards, equipment information, material characteristics, part considerations, and design rules and guidelines for the successful design and production of AM parts (McDuffie, 2019).
19-002 AMSIP	Outlines the AFLCMC EZP strategic plan to address AM challenges within the Air Force (McDuffie, 2019).
19-003 USAF Manufacturing Request Form and AM Parts Tracker	Ensures that engineers, field users, and fabrication elements are aware of the following: • USAF Manufacturing Request Form -- supports TM and AM (McDuffie, 2019).

Notification Title	Purpose
	• Air Force Advanced Technology and Training Center (ATTC) AM Parts Tracker (McDuffie, 2019).
19-004 AM Equipment Purchases	Increases engineers, field users and/or fabrication elements awareness and purchase guidance for Air Force approved polymer AM equipment for production of qualified AM parts, and further outlines desktop AM machines for purposes and uses outside of Air Force equipment applications (McDuffie, 2019).
19-005 Process for Printing Qualified AM Parts	Increases Air Force enterprise-wide awareness and to deliver a path to qualifying technicians as AM equipment operators and qualifying Air Force approved polymer AM equipment to produce qualified AM polymer parts (McDuffie, 2019).
19-006 AM Processes, Categories and Inspection/ Testing at the Advanced Technology & Training Centers	Familiarizes Air Force engineers, field users and fabrication elements with processes employed at the ATTCs in Dayton, OH, and in Warner Robins, GA. Those processes, which are necessary to certify AM parts for Air Force operations are: • AM Product Development Process (PDP) • AM Part Categories, and • AM Part Testing and Inspection criteria (McDuffie, 2019).
19-007 Additive Manufacturing Material Characterization for Metals	Ensures that engineers, field users and fabrication elements are aware of the Air Force AM Material Characterization Process (MCP) for metals (McDuffie, 2019).
19-008 AM Metal Materials and EOS M290 S-Basis Tensile Data and Test Report Repository	Ensures that engineers, field users and fabrication elements are aware of the following: • Air Force AM metal materials and EOS M290 S-Basis tensile data, and • locations of future materials testing reports and data (B-Basis, Fatigue, etc.) (McDuffie, 2019).
19-009 Aircraft MT Field Unit Capabilities (TM)	Familiarizes Air Force engineers with the field level fabrication capabilities of the Aircraft MT shops (McDuffie, 2019).

Notification Title	Purpose
19-010 USAF Manufacturing Request – Part Selection Process	Ensures that engineers, field users and fabrication elements are aware of the following USAF manufacturing part selection process (to) determine the most practical option(s) for manufacture -- AM, TM methods, or both (McDuffie, 2019).
19-011 AM Tracking and Status Updates - Advanced Technology and Training Center of Middle Georgia (ATTC-MG)	Familiarizes engineers, weapons system program offices, and field users with Air Force MTO's process for tracking and providing status updates on parts being produced at ATTC-MG via AM to provide an open line of communication, promote transparency, and manage expectations between the Air Force customer in need and ATTC-MG members (McDuffie, 2019).
19-012 AM within the Air Force: Potential Challenges and Disadvantages	Ensures that engineers, weapons system program offices, and field users are aware of some of the potential challenges and disadvantages that are associated with the use of AM (McDuffie, 2019).

In 2016, the Air Force released the United States Air Force AMSIP, which recognized AM as an enabling tool that can give the Air Force a technological advantage (Naguy, 2016a). As with any emerging technology, the implementation of AM use within the DoD will have its gaps and challenges. Naguy (2016) proposed, "To realize the opportunities of this technology, we must use a deliberate, enterprise approach to address the challenges and gaps" (p. 2). Naguy (2016a) also highlighted the need for the Air Force "to develop a standardized, systematic approach to selecting parts, materials, and processes for AM across the Air Force enterprise" (p. 12). Furthermore, the AMSIP provides a "crawl, walk, run approach" (Naguy, 2016a, p. 12) in the implementation of AM. This approach provides time bounded goals divided into three "terms" (Naguy, 2016a, p. 5):

- **Now Term** – Establishing AM foundational capability in metals and polymers focused on ground vehicles, support equipment, tooling, fixtures, and non-critical weapon system components.
- **Near Term** – Expanding AM capability to establish a network of capability, skills, and qualified parts across metals, polymers, and composites.

- **Long Term** – Global AM network that is agile, flexible, and deployable across various disciplines including vehicles, machines, and critical aerospace components.

B. COMPARING TRADITIONAL AND ADDITIVE MANUFACTURING (COST–BENEFIT)

Both TM and AM have DoD and Air Force applications. The process for acquiring supplies and services is different for each. We need to be able to distinguish the differences between TM and AM. One way we can do this is by determining the cost–benefit, if any, of AM compared to TM. This will help in articulating the proper application and benefits of both types of manufacturing and assist end users in determining whether to use AM, TM, or both for their requirement.

There are plenty of articles that talk about the potential of AM as a disruptive technology that can help address logistics and supply chain issues. While there are a number of qualitative papers, there are few that have evaluated the benefits of AM from a quantitative standpoint. In 2015, the U.S. Army Logistics Innovation Agency (USALIA) conducted a CBA comparing AM and TM given an operational context. The key findings of the study were as follows:

(1) First, the variability in average total cost can be attributed to the location of the operation. Reduced wait-time is the organization's ability to have the part ready within hours or days versus ordering it from the OEM and transporting it, which could take weeks or months. Having the part available sooner increases operational capability by reducing equipment downtime.

> The main benefits of AM are likely to be reduced wait-times and increased operational capabilities. AM enables production of items closer to the point of need, reducing wait-time. AM could also rapidly create custom and specialized items to meet operational needs. AM for item production is more expensive than TM even with significant technology improvements (3 to 28 times greater, average total cost 24 times greater), but could reduce wait-times (6%–99% or 3–153 days). (Leno et al., 2015, p. 1)

(2) Second, locations within the supply chain have cost and benefit trade-offs. Conventional manufacturing within the continental United States (CONUS), as compared to other AM locations, has the lowest cost but potentially the longest wait-time. AM at a

major theater support base reduces wait-time and transportation risk but increases cost. AM at a forward contingency base minimizes wait-time and maximizes flexibility but has the highest cost and transportation requirement (Leno et al., 2015, p. 1).

(3) Third, "AM at a location outside of CONUS will likely increase the support requirement since the AM process requires more materiel than simply shipping the finished items directly" (Leno et al., 2015. p. 1). This means that these locations need to have all the raw materials required and large quantities of support materials for the printer, such as large quantities of argon (for metal printers). Increased support requirements not only mean higher transportation costs; they also mean increased storage requirements and cost.

(4) Last, cost reductions in using AM printers can be attained a couple of ways. One is by increasing the printer's speed and by using the printers for as long as possible.

> Sensitivity analysis shows that the most significant cost reductions would likely come from increasing average printer build speed (to at least 5 cubic inches per hour) and using printers for as long a time period as possible (for at least 4 years, but not less than 2). Leno et al. (2015, p. 1)

Figure 9 is a summary that shows that increasing the use of AM printers and build speed throughout the life of the printer increases efficiency and can bring the cost closer to TM cost. Figure 10 shows the relationship between operational duration and average cost per item and highlights that in order to attain efficiency and cost-effectiveness, "AM facilities should operate for at least 4 years, but not less than 2 years" (Leno et.al, 2015, p. 47).

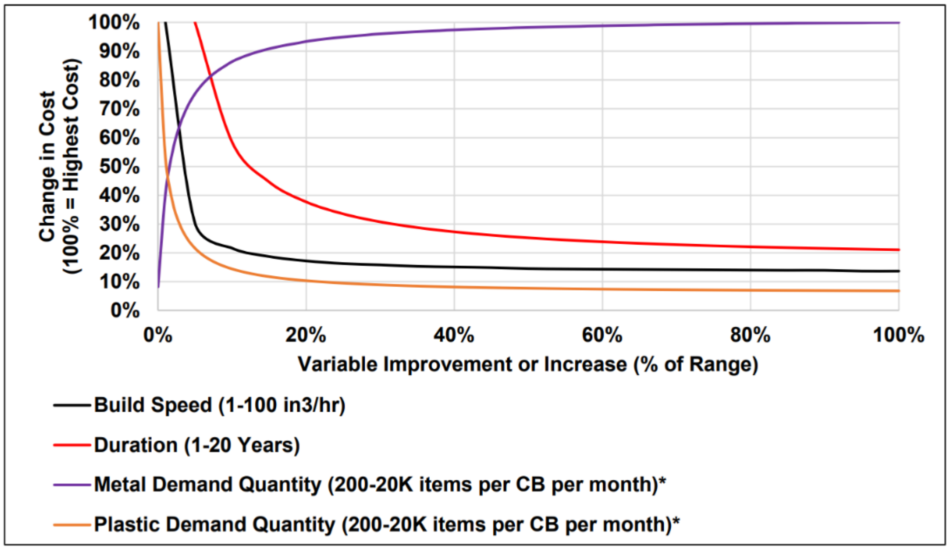

Figure 9. Sensitivity Analysis Summary: Non-linear Relationships. Source: Leno et al. (2015, p. 46).

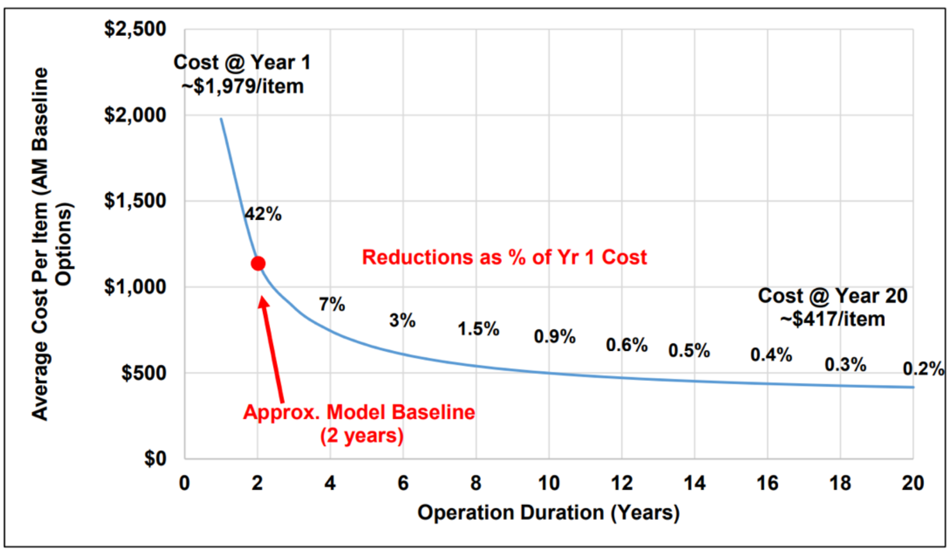

Figure 10. Sensitivity Analysis on Operation Duration. Source: Leno et al. (2015, p. 47).

C. ISSUES AND CHALLENGES WITH AM APPLICATION

AM is a promising technology, but despite it having been around for decades, its adaptation has been slow. This is attributed to the different issues and/or challenges with AM application. One of the challenges that comes up is intellectual property (IP). Paben and Stephens (2015) wrote, “In order for the Navy to manage the challenges associated with IP and data rights of AM, planning for its use in weapon system procurement and life-cycle support should be incorporated into the first stages of acquisition planning" (p. 59). It is safe to say that IP and data rights are challenges not just for the Navy but for the entire DoD. Print component certification is another issue that comes up when using AM. AM has the potential to improve the Navy's supply chain once it overcomes the issues of parts qualification and certification (Lopez, 2019). This is another issue that also applies to the Air Force DoD such as getting the AM airducts certified for use on the C-17.

Naguy (2016b) listed nine challenges that the Air Force can look at when contemplating the use of AM. They are as follows:

- **Material standards and availability.** Creating Air Force specifications and developing a material properties database using enterprise approach and evaluating powder vendors Naguy (2016b).
- **Part selection.** Developing enterprise-wide down-selection tools and process guides Naguy (2016b).
- **Skill set development.** Evaluating standard AM design tools and developing AM training for engineers and operators in AM concepts/ designs for enterprise deployment Naguy (2016b).
- **Configuration control.** Establishing a centralized library, standard technical data packages (TDPs), and standard processes and policies for facility layout, quality control, and material evaluation Naguy (2016b).
- **Reproducibility.** Evaluating process controls and demonstrating manufacturing variations at major commands and depots Naguy (2016b).
- **Cybersecurity.** Developing program protection plans and evaluating secure digital design storage and data transfer to move files for cyber resiliency Naguy (2016b).
- **Part validation and qualification.** Establishing standard processes for non-destructive inspection (NDI) and validation Naguy (2016b).
- **Process validation and qualification.** Establishing a robust and sustainable enterprise process Naguy (2016b).
- **Reverse engineering.** Evaluating tools and training for legacy part TDPs Naguy (2016b).

Air Force MTO AM Developmental Guidance 19–012 also outlined challenges and disadvantages in using AM (McDuffie, 2019). They are as follows:

1. AM equipment and technology are continuously emerging

- The pace of technology and changes may result in a shortened life cycle or equipment obsolescence (2–8 years), making it difficult for large-scale standardization across the enterprise.
- Expectations management. Generally, customers seem to be very either-or in regard to the technology, being either for or against the use of AM.
- Machines are not universal. Build and variability between different machines, models, and various machine technologies are not fully understood.
- In-depth design and/or equipment end-use knowledge is usually required in order to optimize the AM build.
- Multiple print attempts, each usually requiring engineering design and support structure reiterations, may be required in order to produce the final/correct artifact.
- No matured and reliable simulation software for the DMLM or FDM process is available to predict build failures and/or defects within parts.
- Rigid parameter sets (variables) within each machine are required for "approved" printing.
- AM is best suited for low quantity, complex builds. The cost of manufacturing a single part using AM does not decrease with increased volume. Design complexity does not increase AM cost.
- AM equipment needs to be able to print both smaller-scale and larger-scale parts that are currently unavailable within existing equipment.
- Any business case analysis complicates everything.
- What is the time frame during which a machine starts producing "income" (based on revenue, readiness, etc.) and what is that basis—specifically, how many and what type/category of must be produced within a given timeframe to be considered an effective and suitable investment?

2. Materials

- Options are limited; currently, the ATTCsare printing in aluminum, stainless, cobalt-chrome, titanium and Ultem 9085 for airframe use.
- Testing and data review/interpretation take 1–3 years from initial tensile screening through fracture and fatigue testing for each material.
- Material flaws may be unknowingly induced during and as a result of the technology and the build process.
- Destructive testing is typically preferred by Air Force members for any perceived critical or critical part versus NDI testing. This affects time

and costs but should not be waived (TM to reduce test time may be an option under these circumstances).

- The build process results in a layered structure: Material is melted (welded) via a laser at 20–40 microns in thickness until the build is complete. Internal part stresses result from uneven heating/cooling caused by the welding and result in distortion, build inaccuracies, and so forth.
- Significant material variability (chemical composition, partial size distribution/shapes) may exist between vendors, potentially causing a sizable variance in builds and mechanical properties.

3. Mechanical Properties/Inspections

- Due to the layering build process, anisotropy exists in the z-direction (vertical build direction); build part orientation should be considered and contrasted to load transmissions.
- Likelihood/possibility of reduced mechanical properties for AM materials affects part service life in comparison to "equivalent" wrought materials
- Verification per print: Did we build the artifact correctly as it was intended, and how do we verify?

4. Research/Education

- Uncoordinated sharing and/or refusal to share data related to process parameters, materials, materials/mechanical properties, research and/or testing across industry, government and academia exists.
- This results in uncoordinated duplication of research efforts and lack of formal and/or hands-on educational opportunities at the university level.
- There is a high amount of work and low synergy.
- This results in an insufficiently skilled workforce and lack of training opportunities within the government and industry,

5. The building of "parameter sets" varies between each machine/technology and has to be optimized for each material including specific vendors.

- Potential variables must be determined/vetted and optimized (through trial and error) prior to going forward. A few basic examples include build layer thicknesses, beam power and scan/build speed, self-supporting spacing width and angles, hatch spacing (laser path) melt pool, and so forth.

6. Typical defects pre- and post-material research and buildability studies within the AM process

- Internal porosity
- Lack of fusion between portions of layers (internal), though not visible
- Delamination
- Cracks and distortion due to internal stresses (heat buildup)
- Balling, especially on down skin of builds
- Surface roughness, which directly affects fatigue

7. Cybersecurity

- Hacking of AM machines and/or print files

8. Lack of universal methods and/or part production avenues/incentives

- Test data for part qualification and equipment or operator certification(s) between the original equipment manufacturers of parts being produced and the DAF
- Enterprise contracting guidebooks, common practices, languages and/or support
- Lack of standardized production processes that will protect the DAF as well as industry, making AM attractive within the manufacturing network
- Causes questions related to if/can/have manufacturers been able to repeatedly make the same part using machines located globally Supply chain robustness for AM machines, materials and/or parts in demand
- Technology predominately used for "replacement parts" only, not new design, thereby further limiting application, education, and so forth.

9. Production limitations

- Obtaining Air Force-wide contracts/financing for equipment and investments in AM machines, training, and technologies
- No portable equipment for in-theater use within the Air Force; unlikely reality based on current technology and Air Force-specific enterprise requirements"

D. CURRENT AM ACQUISITION METHODS

The Air Force uses FAR and non-FAR based contract strategies in acquiring AM. Data obtained from procurement data system showed Air Force units utilizing FAR based instruments such as purchase orders, delivery orders, and C-type contracts to purchase

AM. Interviews and literature reviews showed the Air Force utilizing non-FAR based instruments such as Cooperative Research and Development Agreement (CRADA) and Partnership Intermediary Agreements (PIA). While most people are familiar with FAR based contracting instruments, most are unfamiliar with non-FAR based instruments such as CRADAs and PIAs. The following paragraphs defined two of the most common non-FAR based contracting instruments used in acquiring AM.

CRADAs, such as the one the Air Force has with General Electric (GE), "Authorizes federal labs to enter into agreements with other federal agencies, state/local government, industry, non-profits, and universities for licensing agreements for lab developed inventions or intellectual property to commercialize products or processes originating in federal labs" (Cooperative Research & Development Agreement (Crada) – 15 Usc 3710a | Adaptive Acquisition Framework, n.d.).

PIAs, such as the one that the Air Force has with UDRI, are used "to facilitate technology transfer to private sector" and "to increase likelihood of success in conducting cooperative or joint activities with small business firms and institutions of higher education to make use of technology-related assistance from a government lab" (Partnership Intermediary Agreement (Pia) – 15 Usc 3715 | Adaptive Acquisition Framework, n.d.)

Our literature review shows the Air Force utilizing these existing methods in acquiring AM-related products and services allowing flexibility in acquisition strategies considering the spectrum of knowledge gaps in AM technology, materials, and capabilities. It allows the Air Force to partner and share resources with industry and academia who are also working towards the same goal of understanding AM.

E. CATEGORY MANAGEMENT

Category management is "a structured, data-driven business practice whereby an organization strategically analyzes and manages common categories of spend in order to eliminate redundancies, increase efficiencies and enhance mission effectiveness" (Introduction to Air Force Category Management, 2020). It has four principles. The first principle is categorizing spend, which allows the Air Force to track how dollars are being spent. The second principle is assigning cost ownership to category managers. The third principle is business intelligence, which is needed to enable data driven decisions. The fourth principle is to drive results by implementing the right solutions using one, or more, of the pillars/areas of category management: managing demand, issuing policy, implementing strategic acquisition, and adopting industry best practice (Introduction to Air Force Category Management, 2020).

Applying category management principles to AM acquisitions came up during our interviews and literature reviews. It also came up during our analysis and mentioned later in our recommendations. We chose to use the adaptive CM framework by Dacanay et al. (2020) and GAO framework (2005) to guide our analysis.

F. CONCLUSION

This chapter covers AM information that we found pertinent to our research topic. The information guided our analysis, and some are reflected in our recommendations. The next chapter covers our research methodology.

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IV. METHODOLOGY

Our methodology includes a mixed method approach consisting of qualitative and quantitative analysis. We begin by analyzing DoD AM policy and guidance, coupled with stakeholder interviews that examine operations within AM organizations. This chapter also includes the steps used to conduct a robust DoD spend analysis of AM products and services through Fiscal Years (FY) 2017–2020. We use an adapted version of GAO's (2005) *Framework for Assessing the Acquisition Function at Federal Agencies* as a criterion to guide our assessment of the AM acquisition landscape in the Air Force. Dacanay et al. (2020) adapted the framework to assess a category management function in previous research conducted at the Naval Postgraduate School. We apply their framework to critique AM as an acquisition function in the Air Force.

Applying the framework to AM acquisitions will inform our answers to the proposed research questions (1 and 3) in the final chapter. The results from the spend analysis inform our answer to Research Question 2. Lastly, we consolidate our findings to develop recommendations that DoD policy makers may consider when developing business models for acquiring 3D-printed requirements. We start by introducing the GAO framework and explain how it was adapted to fit our research objectives.

A. GAO FRAMEWORK

The GAO (2005) created a framework to evaluate an agency's acquisition processes and identify improvement areas (p. 9). The framework is found in GAO-O5-218G, titled *Framework for Assessing the Acquisition Function at Federal Agencies*. It was developed with input from government and industry experts in the fields of human capital, information management, financial management, and acquisitions practices (GAO, 2005). We chose to use these criteria because they are widely used in policy analysis throughout the federal government, and they offer a structure for our interview questions to internal stakeholders. Overall, we use this framework to gauge the state of Air Force AM acquisitions.

The framework has been used as a method for researching acquisition processes of organizations (Lu, 2011; Peterson & Finkenstadt, 2011; Smith, 2014) and has been adapted for special purposes, as exemplified *in Implementing Category Management Across United States Special Operations Command* by Dacanay et al. (2020). We use the adapted framework of Dacanay et al. (2020) to analyze the following content associated with AM within the DoD:

- *Additive Manufacturing Contracting Guidebook—Phase II* (draft; NCMS, n.d.)
- *Department of Defense Additive Manufacturing Strategy* (OUSD[R&E], 2021b)
- *Department of Defense Additive Manufacturing Roadmap* (Fielding et al., 2016)
- Interviews with SMEs in AM and acquisitions

The GAO framework is comprised of four cornerstones: (1) organizational alignment and leadership, (2) policies and processes, (3) human capital, and (4) knowledge and information management, each containing multiple elements and critical success factors (CSFs) that are deemed essential components to a healthy acquisitions agency. Table 1 shows a general overview of the framework tailored to our purposes. It is based on both the original GAO (2005) framework and Dacanay et al.'s (2020, p. 45) adapted *Framework to Assess a Category Management Function*. They created the framework so that future organizations wishing to establish a CM program can better assess their specific needs. We use this framework to assess the state of current Air Force AM acquisition functions, and to determine improvement areas. The original GAO framework (2005) is found in Appendix A, along with the adapted framework from Dacanay et al. (2020) in Appendix B.

Our research focuses on Cornerstones 1, 2 and 4 as the primary means to assess the current acquisition landscape of Air Force AM and to answer our research questions. We did not explore cornerstone 3 (human capital) due to time, available data and resource constraints. Further research into the AM workforce at operational, systems, and expeditionary levels would provide more insight for this cornerstone. We note this in areas of future research.

The framework provides the following indicators that help to determine how well the cornerstones and elements are being met: key questions to ask, situations to look for, and caution areas to be aware of. We use these indicators during the interview and the policy and spend analysis to guide our assessment of whether CSFs are being met. Combined, the CSFs inform how well elements are being met to support cornerstones of a healthy acquisition function. We use select elements (i.e., change management, data integrity, and data analysis) included from the Dacanay et al. framework (2020) to explore the potential for a category management program for AM.

Table 2. Framework to Assess an AM Acquisition Function. Adapted from Dacanay et al. (2020) and GAO (2005).

Cornerstones	Elements	Critical Success Factors
1. Organizational Alignment and Leadership (GAO, 2005)	1. Aligning Acquisition with Agency's Mission and Needs	• Appropriate placement and ownership of AM acquisition functions • Organizing AM acquisition functions to operate strategically • Presence of a clear definition of AM's function and mission
	2. Commitment from Leadership	• Clear prioritization of AM by leadership • Effective communications and continuous improvement • Leadership buy-in
	3. Change Management (Dacanay et al., 2020)	• Early adoption • Drive for change
2. Policies and Processes (GAO, 2005)	1. Planning Strategically	• Governing body or forum to establish strategic direction • Partnership with internal organizations • Assessing internal requirements and the impact of external events • AM collaboration efforts
	2. Effectively Managing the Acquisition Process	• Empowerment of cross-functional teams • Management and engaging suppliers • Monitoring and providing oversight to achieve AM outcomes • Presence of AM operating procedures
	3. Promoting Successful Outcomes of Major Projects	• AM capability gaps are addressed • Performance tracking of AM assets and services • Employing knowledge-based acquisition approaches • Investments are made without strategic considerations to meet long-term and short-term AM objectives
3. Strategic Human Capital	*Unexplored; outside the scope of this research*	
4. Data and Intelligence Management (Dacanay et al., 2020)	1. Data Integrity (Dacanay et al., 2020)	• Ownership of a data management strategy • Ability to extract, cleanse, and organize data • Ability to verify & validate data • Identification of inaccurate data or poor data sources
	2. Data Storage and Safety: *unexplored; outside the scope of interview protocol and spend analysis*	
	3. Data Analysis (Dacanay et al., 2020)	• Access to tools to visualize, analyze, interpret data • Ability to generate business intelligence (BI) and market intelligence (MI) products • Ability to develop and use BI/MI products to generate category management outcomes • Translation of data into meaningful format • Ability to translate BI/MI into discernable acquisition actions and decisions

1. Cornerstone 1: Organizational Alignment and Leadership

Cornerstone 1 covers some essential roles and responsibilities that stakeholders should have in place for agencies and AM functions to operate successfully (GAO, 2005). Executive leadership can determine the relationship between the roles and functional departments that work together to procure AM products and services. While the DoD does not have one governing agency that manages AM programs, its Service components can benefit from organizational alignment and leadership while adhering to common goals and objectives. We have identified critical success factors within each of the three elements that aid our assessment.

Element 1, Aligning Acquisition with Agency's Mission and Needs, describes the requirements to achieve an end goal in which acquisition functions fully support mission needs. To meet this goal, proper management must be in place to support AM stakeholders involved in acquiring AM products. AM acquisition functions should also strive to meet organizational goals and objectives by aligning efforts with leadership guidance and strategy. During our analysis we evaluate the following CSFs in this element:

- **Appropriate placement and ownership of AM acquisition functions**: This factor assesses the appropriateness of acquisition functions' locations within their overall organization. Good placement and priority of AM acquisition within an organization can contribute to achieving agency needs.
- **Organizing AM acquisition functions to operate strategically**: Leading organizations recognize that contracting and acquisitions are an integral part of business success, rather than merely a supporting role (GAO, 2005, p.4). We use this factor to determine how well DoD agencies include AM acquisitions into the larger organizational plan. AM acquisitions that are fragmented among units reflect poorly on the objective to achieve strategic goals outlined in the Department of Defense Additive Manufacturing Strategy (OUSD[R&E], 2021b).
- **Clear definition of AM's function and mission**: We use this factor to determine the extent to which agencies procuring AM are aware of branch-specific and/or DoD roles and responsibilities governing AM procurement. Concerns include unclear roles of AM acquisition, poor communication and cooperation between stakeholders seeking AM requirements, and inefficient operations resulting from stakeholder conflict (GAO, 2005, p. 6).

Element 2, Commitment from Leadership, encompasses the crucial role that leadership has on influencing the vision and direction of an organization. The GAO (2005) framework states that leaders have the responsibility to "set the corporate agenda, define and communicate the organization's values and culture, and remove barriers that block organizational change" (p.7). AM is still an emerging technology yet to achieve mass adoption in the DoD. The evolving landscape of AM poses a number of engineering, technological, and procurement concerns that must be addressed before the DoD can maximize its potential. Therefore, executive leadership is a critical component that must be in place to overcome these challenges while promoting the growth of AM acquisitions. We have identified three critical success factors within this element that closely align with leadership goals outlined in the *Department of Defense Additive Manufacturing Strategy* (OUSD[R&E], 2021b). These are clear prioritization of AM by leadership, effective top-down communication, and lack of leadership buy-in (GAO, 2005, p.7). We assess AM policy, guidance and interviews for each of these factors. They are described in more detail here:

- **Clear prioritization of AM by leadership**: This is reflected by whether senior leadership has implemented a strategic, integrated and agency wide vision for AM acquisitions. Since AM is used differently depending on unit need, prioritization can be difficult to determine. We identify prioritization based on the extent to which leadership continually supports efforts to develop common processes and approaches for AM. A unifying direction or vision regarding AM acquisitions should be defined and in use agency wide.
- **Effective communications and continuous improvement***:* This CSF highlights the importance of leadership's ability to effectively communicate AM acquisition plans and strategy to requirement owners and acquisition teams. Achieving this factor is determined by evidence of open lines of communication between AM users, acquisition personnel and leadership. Effectiveness also includes agency leadership's ability to listen to program units and affected stakeholders' needs and concerns, which may then contribute to policy and process revisions for AM acquisitions. Continuous improvement points to the use of performance measurements to better drive decisions regarding current performance levels, critical processes, goals for improvement, and long-term results (GAO, 2005, p. 9).
- **Leadership buy-in**: Increased AM adoption in the DoD requires an integrated approach to acquisition strategies in and between agencies (Naguy, 2016b). Leadership that enables stakeholders from program,

contracting, finance and human capital offices can enhance the overall acquisition of AM requirements. This level of buy-in is essential for DoD's push to further leverage AM's potential.

Element 3, Change Management, is derived from the research methodology by Dacanay et al. (2020) which expands on the GAO framework to further assess organizational leadership within CM. We include this element to capture two critical success factors needed by leadership to champion the adoption of a new technology and acquisition considerations that AM presents. These include identification of early adopters and lack of drive to challenge resistance by leadership, described here:

- **Early Adoption**: This factor, borrowed from Dacanay et al. (2020), points to units and agencies that exhibit credibility and expertise within AM acquisition functions. DoD publications and stakeholder interviews that reveal leaders in AM will assist our determination of early adopters. It is important for leadership to recognize which agencies excel in AM procurement to provide continued and focused support. Doing so will aid in further adoption of AM throughout the DoD.
- **Drive for change**: Early adopters and agency leaders should anticipate resistance to change and challenges that come with increased adoption of AM (Dacanay et al., 2020). Leadership unable to overcome resistance may inhibit the necessary momentum to align AM acquisitions to the overall *DoD AM Strategy* (OUSD[R&E], 2021b).

2. Cornerstone 2: Policies and Processes

Cornerstone 2 covers strategic decisions that lead to outcomes that agencies are seeking. Achieving them calls for clear and transparent policies and processes that can be applied consistently across an agency (GAO, 2005). The framework states that policies align management expectations with acquisition functions, and processes are the mechanisms that drive functions to better support agency goals (GAO, 2005). We use the three elements and their respective CSFs that we selected within each Cornerstone 2 element to assist our assessment of DoD AM guidance. Each element and CSF are described next. Like Cornerstone 1, elements below include areas to look for and areas of caution.

Planning Strategically (Element 1) explores the following CSFs: evidence of strategic direction, AM partnerships in and around the Air Force, internal and external impacts on AM requirements, and external collaboration efforts (GAO, 2005). Two overarching questions associated with this element from the GAO framework are, “Do stakeholders work together to develop a joint strategy for acquisitions?” (2004, p. 15), and “How does the agency promote coordination among the stakeholders as an acquisition moves through various steps in the process?” (2004, p. 15). These questions are addressed in our stakeholder interviews and targeted in our policy analysis. Our assessment of this element is focused on four CSFs:

- **Governing body or forum to establish strategic direction**: AM has been predominantly used for rapid prototyping and R&D efforts in the DoD. The shift to adopt other applications will require a unifying strategy that guides acquisition functions within Services and across the DoD. This factor helps identify lead agencies/units that provide governance for the projected increase of AM usage and procurement.
- **Partnership with internal organizations**: Leading organizations generally use a multidisciplinary approach to the overall acquisition process (GAO, 2005, p. 13). This requires all stakeholders to be engaged in the acquisition process to successfully support the mission. Typical multidisciplinary approaches to acquisitions incorporate functional support from contracting, program management, engineering SMEs, finance, legal, and for the purpose of this research - other appropriate DoD agencies associated with AM.
- **Assessing internal requirements and the impact of external events** (GAO, 2005, p. 14): This CSF encompasses agency wide needs, market research, assessment of core competencies and opportunities to acquire AM commercially, and identification of contracting methods to best meet user needs (GAO, 2005, p. 14). We assess this factor primarily through conducting a DoD spend analysis of AM goods and services. An effective acquisition agency is expected to analyze external events such as socioeconomic policy objectives, administrative initiatives, fiscal imbalances, and other factors outside of an acquisition agency’s control (GAO, 2005, p. 14).
- **AM collaboration efforts**: We use this factor to search for evidence of an integrated acquisition approach between DoD units that possess similar AM requirements. A lack of integration and collaboration indicates “redundancy, inconsistency, and an inability to leverage resources to meet shared requirements” (GAO, 2005, p. 14).

Element 2, Effectively Managing the Acquisition Process, addresses best practices required to plan, award, and manage a contract from cradle to grave. This includes processes that monitor cost, schedule and quality of contracted goods and services. We tailor select indicators from the critical success factors to assess how acquisition teams are currently procuring and managing AM-related products and services. They are:

- **Empowerment of cross-functional teams**: Leading organizations rely on cross-functional teams to ensure a requirement is developed, procured and managed effectively. This is accomplished by forming teams that include experts from an organization's purchasing unit, internal users of the good or service, and the budget or finance office (GAO, 2005, p. 16). Cross-functional teams are critical to the adoption of AM because of its evolving technology and vast application. Contracting functions will require increased support from external and internal SMEs to better acquire customer needs in this field. We use this factor to identify the extent at which agencies use cross-functional teams to perform AM acquisitions.
- **Managing and engaging suppliers**: The importance of supplier management is increased when acquiring new technology such as AM. The GAO framework supports this notion stating that leading organizations are more successful when their suppliers exhibit the ability to adapt to changing business conditions (GAO, 2005, p.17). Managing this relationship effectively can lead to lower costs and higher quality products or services. As captured in our literature review, mass AM acquisitions face multiple challenges including user and software supportability, machine obsolescence, and material uniformity. AM suppliers and manufacturers that are committed to addressing these issues can strengthen the supplier–buyer relationship and can lead to improved collaboration. Within this factor we look for evidence of AM supplier management.
- **Monitoring and oversight to achieve AM outcomes**: The DoD AM Strategy calls for a strategic sourcing approach to better leverage AM potential agency-wide (OUSD [R&E], 2021b). This effort cannot be accomplished without effective oversight and tracking of how the DoD acquires AM products and services. This factor places emphasis the nature of AM monitoring throughout the DoD. Caution areas include to what extent agencies monitor contract cost, schedule, quality, and performance requirements and whether agencies assign roles and responsibilities for overseeing AM contracts. Overall, we use this factor to examine how AM acquisitions have supported their intended use and agency mission.
- **Presence of AM operating procedures**: AM is used in a variety of ways across and within each DoD Service. Standardizing acquisition methods for like requirements and operating procedures for users can aid in increasing AM adoption. We use this factor to examine the presence of operating and acquisition procedures within AM acquisitions and to what extent they are used agency wide.

The final element of Cornerstone 2, Promoting Successful Outcomes of Major Projects (Element 3), is supported by employing investment strategies and knowledge-based acquisition approaches (GAO, 2005, p. 22). This element guides our assessment of select DoD investments to determine to what extent AM is integrated into the overall acquisition strategy of its projects. Key questions we adopt from the GAO framework include, "Are the agency's capital investments linked to and driven by its missions and long-term strategic goals?" (GAO, 2005, p. 22), and "What are the gaps between current and needed capabilities regarding AM in major projects?" (GAO, 2005, p. 23). Additionally, the framework states that, "…undesirable acquisition outcomes can be reduced when carefully adhering to knowledge points that help achieve cost, schedule, performance, and quality targets" (GAO, 2005, p. 25). We further assess some of the Air Force's major projects to understand how obtaining sufficient knowledge of AM can assist in meeting agency goals. We specifically look for evidence of the following CSFs:

- **AM capability gap are addressed**: This factor examines DoD agencies' current and future needs for AM capabilities. We search for whether agencies have identified the internal and external gaps regarding continued AM procurement. Internal gaps may include appropriate infrastructure to support AM equipment, and training programs for AM end users. External gaps may include vendor capability to provide long-term supportability to AM buyers. Addressing these gaps aid in future acquisitions' risk mitigation and overall value.
- **Performance tracking of AM assets and services**: We look for evidence of performance documentation and acquisition data from agencies that procure AM. An agency's ability to track AM performance may strengthen the case for continued AM use or the abandonment of other types (specific models, software, etc.). This factor aligns with the *DoD AM Strategy* objectives to develop metrics and measures of success and to expand proficiency in AM though learning, practicing, and sharing knowledge (OUSD[R&E], 2021b, p. 7).
- **Employing knowledge-based acquisition approaches**: Approaches include technology maturity (Knowledge Point 1), design stability (Knowledge Point 2), and production process maturity (Knowledge Point 3). Attaining these knowledge points are essential to achieving desirable acquisition outcomes and reducing program risk. We look for evidence that the DoD uses a knowledge-based approach to develop new products that integrate AM technology. We also look for evidence of lessons learned from unsuccessful AM program efforts, as this can improve future AM acquisition processes (GAO, 2005, p. 26).
- **Investments are made without strategic considerations to meet long-term and short-term AM objectives:** This factor serves as a caution to monitor AM acquisitions that do not meet agency or DoD strategy. DoD spend on AM R&D, for example, meets strategic goals to advance the

technology for improved and greater application agencywide. However, a unit purchasing a 3D printer without the proper integration into the AM ecosystem (provided by internal and external support agencies) may not meet desired goals and outcomes for AM advancement at the enterprise level (Naguy, 2016b).

3. Cornerstone 4: Data and Intelligence Management

Cornerstone 4 consists of three elements adopted from Dacanay et al: data integrity, data storage and safety, and data analysis (2020). Accurate data and effective management can inform agency leaders and category management teams on how the Air Force procures AM products and solutions. These elements are critical functions that support an agency's ability to make data-driven business decisions.

Element 1, Data Integrity, encompasses data management strategies that should be in place to accurately capture varied sources of data. A reliable information system should receive and share accurate and complete data. The CSFs within this element are defined by Dacanay et al. (2020) and are identified here:

> **Ownership of a data management strategy**: This practice allows agencies to manage relevant and comprehensible data and provide agencies with visibility, insight, and easy access to make well-informed decisions. (p. 53)
>
> **Ability to extract, cleanse, and organize data**: This practice allows agencies to easily select, strip errors, and organize data into a logical manner such as categories by fiscal year and so forth. (p. 53)
>
> **Ability to verify and validate data**: This practice ensures data reflected in the systems are reliable and can be trusted. (p. 53)
>
> **Identification of inaccurate data or poor data sources**: This area of concern inhibits agencies from rectifying inaccurate data from information systems and enhancing data input accuracy. (p. 53)

Element 2, Data Storage and Safety reflects an agency's ability to safeguard information systems used to store data. This element points to the use of internal control mechanisms that should be in place to promote good data management practices. The CSFs are identified and defined by Dacanay et al. (2020):

> **Ability to safeguard data:** This practice ensures agencies can control access to information systems and data plan security programs. (p. 53)
>
> **Accessibility issues exist:** This area of concern inhibits category management personnel who do not have proper clearances to access data. (p. 53)

Ability to safeguard data: This area of concern encompasses agencies who lack the ability to be proper stewards of data. (p. 54)

As presented in the Table 1 framework, this element was beyond the scope of this research and was not included in our final assessment. We assume that data storage and safety affect AM procurement just as much as any other acquisition and thus do not require further analysis to achieve our research objectives. However, we include this element in future areas of research to address important security issues involved with secure transfers of CAD files and digital blueprints used for 3D printing.

Element 3, Data Analysis, seeks evidence of tools and mechanisms that can transform data into meaningful information for decision makers. This element ensures the data can be translated into comprehensible information to inform better business decisions when acquiring AM solutions. The CSFs within this element are defined by Dacanay et al. (2020) and identified here:

Access to tools to visualize, analyze, interpret data: This practice allows category management personnel to have access to visualization and other business tools to perform data analysis and interpretation. (p. 54)

Ability to generate business intelligence and market intelligence products: This practice ensures agencies establish an office or capability to generate or facilitate business and market intelligence products and assist category management personnel in the collection, analysis and interpretation of business and market data. (p. 54)

Ability to develop and use business intelligence and market intelligence products to generate category management outcomes: This practice ensures category management personnel has the ability to perform data analysis such as but not limited to, CBA, category intelligence reports, spend analysis, market analysis, SME data analysis, and so forth. (p. 54)

Translation of data into a meaningful format: Agencies have mechanisms to accurately translate data into meaningful and understandable information to intended users to drive data-driven business decisions. (p. 54)

Ability to translate market and business intelligence into discernable acquisition actions and decisions: Lack of mechanism to translate business and market intelligence into discernable acquisition actions hinders key category management personnel in obtaining information needed to execute key category management actions such as developing enterprise solutions, demand management strategies and vendor management. (p. 54)

Applying this framework aids in assessing the Air Force's strengths and weaknesses across AM acquisition functions. Our complete assessment, informed by interviews with AM stakeholders, is used to shape our final product: recommendations that inform policy-makers on establishing an AM category management program, and considerations for developing future AM business models.

B. STAKEHOLDER INTERVIEWS

Our analysis of the DoD AM acquisition landscape is enriched with insights from AM-associated agencies. They were selected based on their current and past involvement in advancing AM adoption throughout the DoD. We interviewed the following AM leaders:

- Jason McDuffie, chief of Air Force Metals Tech Office (MTO) at Robins Air Force Base, GA
- Mike Froning, tech director for product support engineering at Wright-Patterson Air Force Base, OH
- John Hedke, director of engineering at Rapid Sustainment Office (RSO)
- Mark Benedict, lead for AM research across at Air Force Research Laboratory (AFRL)
- Adam Hicks, program manager, AM subject matter expert at AFRL
- Debora Naguy, project leader for Logistics in a Contested Environment at MITRE
- Eleanor Shelton, partner outreach specialist at National Center for Manufacturing Sciences (NCMS)
- John Wilczynski, executive director at America Makes, National Center for Defense Manufacturing and Machining (NCDMM)
- Joe Veranese, vice president and chief information officer at NCDMM
- MSgt Sharif Abouomar and SMSgt Joshua Huber, NDI Functional Manager, Air Mobility Command (AMC)
- SMSgt Joshua Bemis, Air Force Life Cycle Management Center (AFLCMC)
- Mr. Mark Surina, LMI, Transportation Command (TRANSCOM)
- Roger Westermeyer, director of Enterprise Solutions Support at Air Force Installation Contracting Center (AFICC)
- Brian Stitt, division head, University of Dayton Research Institute (UDRI): sustainment technologies transition

The interview questions were adapted from the critical success factors for cornerstone 1, 2, and 4 of the GAO (2005) framework. All agencies were asked the same set of questions, as follows:

1. How does your organization currently utilize AM technology?
2. Does your organization currently use a decision-making framework when acquiring AM-related products and services?
3. Has your organization identified a need for a DoD standard business model or acquisition strategy for AM? If so, please describe the need.
4. What factors has your organization identified for developers of the business model or acquisition strategy to consider?
5. What challenges has your organization experienced when procuring AM related products and services?
6. How does your organization currently procure AM technology?
7. Does your organization use a specific business model when procuring AM technology? If so, can you please explain it?
8. What issues or challenges has your organization experienced after procuring AM technology?

Our interview protocol was approved by the Naval Postgraduate School's institutional review board for a human subject research exemption. Interviewees agreed to be recorded and have their answers transcribed for the purpose of this research. We utilized the Acquisition Research Program for transcription services to consolidate the responses. The content from the interviews was qualitatively analyzed through the lens of the GAO framework and current DoD AM guidance. Our findings were used to inform our research questions and provide recommendations that can guide acquisition teams seeking AM requirements.

C. SPEND ANALYSIS

In their book *Spend Analysis: The Window into Strategic Sourcing*, authors Kirit Pandit and H. Marmanis (2008) characterize a successful spend analysis as one that incorporates the following components: data definition and loading (DDL); data cleansing, structure, and enrichment (DE); spend analytics (SA); and knowledgebase management (KB). We based our spend analysis upon such characteristics, following the general principles and guidelines found within each of these factors. As authors Pandit and Marmanis (2008) clearly state in their book, spend analysis is "the starting point of strategic sourcing and creates the foundation for spend visibility, compliance, and control" (p. 5). Our team's spend analysis primarily informs our secondary research questions, helping us observe the status of the Air Force's procurement of AM compared to other DoD agencies, as well as better determining whether the DoD's spend data aligns with Goals 1 and 2 of the *DoD AM Strategy*.

D. LIMITATIONS

Our methodology only utilizes three of the four cornerstones offered in the GAO framework for assessing acquisition functions. We chose Cornerstones 1, 2 and 4 (Organizational Alignment and Leadership, Policies and Processes Data Intelligence Management) as a starting point for this research. A full analysis covering the remaining Cornerstone (Human Capital) would be required to better understand the entire acquisition landscape that governs AM. Additionally, our methodology is limited to a select number of critical success factors and their indicators within Cornerstones 1, 2 and 4.

Our qualitative approach to assessing whether the Air Force meets critical success factors is subjective. Determination is largely based on repeated evidence of factors observed during interviews and policy analysis. Additionally, interview questions and protocol were restricted to guidelines that may have limited the possibility to conduct a full-blown assessment of AM operations. The number of interviewees and the nature of questions were influenced by institutional research policy. Thus, findings and recommendations are based on a limited assessment of DoD and Air Force practices.

It is important to note that AM contracting best practices are reflective of commercial and DoD agency bias. Each entity has a preferred method of participating in AM acquisition functions and is influenced by different factors specific to respective mission sets. However, combined into one framework, overarching and thematic contracting practices can better influence decision-makers in acquiring AM products and services. While each acquisition must be tailored to the requirement, our considerations should be used within a decision-making tool that can guide acquisition teams through key areas and challenges common to many AM acquisitions.

The fractured approach to AM procurement in the DoD presents an opportunity to apply category management principles. Effective use of these principles (aligning spend, assigning cost ownership, developing business intelligence, driving results) can "eliminate redundancies, increase efficiency, and deliver more value and savings from the Government's acquisition programs" (OMB M-19-13, 2019, p. 1). Other advantages are summed up in the OMB category management guidance memo which states, "Increasing the use of common solutions and practices will allow agencies to focus their attention on critical efforts to modernize our information technology (IT) systems; improve data, accountability, and transparency; and develop a workforce for the 21st century..." (OMB M-19-13, 2019, p. 2). While our methodology is designed to uncover strengths and weaknesses of Air Force AM acquisitions, it also serves as initial assessment of category management potential—primarily through the spend analysis and stakeholder interviews. However, our research is limited in scope regarding business intelligence and cost ownership of AM goods and services.

V. ANALYSIS, FINDINGS, AND RESULTS

A. GAO FRAMEWORK ANALYSIS

We begin the analysis by applying the GAO framework to stakeholder interview responses and AM policy documents. First, we assess Air Force AM acquisition practices for organizational alignment and leadership (Cornerstone 1) and then transition to policies and processes (Cornerstone 2) and data and intelligence management (Cornerstone 4). Our findings inform answers to our research questions and shape recommendations for future AM acquisition practices.

1. Cornerstone 1: Findings and Results

Our assessment of each CSF is consolidated in Table 2, which includes the positive areas (*) and areas of concern (!) that we discovered throughout our research. A positive area indicates that an agency is implementing practices which lead to desired outcomes of an effective acquisition function, while an area of caution points to high risk areas that leadership should focus on (GAO, 2005). Next, we present a narrative of our findings, guided by GAO framework indicators to help support our overall assessment. The section concludes with best acquisition practices that support various elements. We conduct the same steps for the remaining cornerstones.

Table 3. Cornerstone 1 Assessment: Organizational Alignment and Leadership

Element	Current State (*) Positive Area (!) Area of Caution
1. Aligning Acquisition with Agency's Mission and Needs	(*) Appropriate placement and ownership of AM acquisition functions (*) Organizing AM acquisition functions to operate strategically (!) Lack of clear definition of AM's function and mission
2. Commitment from Leadership	(*) Clear prioritization of AM by leadership (!) Ineffective communications and continuous improvement (*) Leadership buy-in
3. Change Management	(*) Identification of early adopters (*) Agency is open to culture change

a. Assessment of Air Force's Current State for Cornerstone 1

(1) Element 1: Aligning Acquisition with Agency's Mission and Needs

(*) Appropriate placement and ownership of AM acquisition functions

We conclude that the first CSF "Assuring Appropriate Placement of the Acquisition Function" is supported by two indicators from the GAO (2005) framework:

- "The acquisition function has been assigned the appropriate degree of responsibility and authority for strategic planning, management, and oversight of the agency's purchases of goods and services, and this responsibility is consistent with the significance of acquisition to the agency's missions" (p. 4).
- "Agency leaders view the acquisition function as a strategic asset in support of core agency missions and business processes" (p. 4).

Our interviews uncovered a top-down organizational structure of AM acquisition support throughout the Air Force—where select agencies with expertise advise units seeking AM solutions to tackle respective missions. The expert agencies are AFRL and RSO, both of which are connected to the JAMWG. The DoD AM vision and strategy are applied and advanced by the JAMWG. Together with the JAMWG, AFRL and RSO coordinate with other DoD stakeholders to mature AM applications, increase adoption, and provide support for operational activities that align with DoD AM goals. We find it sensible that the Air Force maintains its relationship with JAMWG for higher support regarding AM acquisition practices.

(*) Organizing AM acquisition functions to operate strategically

The second CSF within this element, "Organizing AM acquisition functions to operate strategically," is supported by the following indicator: "The acquisition function's mission is well-defined, and its vision for the future, core values, goals, and strategies are consistent with and support the agency's overall missions" (GAO, 2005, p. 5).

Our interviews with RSO, AFRL, MITRE, and NCMS all cite the DoD AM Strategy for 2021 as their guiding document for how they operate and how they plan to evolve to meet strategic goals. The strategy offers a clear vision for acquisitions: "The acquisition and industry community will be educated on how to appropriately use AM for system development, production and sustainment" (OUSD[R&E], 2021b, p. 7). The Air Force's Air Mobility Command (AMC) reflects this vision regarding sustainment and educating the workforce on AM. They noted in our interviews that AM purchases flow through the RSO for higher level vetting and requirement analysis. This practice occurs so that requiring units are aware of any limitations of the technology, and the high costs associated with facility modifications and sustainment needed for AM (Sharif Abouomar and Joshua Huber, NDI functional managers, interview with authors, July 23, 2021). The educational element in this example reflects the DoD AM Strategy and helps maintain standardization across system procurement offices seeking AM requirements.

The Additive Manufacturing Business Model Wargame I and II (NCMS, 2016, 2017) also contribute to meeting the CSF, "Organizing AM acquisitions functions to operate strategically." These wargames were conducted by DoD acquisition agencies and public–private organizations, including America Makes and Additive Manufacturing for Maintenance Operations (AMMO), with the ultimate goal of developing best practices to advancing AM adoption across the DoD. The wargames uncovered common areas that affect industry and government when procuring AM, some of which include IP and legal aspects, contracting vehicles, rent versus buy considerations, lack of tailored business models, and processes and training (NCMS, 2017). These areas evolved into considerations and best practices for acquisition teams to implement when seeking AM requirements, many of which are captured in the *Additive Manufacturing Contracting Guidebook—Phase II* (draft; NCMS, n.d.). Guidebooks and exercises such as the business model wargames display evidence that the Air Force and other AM stakeholders are operating within a consistent strategy that seeks to align AM goals with the greater vision stated in the *DoD AM Strategy* (OUSD[R&E], 2021b).

(!) Lack of clear definition of AM's function and mission

The final CSF, "Presence of a clear definition of AM's function and mission," is a caution area that we witnessed in an interview with AFRL. This is based on the following indicator: "Disconnects exist between where the acquisition function is placed in the agency's hierarchy and its role in achieving the agency's missions or supporting its operations" (GAO, 2005, p. 4). As a research lab, the AFRL does not acquire products or services, but rather funds efforts that seek to mature technology that can be applied within the military. Units collaborate with AFRL to determine whether AM capabilities would be a good fit for a specific application. While the ultimate decision to acquire AM is made by the requiring agency, technical expertise and requirement analysis is largely influenced by ARFL's council. AFRL stated that they take many calls from the field and that, "We have to say no a lot. We say yes when it makes sense. It is very much a coalition of participants who have standing relationships that can call on the expertise of AFRL and vice versa: we can reach back to them for requirements and demand signals" (Adam Hicks, Air Force ManTech roadmap lead for AM, interview with author, August 2, 2021). It was noted that a number of operational units were unaware of AFRL's role regarding AM, leading to possible inconsistences procuring AM products and services across the Air Force. While there is no requirement for acquisition agencies to contact AFRL, we believe it is good practice to do so to receive uniform counsel regarding AM procurement practices and technical expertise for requirement development.

(2) Element 2: Commitment from Leadership

(*) Clear prioritization of AM by leadership

The first CSF in this element is, "Clear prioritization of AM by leadership." Our assessment of the current state of Air Force AM acquisitions reflects two positive indicators that support the CSF:

- "Senior leadership promotes a strategic, integrated, and agencywide approach to acquisition" (GAO, 2005, p. 8).
- "Improvement initiatives involve stakeholders from across the agency" (GAO, 2005, p. 8).

Our interviews with MITRE and NCMS uncovered two large projects that involve multiple DoD stakeholders, including the Air Force, which seek to promote AM adoption through improved acquisition methods. The first project is being developed by MITRE and is called the Additive Manufacturing Marketplace (AMM). AMM is a digital platform that connects buyers seeking AM requirements with suppliers capable of providing the solution. It works as follows: The buyer accesses the AMM platform with a funded requirement, then submits an ordering form (essentially a Request for Quote) that is automatically sent to AMM-vetted sources throughout industry, academia, and government. This platform offers digital interaction between both parties to work out finer details of the requirement and move the process from purchase order to production. The AMM platform also has market research and requirement analysis tools for AM use in program acquisitions—prototyping, production, contract incentives, technical data package marking, and pricing considerations to name a few. AMM was designed with inputs from many agencies and represents a strategic approach to AM acquisitions. However, since this program is only in the beta phase, full rollout and DoD adoption is uncertain. The continued development of AMM is contingent on funding, resources, and program priorities within MITRE.

The second project is the *Additive Manufacturing Contracting Guidebook*, currently in draft version and being published by NCMS (draft; NCMS, n.d.). The guidebook is backed by lessons learned and inputs from AM stakeholders across industry, academia and government. It is comprised of contracting considerations common to all DoD agencies procuring AM and is intended to guide all future acquisition teams seeking 3D printed requirements. It includes business and revenue models, technical considerations (i.e., IP and TDPs), acquisition and contracting considerations, and a number of AM acquisition scenarios and sample contract schedules. Our research discovered that the draft version is currently in circulation with JAMWG stakeholders for refined verification and agency-specific inputs. For example, the Air Force may influence content pertaining to contracting scenarios about new weapons systems, sustainment phases of legacy systems, and part obsolescence; and the Marine Corps may influence AM scenarios related to their mission, such as a print-on-demand solutions for expeditionary requirements.

The GAO indicators support our findings and assessment that Air Force meets or is actively working towards this CSF. The two initiatives (AMM and the *AM Contracting Guidebook*) reflect leadership's priority in promoting a more uniform approach to AM acquisitions across the DoD. However, we think senior leadership should continue agencywide collaboration to ensure AM initiatives are pushed beyond beta phases and into the field for operational use by acquisition teams.

(!) Ineffective communications and continuous improvement

Outside of contracting guidebook revisions and updated strategy documents, we found little evidence of actual methods or techniques that have been implemented to track continuous improvement of AM procurement. On the contrary, our interviews and policy analysis uncovered caution areas pertaining to the lack of mechanisms in place to measure AM acquisition effectiveness and/or track performance measures to determine if objectives are being met. The following indicators support our assessment that this CSF remains underdeveloped:

- "The agency has inadequate policies, procedures, techniques, and mechanisms in place to ensure effective implementation of management directives" (GAO, 2005, p. 10).
- The agency has not implemented a program to continuously measure and assess the acquisition function's performance in supporting the agency's missions or achieving acquisition goal" (GAO, 2005, p. 10).

Our research into this CSF was largely guided by the goals promoted in the *DoD AM Strategy* that relate to acquisitions. The strategy, which seeks to address gaps found in the Inspector General report (DoDIG, 2019) and build on the *DoD AM Roadmap* (Fielding et. al., 2016), includes a couple of focus areas that directly encompass the importance of continuous improvement. The first is Area is 1.3: "Develop the metrics and measures of success," and the second is Area 1.4: "Develop and share new business models for AM in contracting and acquisition" (OUSD[R&E], 2021b, p. 20). While the strategy is fairly new, the push for improved processes and performance tracking is not. Therefore, we expected to see evidence of policies, techniques, and mechanisms in place that contributed to these objectives. However, interviews with AM acquisition agencies revealed that elements within those focus areas not present. Our interview question, "Does your organization use a specific business model when procuring AM technology?" received a common answer among all interview subjects: No standard business model exists, but one would be useful. AMC points to RSO and AFRL to develop a model backed with inputs and feedback from each Air Force major command (MAJCOM). AFRL, when asked whether a model or acquisition strategy would be useful, responded, "Yes, if that DoD standard business model or acquisition strategy was able to flow down into the way that the Air Force qualifies additive components for flight, or components in general" (Adam Hicks, Air Force ManTech roadmap lead for AM, interview with author, August 2, 2021).

AFRL shined light on the challenges of developing and using a business model to procure AM. The first being the acquisition of digital data for the components being 3D printed. They stated a model would first need to address digital data to include

> three-dimensional CAD models, material specifications, in some kind of a queryable and manageable way that will allow a business process to automatically route through required parts and parse out which are possible additive candidates, to where an engineer can dig through those down-selected components and provide insight into which are actual additive candidates. (Adam Hicks, Air Force ManTech roadmap lead for AM, interview with author, August 2, 2021).

This process is nearly impossible without proper data. The Air Force maintains aircraft that are more than 60 years old, which consist of parts that often do not have digital data or drawings available.

The other challenge with a model, according to AFRL, is the evolving technological landscape that could render a standard process or model obsolete. One insight is that:

> The landscape is changing so rapidly, it's difficult to keep up with what exactly additive is capable of producing. I would say five years ago, six years ago, if you were producing something in laser powder bed fusion, you had a bunch of supports, and it was accepted and they were going to be bulky, and you were going to have to do a bunch machining. But in the past couple years, there's been technologies that have arisen with the promise of, you know, almost no supports or free-floating parts, and that didn't exist even five years ago, which enables new components to be additively manufactured, which changes the ROI on additive versus other manufacturing processes. And because it's such a vibrant landscape, it's really hard to keep up with that in a process fashion. (Adam Hicks, Air Force ManTech roadmap lead for AM, interview with author, August 2, 2021)

Our research revealed that the majority of Air Force AM spend is concentrated around R&D. This supports the above claim made by AFRL that, due to the evolving nature of AM, a one-size-fits-all business model might not provide long-term value for acquisition teams. However, we still see the need for current business models and standard acquisition processes to avoid AM procurement failures as evidenced by MITRE. Our interview with MITRE highlighted cases in which operational units procured printers without a full understanding of the diverse range of industry capability and of the necessary training and capacity required to stand up the machines. This led to printers sitting in boxes, unused and requiring support that was not originally dictated in the contract.

AM is not a plug-and-play technology and must not be procured as such. It is a niche manufacturing process that still requires a human element to operate, and often ongoing support from the manufacturer to address new technological developments. The Air Force would be wise to continue developing business models and acquisition processes before wider adoption takes places across operational units. Doing so may prevent standardization and supportability issues common to DoD manufacturing operations (GAO, 2019).

(*) Leadership buy-in

We find that the last CSF in this element is present throughout Air Force AM acquisitions based on the following indicator: "Agency leadership listens to its program units and other affected parties' needs and concerns and remains open to revising acquisition processes as appropriate" (GAO, 2005, p. 9).

Interviews revealed that Air Force leadership is actively involved with promoting AM and exploring new avenues of AM applications. This is evidenced by the continued participation at AM tradeshows and industry events—the most prominent being the annual Military Additive Manufacturing Summit, where the most relevant topics are discussed and demonstrated by AM leaders in academia, government, and industry. The Military AM Summit in 2022, for example, will cover DoD initiatives for funding and investing in AM, integrating AM into the defense industrial base, 3D printing for aircraft and equipment maintenance, and innovative AM technologies enabling human space exploration (Defense Strategies Institute [DSI], n.d.). A keynote speaker for this event is Lieutenant General Shaun Q. Morris, commander of the AFLCMC Program Executive Office, Air Force RSO. Advocating for increased AM adoption at venues such as these directly reflects leadership buy-in. This practice was frequently brought up in interviews and described as a positive signal to AM practitioners and acquisition teams.

(3) Element 3: Change Management

The CSFs included in this element are adopted from category management best practices and included in our analysis to determine how well AM acquisitions are posed to implement a category management program. The presence of these factors may be useful for future assessments of category management viability and appropriateness. Additionally, category management for AM may be necessary to achieve the strategic levels of adoption that the DoD (OUSD[R&E], 2021) and Air Force envision (Naguy, 2016b). Our research uncovered two positive areas supporting change management:

(*) Identification of early adopters

We identified AFLCMC and the AFRL as potential early adopters for category management. Our literature review and interviews point to these two agencies as the most appropriate to develop a category management program. AFLCMC has oversight on the majority of current weapons systems utilizing AM, and AFRL has the expertise needed to track emerging developments in the field and integrate them into best practices for acquisition teams. Naguy (2016b) points to the credibility of these two agencies as she advocates for a collaborative, enterprise approach to AM implementation.

(*) Agency is open to culture change

Our interviews with AM stakeholders throughout the Air Force revealed positive signals for necessary management changes needed to implement a category management program. This is evidenced by the multiple CRADAs established between the DoD and industry to advance AM adoption. Examples of this include: NPS and Xerox (Schehl, 2021), RSO and General Electric (GE Additive, 2020), and the partnership agreement between the AFRL, America Makes, and University of Dayton Research Institute (UDRI; America Makes, 2020). Furthermore, the Enterprise Solutions Support office at the Air Force Installation Contracting Center (AFICC) has expressed the value in continued exploration of an AM category management program. These findings lead us to our final assessment that the Air Force is open to culture change and potentially a future category management program.

b. Best Practices

We consolidate best practices that support cornerstone 1 in Table 3. These are practices that were consistently pointed out in interviews or supported by written documents as positive areas that acquisition agencies and AM stakeholders would like to see continue.

Table 4. Cornerstone 1 Best Practices: Organizational Leadership

Element	Best Practices
1. Aligning Acquisition with Agency's Mission and Needs	• Strategic alignment with JAMWG • AM Business Model Wargames
2. Commitment from Leadership	• AM Marketplace • *AM Contracting Guidebook* • Strong Representation at Military AM Summit
3. Change Management	• CRADAs and partnerships • Exploration of category management for AM

2. Cornerstone 2: Findings and Results

Cornerstone 2 focuses on strategic considerations, governance structures, procedures, and plans that guide the current and future implementation of AM within the Air Force. This section has two parts: (1) an assessment of the Air Force's current state using CSFs outlined in the methodology, and (2) a list of best practices. Our assessment of each CSF, adapted from the GAO Framework (GAO, 2005) and CM Framework (Dacanay et al., 2020), is consolidated in Table 5, which includes the positive areas (*), areas of concern (!), and mixed findings of positive areas and areas of concern (*!) that we discovered throughout our research.

Table 5. Cornerstone 2 Assessment: Policies and Processes

Elements	Current State **(*) Positive Area (!) Areas of Caution (*!) Mixed Findings**
1. Strategic Planning	(*) Appointed a primary organization for establishing and implementing strategic direction (*) Partnered with other organizations within the Air Force (!) Lack of assessment of core requirements and the effect of outside events (*) Conducts AM collaboration efforts
2. Process Management	(*) Empowers AM cross-functional groups (*!) Manages and engages AM vendors (!) Lack of oversight to reach AM results (*) Existence of AM acquisition procedures
3. Outcomes Promotion	(*) Identified AM capability gaps (!) Performance tracking of AM assets and services (*) Employing knowledge-based acquisition approaches (*) Investments are made with strategic considerations to meet long-term and short-term AM objectives

a. Assessment of Air Force's Current State for Cornerstone 2

(1) Element 1: Strategic Planning

Element 1, Strategic Planning, is about managing and identifying AM process stakeholder relationships. In addition, it focuses on the need for a governing body to create and evaluate AM strategic direction to fulfill agency requirements. For this element, we identified the following positive areas (*), areas of caution (!) and mixed findings (*!):

(*) Appointed a primary organization for establishing and implementing strategic direction

Our research found that AM-related procurement in the Air Force is currently at the direction and discretion of the RSO. We learned that while major commands (MAJCOMS) have the discretion of acquiring AM-related products and/or services using their local acquisition office and procedures, they are still required to seek approval from the RSO. Currently, the RSO is the Air Force representative at the JAMWG. In addition, we found that AFLCMC/EZP utilizes the AMSIP to provide strategic guidance and address AM challenges within the Air Force. Air Force MTO, which falls under EZP, issued a series of AM Developmental Guidance Notifications in an effort to consolidate current and existing guidance and processes and increase AM awareness within the Air Force enterprise. AM Developmental Guidance Notification 19–002 states, "AFMC/CC appointed EZP as the lead within AFMC for enterprise implementation of AM" (McDuffie, 2019)

Based on these findings, we conclude that the Air Force is making conscious efforts to establish a governing body to provide AM strategic direction to MAJCOMS. We consider this a positive area.

(*) Partnered with other organizations within the Air Force

We found that the Air Force's efforts toward partnership with internal organizations are meet by the following positive area indicators from the GAO (2005) framework.

- "The agency has empowered stakeholders and holds them accountable for coordinating, integrating, and implementing effective acquisition decisions" (p. 14).
- "Stakeholders work on an ongoing basis to define key business and acquisition drivers and to understand each other's needs" (p. 14).
- "Lessons learned are identified and shared among stakeholders" (p. 14).
- "The agency has structures in place that require appropriate coordination among stakeholders developing and implementing acquisition strategies" (p. 14).

Our research found evidence that current Air Force initiatives toward AM-related procurement involve partnering with internal organizations to a certain extent. Our interviews and documents show the Air Force appointing an organization to direct AM-related decisions as well as the development of a strategic implementation plan. In addition, our interviews indicated stakeholder familiarity and working relationships with other internal organizations heavily involved in AM. We also found evidence of efforts to create and consolidate documents and information into a single database and make it available to stakeholders. AM-related products and services are currently being acquired using FAR and non-FAR based methods, so we assume that each acquisition followed procedures that required the engagement of all stakeholders.

(!) Lack of assessment of core requirements and the effect of outside events

Our research found that the Air Force assessment of internal AM requirements have areas of concern indicated by the following indicators from the GAO framework (2005):

- "The agency does not consider recurring purchases and develops acquisition plans that best leverage these acquisitions" (p. 15).
- "The agency lacks a strategic acquisition plan" (p. 16).
- "Acquisition planning is completed on a contract-by-contract basis rather than with consideration of agencywide needs" (p. 16).
- "The agency lacks data on the types of contracts used on procurement actions" (p. 16).

Our research found that there was a memorandum issued to coordinate AM equipment purchases over $100,000 (McDuffie, 2019). However, this is more to satisfy engineering requirements than as part of a strategic acquisition plan to gain efficiencies and cost savings on our purchases as an enterprise. Our research also found that some units purchase printers while some purchase services and have a contractor print parts. We did not find an acquisition framework that guides the decision on whether to purchase AM as a product, service, or hybrid. AM printers are commercially available and can be purchased from both large and small businesses. However, our interviews identified equipment support (repair, maintenance, training, etc.) issues from printers purchased from small businesses. Some small businesses lack the logistics and manpower capability to support AM printers. The Air Force may be able to meet its socioeconomic goals but without strategic acquisition plans, individual units may be stuck with printers that are broken or that no one knows how to use. Finally, our spend analysis revealed the difficulty in tracking Air Force AM purchases due to being mislabeled/miscategorized and having a separate database for GPC purchases. The Air Force's lack of current capability to track all AM purchases tied with the lack of strategic acquisition plan makes it difficult to assess whether appropriate contracting tools are being used.

Our research found that AM products are currently being purchased by individual units. We did not reach out to individual contracting units in the Air Force as it is outside the scope of our study thus we were unable to determine if the Air Force "appropriately selects among contracting tools available, including commercial item acquisition, performance-based contracting, and government purchase cards to best meet end-user needs in a cost-effective manner" (GAO, 2005, p.15). We were also unable to determine if "adequate and relevant data are available and are used to make strategic decisions about what work the agency should perform in-house and to identify opportunities to compete work with the private sector" (GAO, 2005, p.15).

Our research did not assess the impact of external events.

(*) Conducts AM collaboration efforts

Our research found that the Air Force conducts AM collaboration efforts with Air Force units, DoD, academia, industry, and MIIs. Interviews and literature reviews showed the Air Force issued CRADAs to industry, which aims to expand AM knowledge and explore AM applicability and capability using different materials. Also, the Air Force worked with America Makes, an MII, in awarding an $8 million cooperative agreement to UDRI to use AM in sustaining aircraft. Furthermore, the Air Force is a member of the JAMWG, which aims to maximize AM applications in support of the DoD mission. Finally, our interviews and documents indicated that units within the Air Force such as RSO, AMC, EZP, and MAJCOMS work together on AM efforts including aligning AM equipment purchases to "Air Force goals of standardization, interoperability, repeatability, efficiency, networking, and quality control" (McDuffie, 2019).

Based on these findings, we conclude that the Air Force conducts AM collaboration efforts to expand AM understanding and capability. We consider this a positive area.

(2) Element 2: Process Management

Element 2, Process Management, aims to ensure that agency processes are adequate so that purchases of AM-related products meet cost, schedule, quality, and quantity constraints. It also aims to ensure oversight of the whole AM acquisition process. For this element, we identified the following positive areas (*) and areas of caution (!):

(*) Empowers AM cross-functional groups

Our research found evidence that the Air Force empowers cross-functional teams, which is a positive area supported by the following indicators from the GAO (2005) framework:

- "The agency uses cross-functional teams to plan for and manage projects. These teams develop a project plan to implement projects effectively" (p. 17).
- "The agency systematically monitors project performance and establishes controls and incentives for accountability" (p. 17).
- "Project team members feel empowered to make decisions or invested in the project outcome" (p. 17).

Our research found evidence of the Air Force utilizing cross-functional teams to ensure that appropriate skillsets, knowledge, and technical expertise are utilized in the acquisition of AM-related products and services. From our interviews, we found that team members who utilize AM technology are knowledgeable on AM processes and procedures. They are articulate on the projects they are working on, familiar with existing partnerships with industry, and aware of current challenges with AM-related purchases. Interviews and documents also show efforts to develop and standardize guidance and procedures on AM, currently more towards printing parts, quality inspection, testing, and materials characterization. From an acquisition standpoint, there is evidence of vetting certain AM printers requirements for technical acceptability and AM-related purchases utilizing the expertise of local contracting units.

(!) Manages and engages AM vendors*

Our research showed evidence that the Air Force manage and engage with AM suppliers, which is a positive area supported by the following indicators from the GAO (2005) framework:

- "The agency takes full advantage of the suppliers' intellectual capital, such as design or product ideas" (p. 19).
- "The agency uses stringent supplier selection criteria while maintaining an appropriate level of competition among suppliers" (p. 18).
- "Knowledge of its key suppliers is shared across the agency" (p. 19).

Our research shows that the Air Force is trying to leverage the industry's AM knowledge and capabilities. We found partnership agreements with industry leaders in

AM. We also found that even partnerships with academia involve inputs from industry. There is also evidence of a coordination requirement for AM equipment purchases within a certain threshold and, depending on the criticality of items to be produced using the equipment, there are certain printer types prescribed, which translates into a stringent selection criterion. As mentioned previously, AM printers, including those prescribed for production of critical parts, are commercially available. Those that are not used for production of critical parts to include tabletop versions of the printer are also commercially available and some are even available for purchase on GSA.

Under this same CSF, our research showed areas of caution supported by the following indicators from the GAO framework (2005):

- "The agency makes limited or no use of commodity managers to manage the acquisition of AM goods and services" (p. 19).
- "The agency has not established commodity managers for AM goods and services" (p. 18).
- "The agency has not fully established an effective communication and feedback system with its suppliers" (p. 19).

Our research did not find established commodity managers for the acquisition of AM goods and services as purchases are currently being done by local contracting units. That being said, issues with regards to purchases of AM equipment including setup, maintenance, and repair are handled locally so the Air Force is unable to track recurring issues or trends and provide information to contracting units for consideration in their acquisition strategy.

(!) Lack of oversight to reach AM results

Based on these findings, we conclude that the Air Force lack monitoring and oversight to achieve AM outcomes in acquisition, which is an area of caution as the Air Force continues to explore AM capabilities. This conclusion is supported by the following indicators from the GAO framework (2005):

- "The agency does not monitor whether its contracts meet cost, schedule, performance, and quality requirements" (p. 20).
- "The agency monitors the effectiveness of policies and processes, completes a cost benefit analysis when considering alternative policies and

processes, and follows up on findings identified in monitoring efforts" (p. 20).

- "Personnel responsible for contract management have skills and knowledge gaps that inhibit their ability to properly oversee the types of contracts used by the agency" (p. 20).

As previously stated, our research found that the Air Force has established certain procedures for AM implementation and is currently using existing acquisition methods to purchase AM-related products and services at local units. Our research also found that the Air Force as an enterprise is currently not monitoring all AM-related purchases and have separate tracking systems for AM products and services purchased using a contract and purchased using a GPC. This creates a knowledge gap especially as the Air Force is still trying to understand AM capabilities. A finding from one of our interviews suggests supportability issues of AM printers bought from small businesses due to the small business' lack of in-house expertise or technical skills to set-up, maintain, and/or repair the product. Identifying these issues as an enterprise can be a challenge and create knowledge gaps within the workforce. Finally, we found no evidence of CBA currently being done to assess the benefits of AM compared to TM.

(*) Existence of AM acquisition procedures

Our research found that the Air Force is utilizing existing acquisition procedures in purchasing AM-related parts and services. We also found that different contracting techniques and vehicles, FAR and non-FAR based, are being used to acquire the products and services needed. Some units that are still in the process of discovering AM capabilities are using CRADAs, some units are essentially acquiring AM as a service and sending requirements for contractors to print, and some utilize simplified acquisition procedures to purchase AM equipment. We conclude that the existence of AM acquisition procedures is a positive area.

(3) Element 3: Outcomes Promotion of AM Initiatives

Element 3, Outcomes Promotion of AM Initiatives, aims to focus on the analysis, support, and review, typically required on capital investment projects and research and apply it to AM as we continue to invest hours and funds in understanding and developing

AM capabilities. For this element, we identified the following positive areas (*) and areas of caution (!):

(*) Identified AM capability gaps

Our research found that with evolving AM technology, the Air Force is still working on identifying AM capability gaps-primarily on the technical side. Evidence of that is the CRADA between the Air Force and General Electric. Our interviews and literature reviews indicated awareness of the existence of these capability gaps and willingness to understand and bridge them. Evidence of this is Debbie Naguy's (2016b) article, which identified challenges in implementing AM. Some of the challenges identified in the article are same as the challenges identified in the Air Force's MTO office's memorandum released in 2019 that listed current AM challenges (McDuffie, 2019). As far as acquisition capabilities are concerned, we have the tools to meet AM requirements. It is just a matter of figuring out if the Air Force wants to take it a step further and manage AM product and services acquisition as an enterprise. Based on these findings, we conclude that the Air Force's AM capability gaps identification initiatives are a positive area.

(!) Performance tracking of AM assets and services

As previously mentioned, our research found no evidence of centralized tracking of AM equipment and services or AM initiatives within the Air Force. This makes the analysis of aggregate acquisition difficult. Without proper analysis on current status and capabilities, to include challenges and best practices, it is hard for the Air Force to provide support to local units. Our spend analysis also indicated some AM buys miscategorized, which makes it difficult to track dollars spent on AM equipment and services. Based on these findings, we conclude that the Air Force's performance tracking of AM assets and services is an area of caution.

(*) Employing knowledge-based acquisition approaches

We found evidence that the Air Force is employing knowledge-based acquisition approaches, which is supported by the following indicator from the GAO (2005) framework, "The agency embodies a knowledge-based approach to acquisition that is reinforced in its policies, implemented in its processes, reflected in individual acquisition decisions, and demonstrated through knowledge-based deliverables" (p. 26).

The GAO (2005) framework states, "Undesirable acquisition outcomes often occur...because agency officials proceed further into development or production without obtaining sufficient knowledge that the product will be able to meet established cost, schedule, performance, and quality targets " (p. 25). Our research found multiple pieces of evidence that the Air Force is trying to get as much knowledge and understanding of the AM process as possible. As previously mentioned, the Air Force works with industry and academia to learn more about capabilities and explore potentials of AM using CRADAs and partnership agreements. While efforts are primarily directed towards the technical aspect of AM, we found gaining interest in the acquisition community. AM related purchases are currently done using FAR and non-FAR based methods, as appropriate on the type of requirement. Also, previously mentioned is that the Air Force is using existing acquisition procedures to purchase AM products and services. Gaining interest within the acquisition community could mean using knowledge found in existing and future efforts to review existing policies and procedures and adjusting as needed.

(*) Investments are made with strategic considerations to meet long-term and short-term AM objectives

We found through interviews and spend analysis that the Air Force already made investments in the acquisition of AM equipment and services. Investments were made through partnerships with industry and academia to further the understanding of AM capabilities. Examples include previously mentioned CRADA with GE and partnership agreement with UDRI. In addition, the Air National Guard utilized strategic financing (STRATFI) to overcome the challenges faced by startups when transitioning the use of technology into a program of record (Fetter, 2020). It works by utilizing the SBIR program wherein funds committed by units investing in the growth of the technology, in this case AM, are matched, which attracts venture capital investments from the private sector (Fetter, 2020). This effort "raised $45.5 million from the private sector, which results in a combined $72 million spread across a four-year contract that will bolster the logistical chain and cybersecurity of the company's machine and "ruggedize" it for expeditionary operations" (Fetter, 2020). As previously mentioned, there are still a lot of unknowns when it comes to AM capabilities and how it fits in Air Force processes. Investments toward understanding AM and training/familiarizing military personnel on this technology is a step towards the right direction.

b. Best Practices

We consolidate best practices that support Cornerstone 2 in Table 6. These are practices that were consistently pointed out in interviews or supported by written documents as positive areas that acquisition agencies and AM stakeholders would like to see continue.

Table 6. Cornerstone 2 Best Practices: Policies and Processes

Elements	Best Practices
1. Strategic Planning	• Identifying a governing body for AM-related questions and decisions early in the process • Collaboration with industry and academia (CRADAs and partnership agreements)
2. Process Management	• Empowering experts and members of cross-functional teams • Flexibility in acquisition methods
3. Successful Outcomes Promotion	• Ability to use FAR and non-FAR based acquisition methods depending on the requirement • Working with industry and academia in identifying AM capability gaps

3. Cornerstone 4: Findings and Results

a. Assessment of Air Force's Current State for Cornerstone 4

We consolidate best practices that support Cornerstone 2 in Table 5. These are practices that were consistently pointed out in interviews or supported by written documents as positive areas that acquisition agencies and AM stakeholders would like to see continue.

The final assessment covers data and intelligence management. This section discusses the current state of AM using two elements from the Dacanay et al.'s (2020) framework (data integrity and data analysis). Each element will briefly cover CSFs since a full analysis is covered in Section B of this chapter. A consolidated assessment of each

CSF is listed in Table 7. We reference FPDS-NG and AFBIT Lite throughout our assessment of cornerstone 4 and in the spend analysis section. Definitions of each are included here:

Federal Procurement Data System-Next Generation (FPDS-NG): FPDS-NG is the authoritative data source for federal acquisitions. It serves as a searchable repository of contract data reported from various contract writing systems across the U.S. Government.

Air Force Business Intelligence Tool (AFBIT) Lite—AFBIT Lite is a website that offers searchable dashboards using a data visualization tool called Tableau. It is maintained by AFICC and summarizes U.S. Government spend over the past 5 years. Those seeking quick insight into Government procurement data can use AFBIT Lite to narrow down searches based on agency, PSC, NAICS and other filters. It also includes monthly spend, small business spends, and proximity of buyers within a certain location.

Table 7. Cornerstone 4 Assessment: Data and Intelligence Management. Adapted from Dacanay et al. (2020).

Elements	Current State (*) Positive Area (!) Area of Caution
1. Data Integrity	(!) Inability to track accurate AM procurement data (*) "Ability to extract, cleanse, and organize data" (Dacanay et al., 2020, p. 46). (!) "Ability to verify and validate data" (Dacanay et al., 2020, p. 46). (*) "Identification of inaccurate data or poor data sources" (Dacanay et al., 2020, p. 46).
2. Data Analysis	(*) "Access to tools to visualize, analyze, interpret data" (Dacanay et al., 2020, p. 46). (!) Inability to generate BI/MI products (*) "Ability to develop and use BI/MI products to generate category management outcomes" (Dacanay et al., 2020, p. 46). (!) Limited ability to translate data into meaningful format

(1) Element 1: Data Integrity

Data integrity refers to an agency's ability to ensure that data can be captured and used accurately across various sources. In the context of acquisitions, an example could be contract data that administrators input into a contract action report to capture various pieces of information to describe the nature of a contract—how much is spent, on what, how many, by whom, and so forth. The data then flows to a database that consolidates inputs from thousands of actions that occur daily across the government. To be useful for decision-makers, data must then be stored on an information system that reflects complete, organized, and reliable data.

Our spend analysis combined with stakeholder interviews revealed positive areas and areas of caution when identifying CSFs:

(!) Inability to track accurate AM procurement data

All agencies that procure AM are subject to the same data management strategy as non-AM procurement teams. Similar challenges exist regarding transparency and accuracy of AM contracting data. This lack of visibility, insight and accessibility to data may lead to ununiformed management decisions.

One of the key category management actions is to, "share data across the Federal Government to differentiate quality and value of products and services in making buying decisions" (OMB, 2019, p.3). We found that neither the Air Force or DoD utilize devoted fields for tracking AM acquisition data and performance within an information system. Useful AM procurement data is not shared or tracked among agencies. An example brought up during stakeholder interviews is the that the Air Force is not tracking how many 3D printers are owned or leased, or what decision factors went into procuring AM as a product or service.

The lack of data makes it difficult to determine optimal strategies for future AM purchases by teams seeking spend data or lessons learned. This is supported by the OMB category management memo. It highlights that sharing price and other procurement data of similar goods and services (prices paid, terms and conditions, practices) routinely result in best contract outcomes (OMB, 2019, p.10). Our research did not reveal an AM data strategy that is used enterprise wide in the Air Force. Therefore, we assess the original CSF (ownership of a data management strategy) to be a caution area.

(*) Ability to extract, cleanse, and organize data

Currently FPDS-NG is the main information system that can be used to extract and cleanse federal government procurement data. AFBIT Lite is better suited to organize and view data. We found that the Tableau-powered dashboards in AFBIT Lite to be the most useful business intelligence tool for gaining quick insights into government spend. However, AFBIT Lite is backed by FPDS-NG and contract action report data that may include errors, possibly offering incomplete or inaccurate spend data. These challenges exist DoD-wide, and should not be attributed to acquisition teams procuring AM. We believe this CSF should be addressed as both a caution and positive area.

(!) Ability to verify & validate data

Data in FPDS-NG can be trusted because it is the authoritative source used by the federal government. While prone to human error, it is the best source currently in use by all federal agencies. While inaccuracies may exist based on human error inputting data, the information system as a whole is the main source used to research and make inferences on government spend. However, in the context of AM, we asses this CSF as a caution error. Inaccurate AM spend data may be caused by an unsuitable selection of Product and Service Codes (PSCs) and North American Industry Classification System codes (NAICS). The PSC indicates what was bought for each contract action reported in FPDS-NG. The NAICS is used to categorize businesses based on the type of activity they are engaged in. We found that both codes are not equipped to capture various types of AM usage (products, services, R&D, material).

(*) Identification of inaccurate data or poor data sources

The Air Force is moving towards improved methods of addressing data equipment and security. We uncovered a positive area that supports this CSF—the establishment and use of the joint AM model exchange (JAMMEX). JAMMEX is a portal that allows sharing of approved AM data sets between DoD agencies seeking 3D printed solutions. In terms of data management and security, new policy calls for AM agencies to "Provide safe and secure interoperable digital business information and data systems, including, but not limited to, JAMMEX to support use of AM across the entire life cycle that enables sharing and exchange of data between DoD and its suppliers, including small businesses" (p.13, DoDI 5000.93, 2021). Our interviews with AM stakeholders reveal that the use of JAMMEX is growing in use and popularity.

(2) Element 2: Data Analysis

Data analysis is defined as "a process of inspecting, cleansing, transforming, and modelling data with the goal of discovering useful information, informing conclusions, and supporting decision-making" (Kudyba, 2014). It requires tools to help analyze and visualize large amount of data. In addition, it requires personnel who have access to data, knowledgeable in data cleansing, have access to data analysis tools, and have the knowledge and skills to use the tools to produce products that are not only visually appealing but also formatted in a way that is easy to understand and conveys the appropriate information.

Our spend analysis combined with stakeholder interviews and literature reviews revealed positive areas (*) and areas of caution (!) for the following CSFs:

(*) Access to tools to visualize, analyze, interpret data

The Air Force has access to tools to visualize, analyze, and interpret data. Air Force Business Intelligence Tool (AFBIT) Lite are dashboards that summarize Air Force spend for up to 5 years It is the primary visualization tool for acquisition data and is maintained by the AFICC (ACE for Services, n.d.). Both AFBIT Lite and the full version have five years of data. The full version is updated quarterly while the Lite version is updated a quarter later for contract competition sensitivity (ACE for Services, n.d.). Both AFBIT Lite and the full version "show other organizations buying like items or services, monthly spend and small business spend, proximity of other buyers to your location (or any location on a map)" (ACE for Services, n.d.).

In addition to AFBIT full version and Lite, Excel has the basic functions needed to generate graphs, tables, and charts. Most government computers have license to use

Excel. There are other data visualization tools such as Google Charts, Tableau, and Infogram but some of these tools are not free to use.

(!) Ability to generate BI/MI products

The Air Force has the ability to generate BI/MI products just as it has access to data analysis and visualization tools. Areas of caution include issues that could affect the Air Force's ability to generate BI/MI products such as access to data; quality of data; computer bandwidth to generate, cleanse, and house the data; personnel shortage; and personnel knowledge on BI/MI. Not every unit in the Air Force will have the ability to generate BI/MI products, especially smaller units as they will be restricted by one or more of the issues mentioned.

(*) Ability to develop and use BI/MI products to generate category management outcomes

AFICC has an office dedicated to developing and generating BI/MI products to generate category management outcomes. Although the ability is there, the speed and amount of products generated may be limited due to constraints in resources. In that case, the Air Force has access to educational institutions such as the Air Force Institute of Technology (AFIT) and Naval Postgraduate School (NPS) that may be able help.

(!) Translation of data into meaningful format

The Air Force has the ability to translate data into a format. Whether that is meaningful or not will depend on factors such as articulating clearly what the data will be used for. understanding what the data will be used for, personnel having knowledge on data analysis, and personnel having the ability to relay the information in a way that makes sense. Some of these factors require education and/or training on data analysis and data visualization. Not every acquisition practitioner has that education and/or training.

b. Best Practices

We consolidate best practices that support Cornerstone 4 in Table 8. These are practices that were consistently pointed out in interviews or supported by written documents as positive areas that acquisition agencies and AM stakeholders would like to see continue.

Table 8. Cornerstone 4 Best Practices: Data and Intelligence Management

Elements	Best Practices
1. Data Integrity	• Identifying a governing body for AM related questions and decisions early in the process
2. Data Analysis	• Availability of visualization and data analytics tools • Empowering experts and members of cross-functional teams

Best practices from Cornerstones 1,2, and 4 are consolidated in the final chapter. The next section builds off Cornerstone 4 and contains our analysis of DoD AM spend during FYs 2017–2020.

B. SPEND ANALYSIS

1. Spend Analysis Overview Objectives

The goal of our spend analysis was to evaluate pertinent data to address the following two overarching research questions:

- Question 1: How is the Air Force purchasing AM compared to other DoD agencies?
- Question 2: Is the DoD meeting the intent of the acquisition Goals 1 and 2 of the Department of Defense Additive Manufacturing Strategy (OUSD[R&E], 2021b)?
    - Goal 1: Integrate AM into the DoD and the defense industrial base
    - Goal 2: Align AM activities across the DoD and external partners

We analyzed the following two main data sets in order to conduct the spend analysis:

Federal Procurement Data System – Next Generation (FPDS-NG): This data set includes only Air Force contractual actions and is limited solely to fiscal years (FYs) 2017–2019.

AFBIT Lite: This data set includes Air Force, Army, and Naval contractual actions and is limited solely to fiscal years (FYs) 2019–2020.

2. Limitations

Our team made a few assumptions regarding the FPDS-NG and AFBIT Lite figures that imposed certain limitations on our ability to interpret and conduct analysis of the data. First, the DoD data for FY2019 within AFBIT Lite was incomplete, resulting in the removal of values that appeared as "Null," which comprised approximately 14% of total contract actions in that respective repository. Secondly, our team assumed that the PSCs and the "Description" input for each contract action were accurately updated into the data repositories. Also, it is important to note that AM-related materials purchased with the GPC are not included in these data sets; our data are therefore limited to AM-related products and materials procured via contractual methods. This assumption may have led to 3-D printers, raw material, and other AM-related purchases under the micro-purchase threshold to be excluded.

Lastly, it is important to note that our two data sets (AFBIT Lite and FPDS-NG) cover different fiscal years and agencies. The AFBIT Lite data set was limited solely to FY19–FY20 and comprised Air Force, Army, and Navy spend data used to compare AM spending across the services. The FPDS-NG data set was limited to FY17–FY19 and only included Air Force spend data but allowed us to look deeper into Air Force spending. This explains the large spending difference between our data sets, as FPDS-NG only shows data for one single agency. This results in our assessments of Air Force AM spending trends compared to those found in the Army and Navy being limited to solely FY19 and FY20. In the following section, we discuss the methods of data cleansing utilized, which we believe helped improve the accuracy of our data.

3. Methodology for Data Set Cleansing

a. FPDS-NG Data Set

To execute a spend analysis using FPDS-NG data, our team first decided to identify the PSCs most commonly utilized within the AM industry. A PSC is defined as "a four-digit code used by all federal government contracting activities for identifying and classifying the services, supplies and equipment that are purchased under contract" (Air Force Medical Operations Agency, 2019, p. 23). In order to select PSCs, we input key AM terms into the ezSearch tool at fpds.gov as well as utilized GovShop on the Public Spend Forum to survey contracting data related to AM. The ezSearch tool is a search interface that allows users to explore individual transactions found within the Federal Procurement Data System (FPDS) such as definitive contracts, task orders, and purchase orders (Federal Compass, 2019). The Public Spend Forum, founded by entrepreneur Raj Sharma in 2013, is a "public sector procurement global community and market intelligence platform dedicated to improving public buying everywhere" (Clinton, 2021, para. 1). GovShop is Public Spend Forum's AI-enabled, free-to-use research tool that provides its users with advanced market intelligence regarding suppliers (Clinton, 2021). Through surveying both databases we identified four PSCs as the codes most consistently utilized/listed with the AM-related contract actions we sought to capture, two tailored to 3D Printers and two for AM-related raw materials. Below are the four PSCs with their respective descriptions:

3610 – Printing, Duplicating, and Bookbinding Equipment
3695 – Miscellaneous Special Industry Machinery
9630 – Additive Metal Materials,
9330 – Plastics Fabricated Materials.

We then applied a filter to our FPDS-NG data set based upon these four PSCs. However, when doing this we found that PSCs 3610 and 3695 encompassed much more than 3D printing/AM material, preventing us from capturing solely AM-related purchases. For example, the federal category of PSC 3695 included many traditional machinery items that are not related to AM at all. We also discovered that only one PSC exists within the entire PSC manual that is explicitly tailored toward AM, PSC 9630 Additive Materials. Such findings indicated that solely using these PSCs to filter our data sets for AM-related purchases could not serve as an accurate methodology in organizing the data sets to capture AM spending.

In response to this, our team jointly developed a data cleansing methodology in close coordination with NPS faculty, an approach based primarily off data cleansing principles found in authors Kirit Pandit and Haralambos Marmanis' (2008) book, Spend Analysis: The Window into Strategic Sourcing. Our methodology stipulated the tracking/ filtering of certain designated fields we felt best related to our desired research questions (Refer to Appendix C for all criteria). Moreover, since PSCs were found to be inadequate in pinpointing AM-specific inputs within the data repositories, we were forced to create and apply a key terms filter to descriptions to identify AM-related data points in our FPDS-NG data set instead of a filter based upon PSCs. Once we applied this filter, we were forced to then conduct a line-by-line analysis of the "Description" column for each contract action to ensure that all data was truly AM-related, further deleting line items that possessed ambiguous descriptions or ones completely unrelated to AM (refer to Step 9). Table 9 shows the exact step-by-step process of the methodology we utilized to cleanse the FPDS-NG data.

Table 9. FPDS-NG Data Cleansing Methodology. Adapted from Pandit and Marmanis (2008).

1	Complete FPDS-NG Data – All contract actions for FY2017 – FY2019
2	Identify Necessary Columns and compile all data into single spreadsheet
3	Apply Designated Key Term Filter on "Description" Column (See Appendix C for all terms used)
4	Sort data smallest to largest numerically by "Dollars Obligated" Column
5	Remove all Contract Actions with "Dollars Obligated" < or = 0
6	Manually remove all remaining line items with "Description" column that is implicitly not related to AM
7	Re-sort data first to last (alphabetic/numeric) by PSC
8	Create additional "Description" Column with one of the four new Category Designations per PSC/Description Analysis
9	De-conflict line items with vague PSCs and Descriptions (i.e., When Description column is clear, grant preference to Description and categorize contract action according to "Description" column, if unclear when compared to PSC, remove line item completely)

The overall FPDS-NG data set started at 356,362 contract actions totaling $210 billion in spend. After applying our team's data cleansing methodology, the results showed 185 contract actions and approximately $46.8 million in total spend. The relatively small total number of contract actions combined with a three-member team enabled the manual aspects of our developed FPDS-NG Data Cleanse Methodology. Through this rigorous process, we found that a total of 48 PSCs were used in classifying the 185 AM-related contract actions that remained in our data set. Figure 11 gives a quick, easy-to-read breakdown of the impact on the data after our FPDS-NG data cleanse methodology was applied to it.

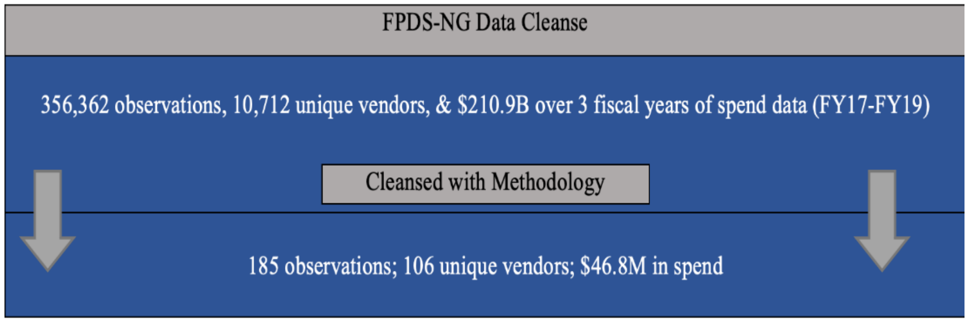

Figure 11. FPDS-NG Data Cleanse Results. Adapted from Air Force Medical Operations Agency (2019).

b. AFBIT Lite Data Set

To conduct a spend analysis over the AFBIT Lite data set, our team applied a similar data cleansing methodology to that applied on the FPDS-NG data set, with one key difference and some minor variances. First, the key difference is that instead of applying the key terms filter used on the FPDS-NG data set, we filtered the AFBIT Lite data set by the 48 PSCs we identified in the already-cleansed FPDS-NG data set mentioned in the previous section. Our methodology stipulated the tracking/filtering of all the same fields applied to the FPDS-NG data with the addition of "Small Business Determination" and "Extent Competed" columns. Table 11 shows the step-by-step process of the methodology utilized to cleanse the AFBIT Lite data set, with step 3 representing the key difference between cleansing methodologies imposed on our two data sets.

Table 11. AFBIT Lite Data Cleanse Methodology. Adapted from Pandit and Marmanis. (2008).

AFBIT Lite Data Cleanse	
1	Complete AFBIT Life Data – All contract actions for FY2019-FY2020
2	Identify Necessary Columns and compile all data into single spreadsheet
3	Apply Designated PSC filter on data set (See Table 9 for full list of PSCs)
4	Sort data smallest to largest numerically by "Dollars Obligated" Column
5	Remove all Contract Actions with "Dollars Obligated" < or = 0
6	Manually remove all remaining line items with "Description" column that is implicitly not related to AM
7	Re-sort data first to last (alphabetic/numeric) by PSC
8	Create additional "Description" Column with one of the four new Category Designations per PSC/Description Analysis
9	De-conflict line items with vague PSC and Descriptions i.e. (When Description column is clear, grant preference to Description & categorize contract action according to "Description" column, if unclear when compared to PSC, remove line item completely)

The overall AFBIT Lite data set started at 112,884 contract actions totaling $655.2 billion in spend. After applying our team's data cleansing methodology, the results showed 326 contract actions and approximately $81.6 million in total spend. Similar to the FPDS-NG data set, the relatively small total number of contract actions combined with a three-member team of researchers enabled the feasibility and accuracy of the manual line-by-line analysis we conducted on all data points resulting from the PSC filter. Once again, we were forced to do this line-by-line comparison in order to ensure the data points actually represented AM procurements, as only one PSC code (9630) explicitly states that it is AM. Figure 12 gives a quick, easy-to-read breakdown of the impact made on the data after the AFBIT Lite data cleanse methodology was applied.

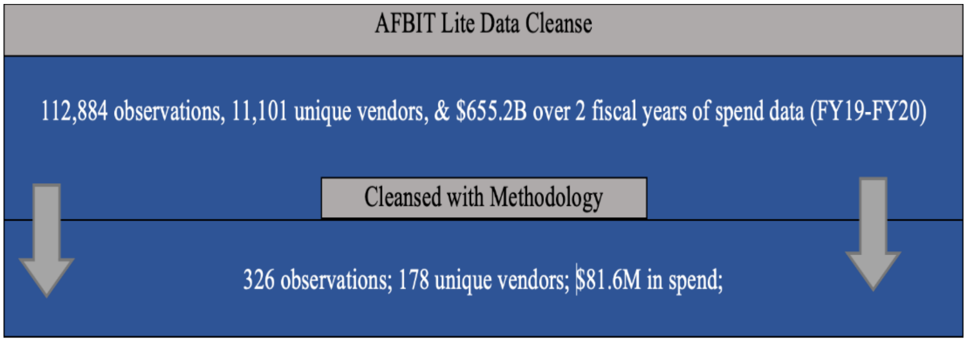

Figure 12. AFBIT Lite Data Cleanse Results. Adapted from Air Force Medical Operations Agency (2019).

4. Category of Spend Determination and Product Service Codes

CM is "a structured approach to create common categories of products and services that enable the Federal Government to eliminate redundancies, increase efficiency and effectiveness, and boost satisfaction with the products and services we deliver" (Bullock, 2017, p. 14). Due to recent congressional mandates and senior leadership's buy-in regarding the principles and benefits of category management, our team thought it necessary to create categories of spend for the FPDS-NG and AFBIT Lite data sets to gain deeper insight into key spending trends and behaviors, vendor segmentation, and the overall state of AM technology within the DoD.

To create common categories of AM spend, we assessed the 48 PSCs mentioned earlier, identifying each of their definitions in the October 2020 PSC manual and compared them to each contract action's individual descriptions (see step 8 of data cleansing methodologies). Based upon the nature of the PSCs used and descriptions given for each contract action, we cataloged all AM-related data points (FPDS-NG and AFBIT Lite data) into the following four categories of spend:

1. Research & Development
2. 3D Printers & Scanners
3. Maintenance & Support Services
4. Raw Materials

If a certain PSC did not correctly align with the description of the contract action, we gave preference to the description provided. Our thesis team determined on a case-by-case basis if the description of the contract line item was clear enough to be included in one of the categories. If the description provided was not clear or was unrelated to AM, we excluded the data point. If the description was clear and made logical sense when compared to the obligated amount of the contract action, we included the data point and categorized it under the appropriate PSC designation. As seen in Table 10, the PSC code and description of the contract item only occurred contradicted with a total of two data points under the "Maintenance & Support Services" category, with PSCs 7030 and 6760 (highlighted in yellow) being linked to actions that should have instead possessed a service PSC. Table 10 displays the four categories of spend we created and the PSCs that correlated with each respective category.

Table 10. Categories of Spend and PSC Designation

Category of Spend	Product Service Code
Research & Development	AE32 AD21 AE34 AD22 AD91 AD92 AD95 AC11 AJ12 AC12 AJ43 AC21 AC22 AZ11 AC51 AZ12 AC61 AZ14 AC62 AZ15 AC63 AC92
Printers & Scanners	3419 3590 3610 3620 3695 6110 6515 6520 6640 6740 6940 7010 7025 7035 7050
Maintenance & Support Services	7030 J035 J059 J070 J099 H970 6760
Raw Materials	3695, 3610, 9630, 9330

It is important to note that while the previous four categories of spend were created independently by our team via our developed data cleansing methodology, the chosen categories closely mirror the commercial industry's current segmentation of AM products and services. For example, the 2021 Industry Report published by IBIS World (Kennedy, 2021) identifies the following three categories of revenue within the AM industry:

1. Primary production of 3D printers
2. Secondary production including build materials
3. Maintenance and services

Figure 13 provides a breakdown of revenue percentages for each of these respective categories in the commercial 3D printer manufacturing industry (Kennedy, 2021).

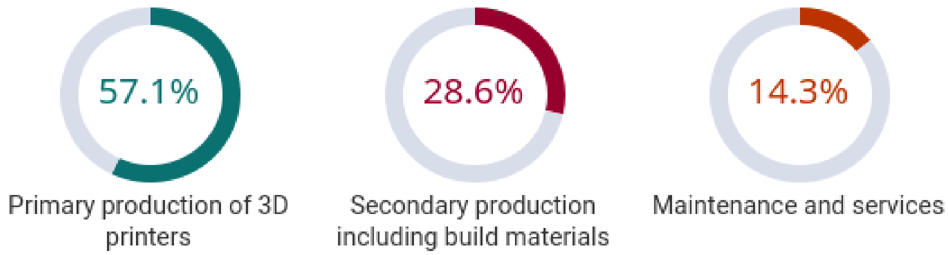

Figure 13. Segmentation of the Commercial 3D Printer Manufacturing Industry. Source: Kennedy (2021).

This similarity validated our chosen spend categories, highlighting an overall alignment between the categories our team developed and the standard set forth by the commercial 3D printing industry. While the IBIS report segmented the industry's revenue into three categories, we determined a fourth additional category of R&D to be necessary for a more accurate categorization of AM spend data across the DoD. R&D actions encompass a large portion of the DoD's AM-related expenditures and the Air Force Research Labs that conduct a large proportion of R&D acquisition are pivotal in the Air Force AM acquisition function. While our approach includes an additional category compared to the IBIS report's categorization of AM, our difference in approach is quite reasonable given the simple fact that R&D expenses are typically a cost that commercial companies document on their income statement as expenditures. The three categories provided in the IBIS report are specifically linked to the revenue each category earns for each respective company, while all our thesis team's categories are linked to governmental obligation amounts (i.e., governmental spending data; Kennedy, 2021).

5. Overall AM Spending Trends

a. Aggregate Spending Across the Air Force

Results from our spend analysis show that the Air Force in recent years has been purchasing AM-related materials at a moderately high rate, with the annual total obligations more than doubling between FY2017 and FY2019. Figure 14 displays the amount the Air Force obligated each year (FY 2017–FY2019) for AM-related purchases.

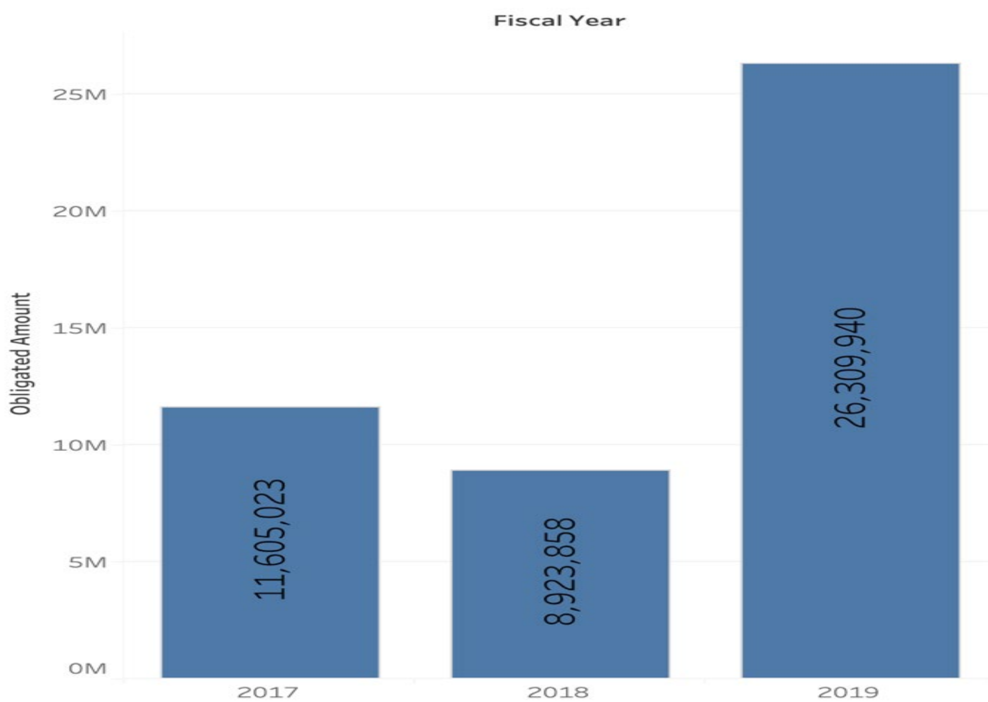

Figure 14. FPDS-NG Air Force Obligations (FY2017–FY2019)

The data captured in Figure 14 indicates that the Air Force obligated an average of $15,612,940.33 per FY toward AM-related purchases between FY2017 and FY2019. When combining both the FPDS-NG and AFBIT Lite obligations, assuming perfect overlap between the two sets, the Air Force's average annual obligation amount was $16,713,845.75 per FY.

When analyzing the Air Force's AM spend per our four defined categories, both the FPDS-NG data (FY2017–FY2019) and AFBIT Lite data (FY2019–FY2020) indicate that R&D is the category that occupies the highest percentage of AM-related obligations. Between FY2017 and FY2019, the data indicate that the Air Force obligated a total of $38,419,349 in R&D efforts, an overwhelming 82.2% of all AM-related purchases. Our AFBIT Lite data set (FY2019–FY2020) indicates a similar trend, with $28,781,579 obligated toward R&D efforts, still comprising the majority (59%) of total AM-related expenditures. Figure 15 provides a detailed visual of such obligation trends per our four defined categories.

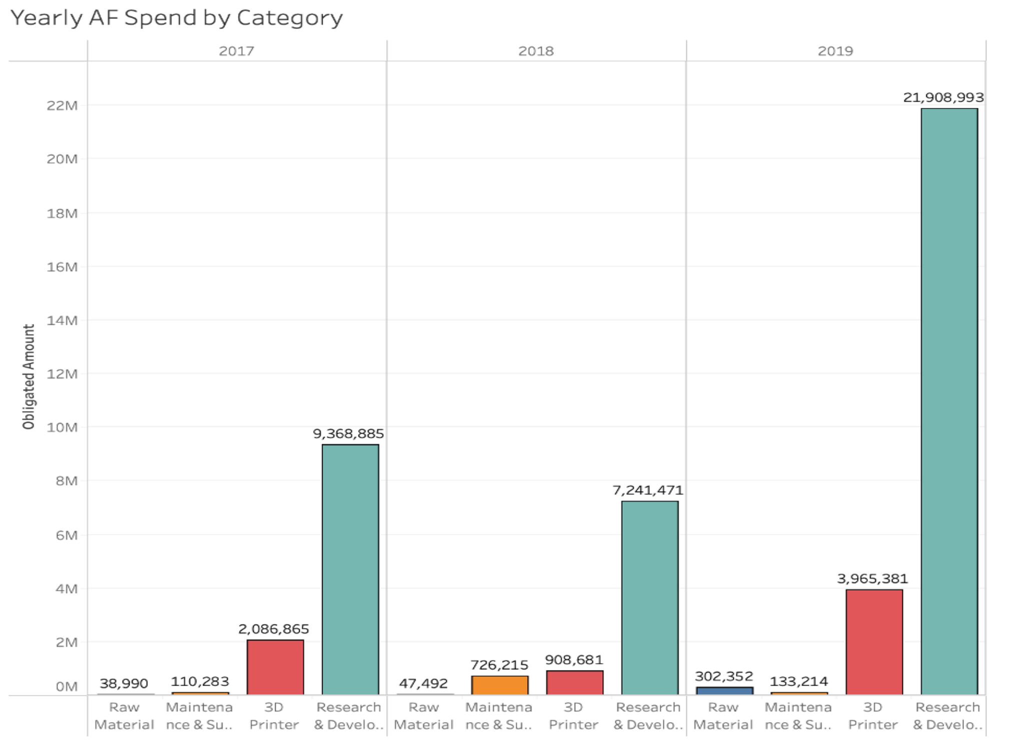

Figure 15. Air Force Category Spend (FY2017–FY2019

Figure 15 identifies the 3D Printers & Scanners category as the second-largest category with respect to total dollars obligated. The AFBIT Lite data set conveys the same trend that is found in the FPDS-NG data set; R&D is still the leading category, with 3D Printers & Scanners in second place. Between FY2017 and FY2019, the Air Force obligated a total $6,960,927 within this category, equaling approximately 14.9% of the total Air Force AM-related obligations. Overall, we found that the R&D and 3D Printers & Scanners categories encompassed 97.1% of the Air Force's total AM spend between FY2017 and FY2019, with the Maintenance & Support Services and Raw Material categories encompassing a relatively small portion of AM-related obligations (2.9%). As will observed in the next subsection, similar spending trends across our team's created categories appeared when conducting a cross-comparison of Air Force, Army, and Navy AM spend data.

b. Aggregate Spending Across the Air Force, Army, and Navy

The AFBIT Lite data set enabled our team to conduct a cross-comparison of Air Force AM-related procurements with the contract actions of other DoD agencies, specifically the Army and Navy. This informed our secondary research question, as we were able to apply our four created spend categories not only to the Air Force but evenly across all three of these DoD agencies. Since our FPDS-NG data set was limited to only Air Force data points, the AFBIT Lite data set is what was utilized to compare the Air Force with other agencies (FY2019–FY2020).

Figure 16 displays the total amounts obligated for AM-related items within each of our four spend categories between FY2019 and FY2020. Each DoD agency is color-coded accordingly with obligation percentages included inside each individual bar graph.

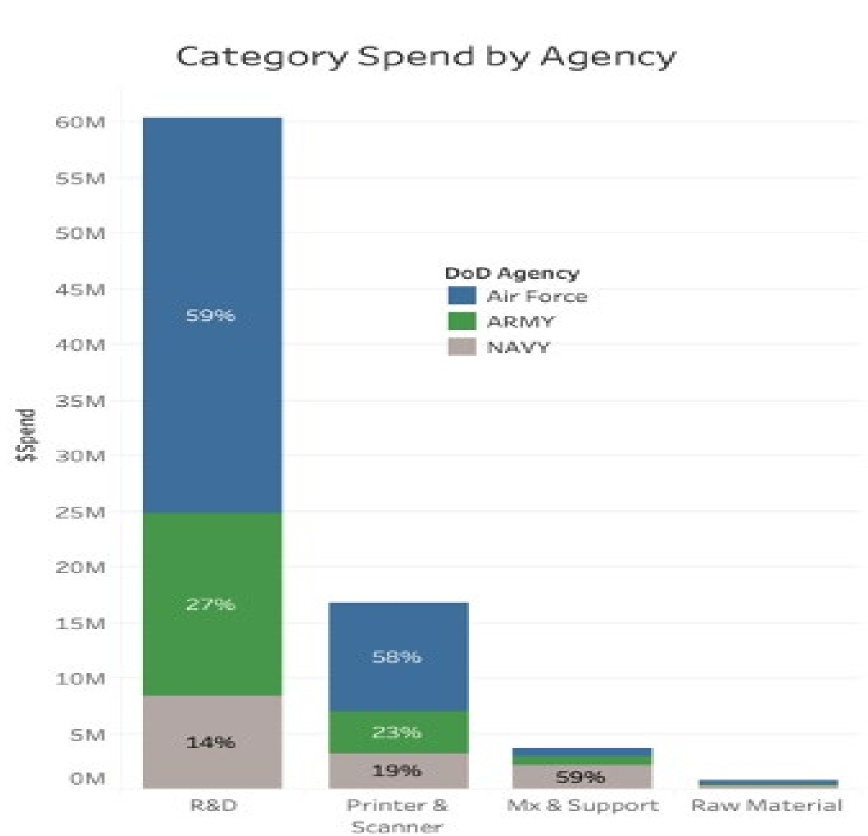

Figure 16. AM Spend Profiles for DoD Agencies

When comparing Air Force spend data from FY2019–FY2020 to the Army and Navy's spending profiles, the data indicates that the Air Force is the current leading agency in overall obligations made toward AM. As seen in Figure 20, out of the total $81.6 million obligated across these three DoD agencies, the Air Force comprises 57% of total AM obligations at $46,362,502, with the Army coming in second place at $21,184,057, and the Navy third at $14,101,407.

Another key finding is that the Air Force is not only the leading DoD agency regarding total AM-related obligations, but also leads across most of our defined categories. With exception to the Maintenance & Support Services category, which is comprised of 59% of obligations coming from the Navy, the Air Force leads in all categories. This trend is apparent in Figure 20 as well, as it conveys the percentage of spend for each DoD agency within each respective category. Figure 20 shows that Air Force leads in the total amount obligated toward R&D, 3D Printer & Scanners, and Raw Material categories, comprising 59% of R&D obligations, 58% of 3D Printer & Scanner obligations, and 53% of Raw Materials obligations.

Based upon these findings and the relatively large number of resources going toward R&D for AM technology, the Air Force is actively prioritizing and aligning its investments in accordance with the *Department of Defense Additive Manufacturing Strategy's* intent of advancing AM technology to inform design. However, with R&D investments comprising such a large portion of expenditures (82.2%) it does also indicate that AM technology may not be as mature regarding its implementation and overall present-day capabilities as many of its proponents claim it to be.

c. Small Business Spend: Air Force, Army, and Navy

We deemed it necessary to gain insight into the size of suppliers for each government agency, I.e., the number of small businesses supporting AM requirements compared to other than small businesses. The federal government's current procurement goal "requires that at least 23% of all federal government contracting dollars be awarded to small businesses" and we sought to see if the DoD is in fact playing its part in meeting this goal with its AM-related procurements (Small Business Administration, n.d., para. 7). This data helps inform our secondary research question, providing deeper insight into how the Air Force is procuring AM compared to the other service agencies. Secondly and more importantly, the size of an AM vendor possesses important sustainability implications, which may directly influence the strength of AM's integration within the Air Force's defense industrial base (i.e., Goal 1 of the *Department of Defense's Additive Manufacturing Strategy).* Figure 17 provides a breakdown of each DoD agency and its total AM-related obligations toward small businesses and as well as across our four defined spend categories.

Total Small Business Spend FY19-20

SB Determination	$Spend	% of Total $Spend along S..
Small Business	43,764,635	54%
Other Than Small Business	37,847,331	46%

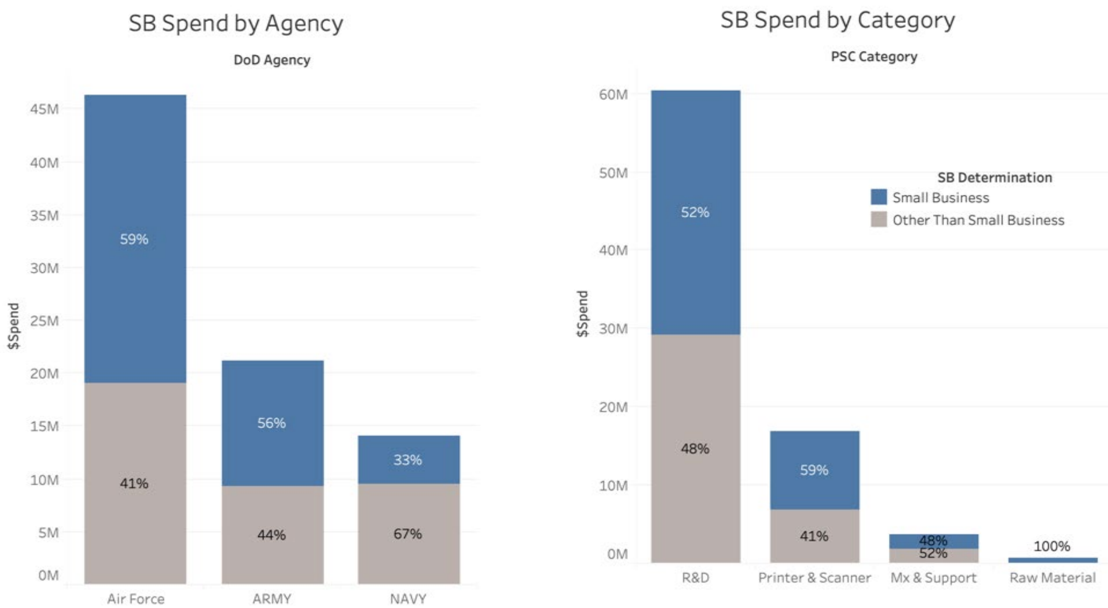

Figure 17. Small Business DoD AM Obligations

The data above indicate a total of $43,764,635 being awarded to small businesses from FY2019–FY2020, representing 54% of the total AM obligations across the three agencies observed. The data also showed that the Air Force is the leading agency regarding small business set-asides, awarding most of its AM-related contracts (59%) to small businesses, with the Army in second place at 56%, and the Navy at 33%. Except for the Maintenance & Support Services category, all three of the DoD agencies awarded most of their AM-related contracts to small businesses. Such data indicates a healthy level of small business representation, increasing the potential for future competition and business opportunities for non-traditional manufacturers and AM service providers, which is key in establishing the strong AM defense industrial base outlined in Goal 1 of the *Department of Defense Additive Manufacturing Strategy.* Overall, the majority of the vendors in our AFBIT Lite data set were found to be small businesses (138 out of 178).

This large amount of AM capability spread across the United States. can strengthen domestic supply chains by providing redundancies and alternative means to crisis response efforts (2021 SC Biden Report and America Makes). However, it is important to assess this data within the context of the qualitative findings gathered during our stakeholder interviews with MITRE and the UDRI.

It was noted in these interviews that AM decision-makers across the DoD must consider a myriad of future implications when matching AM requirements with small business capabilities. Interview subject Debbie Naguy, who is the Outcome Leader for Logistics at MITRE, explained that while small business participation possesses benefits regarding cost and expediency, a business model so highly saturated with small businesses poses serious challenges to long-term supportability (D. Naguy, Outcome Leader for Logistics, interview with author, August 14, 2021). Small businesses that produce and sell 3D printers are often stood-up and go out of business within a few years due to the difficulties of keeping up with the rapidly changing nature of AM (D. Naguy, Outcome Leader for Logistics, interview with author, August 14, 2021). Naguy noted that this had led to customers many times purchasing equipment that cannot then be serviced by the original manufacturer, forcing parts to be requalified on other printers. According to Naguy, many small businesses simply do not possess the necessary capacity to adapt to the evolving technology, provide adequate operational training for customers, or provide robust support services needed when parts break. Naguy also noted that MITRE and Air Force units have procured 3D printers from small businesses that resulted in the equipment sitting in boxes at the respective units, as the company that delivered the 3D printer did not possess the level of capacity needed to get out and service it (D. Naguy, Outcome Leader for Logistics, interview with author, August 14, 2021).

Our interview with UDRI further emphasized challenges that AM businesses and users face after a part is printed. Material uniformity and the integrity of a 3D printed part can differ when created across different printers, and often between the same models. For example, the UDRI AM director stated that comparisons of a part printed by the DoD using the same CAD design, but on various printers of the same model resulted in structural differences during stress tests (Brian Stitt, Division Head of Sustainment Technologies Transition, interview with author, August 14, 2021). While not a significant issue when printing widgets or non-critical spare parts that can easily be substituted, uniformity is essential when integrating parts into major weapon systems to ensure safety standards are upheld. Therefore, the Federal Aviation Administration (FAA) must approve both critical and non-critical AM components that are intended to be installed on aircraft. Designing and producing aircraft parts via AM requires a high level of scrutiny during quality control and testing for the part to be deemed airworthy by various stakeholders (FAA, DoD, airlines, etc.). This process takes time and resources not available to all AM small businesses. While our spend analysis and interviews with UDRI and MITRE support the notion that a high amount of small business participation may be a positive trait, the major players capable of providing long-term supportability and critical AM parts to the DoD are primarily large firms. While small businesses excel in creating short term AM solutions, they struggle to meet evolving customer requirements that are influenced by maturing technology and new certification standards that arise. This was found in our interview to be one of the major limitations that keeps AM from achieving mass adoption.

AFBIT Lite data (FY 2019–FY 2020) also shows that small businesses comprise a large portion of the Air Force's top AM suppliers. Our data set indicated that the top 10 AM suppliers make up a majority (52%) of total AM spend, five of which were small businesses. These vendors are Essentium, Titan Robotics, Ada Technologies, Imaginestics, and Aris Technology, all which are displayed in Figure 18.

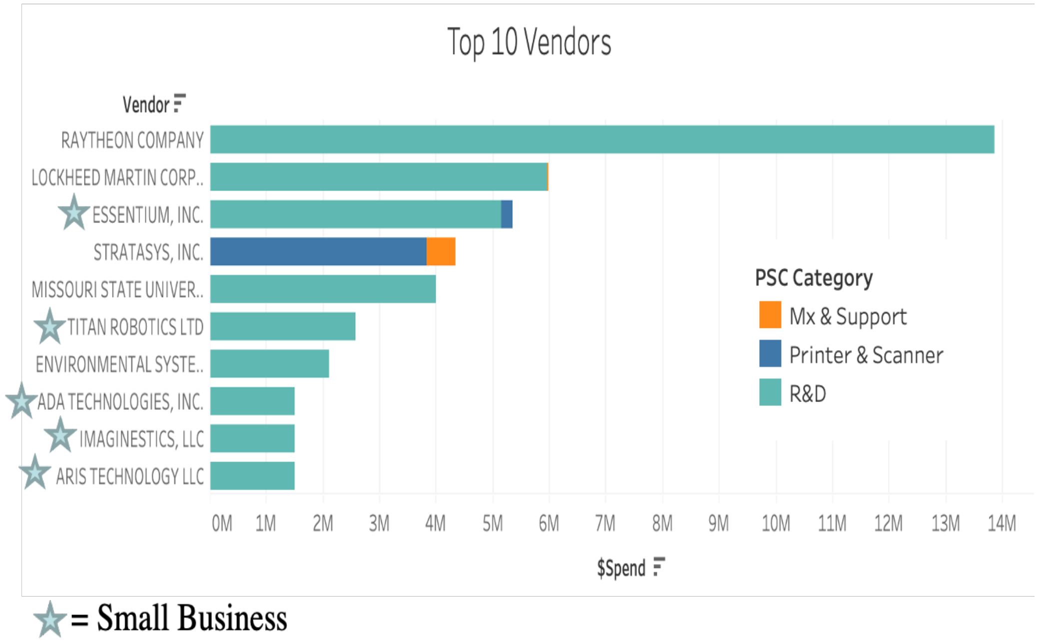

Figure 18. AFBIT Lite Top Ten Vendors

Such findings further emphasize the concern of long-term supportability, as a high concentration of small business spend (especially in the top suppliers) may send the wrong signal to acquisition teams seeking AM-related solutions. While some small businesses can adapt to the changing landscape and provide adequate service, many cannot (D. Naguy, personal communication, August 3, 2021). It is imperative for decision-makers that are considering AM requirements to ensure firms not only have the capability to provide the initial deliverance of an AM need, but also continual supportability of its operations. At a minimum, market research should be conducted that reveals a track record of positive customer support and the firm's ability to adapt to the constantly evolving AM landscape.

d. Additive Manufacturing Geographical Spending Trends

To further test whether the Air Force is properly aligning AM activities with its external partners (Goal 2), we examined geographical obligation trends. As previously noted in Chapter I of this thesis, (see Figure 7), the DoD has established eight MIIs specifically geared toward AM. These MIIs are public–private partnerships and are part of a larger public network, working to bring together "industry, academia, and government partners to advance the state of the art and maintain U.S. manufacturing competitiveness" (OUSD[R&E], 2021b, p. 11). Goal 2 of the *Department of Defense's Additive Manufacturing Strategy* requires that the DoD "tactically engage in investments" (OUSD[R&E], 2021b, p. 11) through these MIIs to advance AM and related technologies. The locations of these eight MIIs appear to be strategically located to effectively cover the entire region of the United States, and we sought to examine whether the Air Force AM obligation trends are geographically aligned with MII geographical locations.

We then compared MII placement to findings in a 2021 IBIS industry report over the 3D Printer industry. This report found an even spread of 3D Printer establishments throughout the United States as well (Kennedy, 2021). Figure 19 displays this distribution, color-coding the percentage of 3D printer establishments that exist within each state, with darker shades of blue indicating a higher concentration and lighter shades indicating a lower concentration. The percentage of 3D printer establishments seem to correlate closely with the geographical positioning of the MIIs displayed in Figure 7 of this thesis report. This close geographical distance between MIIs and 3D printer establishments poses many benefits to the communication, integration, and collaboration efforts intended in Goal 2 of the *Department of Defense's Additive Manufacturing Strategy.*

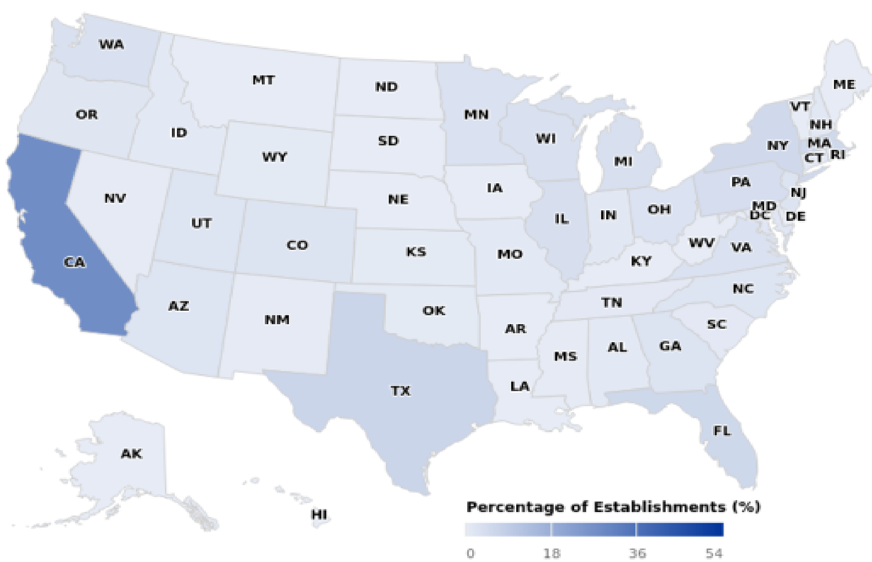

Figure 19. IBIS Report Summary on 3D Printer Establishments

Furthermore, we input the FPDS-NG spend data into Tableau and generated a similar heat map to that observed in Figure 19. The main difference is that our spend data was based off obligation rates for Air Force AM-related items rather than the percentage of 3D printer establishments within each state. Figure 20 provides a geographical overview of the Air Force AM-related obligations within our defined spend category of R&D, with darker shades of blue showing a higher percentage of 3D printer obligations and lighter shades showing lower obligations.

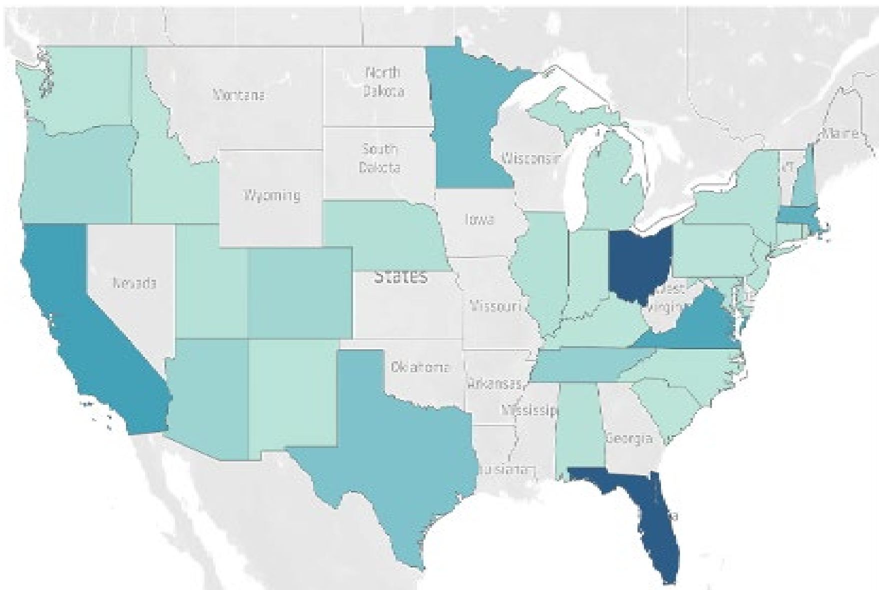

Figure 20. Air Force Obligations for R&D per State

Most notably, this heat map shows a healthy distribution of AM-related procurements across the United States which bolsters Goal 1 of the *Department of Defense's Additive Manufacturing Strategy,* that AM is being integrated into the DoD and the defense industrial base. Moreover, it also strengthens the belief that the Air Force is effectively aligning AM activities with its external partners, meeting the intent of Goal 2. When comparing the physical locations of MIIs in Figure 7 to the geographical distributions provided in Figure 20, a relationship appears to exist, as states with higher AM obligation rates correlate to the proximity of MIIs. We could not confirm whether these obligation patterns were due primarily to the heavier MII presence in the region or simply due to the higher percentage of 3D printer establishments found in the IBIS report (see Figure 19). However, when jointly observing this data, the Air Force's procurement of AM-related items between FY2017 and FY2019 does not appear to have been done in a sporadic manner, but in a way that aligns with both industry and MII concentration levels. Overall, we may conclude that a healthy distribution of 3D printer companies exists across the United States, and that such distribution levels closely mirror Air Force AM obligation trends and are aligned with the location of the MIIs. This may show that the Air Force is indeed collaborating and bringing together stakeholders to align AM activities, effectively meeting the intent of Goal 2 found in the *Department of Defense Additive Manufacturing Strategy*.

e. Spend Per Contracting Office – Air Force, Army, and Navy

To further inform our secondary research question regarding how the Air Force is procuring AM compared to other DoD agencies, we analyzed the total number of contracting offices with AM-related obligations as well as examined the top-five contracting offices in terms of AM obligation amounts (AFBIT Lite data set, FY19–FY20). Table 11 shows the total number of contracting offices we identified as having AM-related obligations for each service branch across all four spend categories.

Table 11. Total Number of Contracting Offices per Category

	3D Printers & Scanners	Maintenance & Support Services	Raw Materials	R&D
Contracting Offices (Air Force)	35	14	2	7
Contracting Offices (Army)	17	19	1	8
Contracting Offices (Navy)	19	19	2	4

Table 11 shows that between FY19 and FY20 a total of 58 Air Force contracting offices making AM-related obligations, 45 for the Army, and a total of 44 in the Navy. With exception of the 3D Printers & Scanners category, all service agencies observed possess a similar number contracting offices with AM-related obligations. However, the Air Force clearly has more offices procuring within the 3D Printers & Scanners category, with a total of 35 contracting offices. Apart from the raw material category, the data in

Table 11 also indicates that each agency overall possesses a healthy number of contracting offices awarding AM-related contracts across all four spend categories. The Raw Material category shows a small number of contracting offices that are dedicated to procuring AM raw materials, with only two in the Air Force and one in the Army and Navy. From this data the DoD appears to be failing to meet Goal 1 of the DoD AM Strategy's intent regarding the integration of AM raw materials. However, this may be due to a lack of sufficient data and tracking mechanisms to accurately capture/evaluate the status of AM raw material inventories or that AM raw materials are currently being bundled into contract actions that occur under our other three spending categories.

As stated earlier, we chose to examine the top-five contracting offices in terms of AM obligations across all four categories of spend for each agency. Figure 21 provides a breakdown of this data, color-coding higher obligation amounts with darker greens and smaller amounts with varying shades of yellow.

Agency	Contracting Office ID	3D Printer	MX & Support Services	Raw Material	Research & Development
Air Force	FA8224	$ 2,185,602.00			
	FA4690	$ 1,888,031.00			
	FA4887	$ 856,029.00			
	FA7000	$ 538,797.00			
	FA9401	$ 533,010.00			
	FA4417		125,397.00		
	FA8571		92,850.00		
	FA9401		75,050.00		
	FA2823		49,036.00		
	FA8527		47,363.00		
	FA8132			340,901.00	
	FA8649			25,000.00	
	FA8730				13,854,408.00
	FA8649				10,424,912.00
	FA8100				5,715,983.00
	FA8222				2,549,520.00
	FA8650				1,734,226.00
	Top 5 Total Obligations	$ 6,001,469.00	$ 389,696.00	$ 365,901.00	$ 34,279,049.00
	% of Total Obligations	61.1%	63.5%	100.0%	96.5%
Army	W911QX	1,198,381.00	228,375.00		
	W911QY	890,455.00		50,837.00	
	W911S8	249,775.00			
	W911KF	249,583.00			
	W911S2	209,399.00			
	W912PQ		169,000.00		
	W15QKN		94,191.00		
	W9127N		69,500.00		
	W81XWH		52,020.00		
	W912HZ				7,077,139.00
	W31P4Q				3,011,709.00
	W5J9CQ				2,704,236.00
	W909MY				1,222,859.00
	W911SR				1,167,990.00
	Top 5 Total Obligations	$ 2,797,593.00	$ 613,086.00	$ 50,837.00	$ 15,183,933.00
	% of Total Obligations	73.11%	68.47%	100%	92.52%
Navy	N00164	647,744.00		8,200.00	
	N00167	393,621.00			113,034.00
	N00173	327,450.00			
	N62271	203,858.00			
	N42158	202,271.00			
	N61331		482,900.00		
	N00421		302,076.00		
	N61340		213,231.00	351,946.00	
	N66604		174,461.00		
	N64267		156,433.00		901,422.00
	N00014				6,563,461.00
	N00024				847,000.00
	Top 5 Total Obligations	$ 1,774,944.00	$ 1,329,101.00	$ 360,146.00	$ 8,424,917.00
	% of Total Obligations	62.3%	63.2%	100.0%	100.0%

Figure 21. AM Leading Contracting Offices per Service Branch Spend

Our data in Figure 21 shows that the top five contracting offices for each category comprise a substantial portion of the total AM-related obligations made by all contracting offices listed in Table 11, comprising 61% or more of total AM obligations in every category (See % of Total Obligations per category). Figure 21 also indicates that the top Air Force contracting offices are purchasing AM-related items in a discrete manner across our four categories of spend, meaning there is no overlap between contracting offices making obligations in the 3D Printers & Scanners and R&D categories and so on. However, it is not the same in the Army and Navy. Army Contracting Office W911QK obligated in both our 3D Printers & Scanners category as well as the Maintenance & Support Services category. Also, Army contracting office W911QY obligated in both the 3D Printers & Scanners and the Raw Materials category. Contracting offices in the Navy overlap even more, with NOO164, NOO167, N61340, and N64267 all obligating in more than two of our four defined categories.

Overall, the data in Table 11 and Figure 21 shows that the policy, guidelines, and agency level implementation plans are having somewhat of a positive effect, as AM priorities are not remaining at the high echelons of the DoD leadership nor is it only impacting the actions of a few contracting offices in each Service branch. Instead, such priorities are permeating down to local contracting squadrons and resulting in a more widespread, evenly distributed effort to integrate AM technologies within the defense industrial base. Furthermore, this data shows that an even distribution of contracting offices regarding AM-related procurement exists across most of our defined spend categories, indicating that the DoD is becoming more experienced and skilled as a force in procuring not only physical 3D printers, but in R&D, maintenance, and support of AM technology. This indicates AM prioritization across the DoD and evidence that such actions are being done in a collaborative, coordinated manner, meeting the intent of Goal 1 of the *Defense Department Additive Manufacturing Strategy* integrating AM into DoD and defense industrial base (OUSD[R&E], 2021b).

6. Conclusion

Chapter V began with applying the GAO framework to assess the Air Force's AM acquisition function. The findings in this chapter provided insight on AM acquisition policies and processes, organizational alignment, and data and intelligence management. Through the application of this framework, we uncovered various positive areas, caution areas, and best practices regarding how the Air Force acquires AM. Overall, we found that the Air Force is embracing the adoption of AM and is making significant effort to improve acquisition practices to align itself with the DoD's AM Strategy. However, we also found that most of the positive areas are still in development and need additional leadership support to render them useful on a larger scale.

Secondly, Chapter V included a spend analysis of two sets of data, one from AFBIT Lite (FY19–FY20) and one from FPDS-NG (FY17–FY19). The goal of this spend analysis was to evaluate these data sets to inform our secondary research questions. Through applying our data cleansing methodology, we were able to create four categories of spend that were then used as a framework to better assess the state of AM across the DoD. When comparing Air Force AM purchasing trends to the Navy and Army, we identified the Air Force as the clear leader in total AM obligations as well as in obligation amounts across three of our four created categories. We also found that the Air Force is making great strides towards meeting Goals 1 and 2 of the *Department of Defense Additive Manufacturing Strategy*. In the next chapter we will conclude this report by providing an in-depth summary of our key research findings, recommendations for improvement, and potential areas for future research.

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VI. CONCLUSION, RECOMMENDATIONS, AND AREAS FOR FUTURE RESEARCH

In this chapter we conclude by providing a summary of our research findings, recommendations, and potential areas for future research. The purpose of our research was to examine acquisition practices related to the increased adoption of AM in the Air Force and identify areas that need improvement. The methodology we utilized consisted of two parts. First, it involved using an adapted GAO (2005) framework to systematically assess the state of AM acquisitions. Secondly, it included a DoD spend analysis of AM, policy and guidance analysis, and stakeholder interviews with multiple agencies throughout the DoD AM ecosystem. We consolidated our findings to develop recommendations that DoD customers can use when seeking 3D printed requirements.

A. CONCLUSION

We used the GAO framework to explore our research questions and gain more insight on the state of Air Force AM acquisition policies and processes, organizational alignment, and data and intelligence management. We analyzed policy, government spend, and stakeholder interviews to determine strengths and weakness of AM acquisitions. The GAO framework helped guide our assessment and uncover positive areas, caution areas, and best practices relating to how the Air Force acquires AM.

Overall, the Air Force is embracing the adoption of AM and is making efforts to improve acquisition practices to better align with the *DoD AM Strategy*. Our findings highlight many critical success factors that lead to efficient, effective, and accountable acquisition processes among AM acquisition agencies. However, most positive areas are still in development and need further leadership support to render them useful on a wider scale.

1. Primary Research Questions

1. How well do Air Force AM acquisition practices meet the GAO (2005) *Framework for Assessing the Acquisition Function at Federal Agencies*? What are the strengths and weaknesses of Air Force's AM acquisition practices?

The presence or lack of identified CSFs combine to form our final assessment: as an AM acquisition function, the Air Force is strong in Organizational Alignment and Leadership (cornerstone 1), but weak in Policies and Processes (cornerstone 2) and Data and Intelligence Management (cornerstone 4). After applying the GAO framework to AM stakeholder interviews, policy, and spend data we found that 6 of 8 CSFs were met for cornerstone 1, 9 of 16 for cornerstone 2, and 5 of 10 for cornerstone 4. It's notable that if assessed individually, each agency we researched may have yielded different results in how well they met GAO cornerstones and CSFs. However, we applied the framework broadly to assess the general state of how the Air Force procures AM as a single acquisition function. This allowed us to make general recommendations on how the Air Force can improve AM procurement practices.

Our assessment reveals that the Air Force is strongest in Organizational Alignment and Leadership compared to the other cornerstones. This is reasonable, as it is the first cornerstone of the GAO framework and sets the stage for the subsequent elements of an effective acquisition function - such as workforce training and data management. The Air Force closely aligns its practices with the vision and strategy established by the *Department of Defense's Additive Manufacturing Strategy*, and is working to improve its policies, processes, and data and intelligence management.

AM is an emerging technology and predominantly procured by the DoD for research and development. It has numerous capabilities and has been proven to solve a variety of manufacturing and design requirements. However, more time and testing are needed for increased AM adoption at the operational, expeditionary, and weapon system environments. Until this occurs, cornerstones 2, 3, and 4 will remain unprioritized. We believe the cornerstones reflect this timeline and that the Air Force will incorporate the respective CSFs as AM use matures. Since AM technology continues to evolve, it would be imprudent to focus efforts on the remaining cornerstones. Doing so runs the risk of locking in policies, processes, and workforce capabilities that may become obsolete with new AM discoveries. It is appropriate that the Air Force currently focuses on Organizational Alignment and Leadership until AM becomes common practice and is procured on a more consistent basis.

2. Secondary Research Questions

2. How is the Air Force purchasing AM compared to other DoD agencies? Is the DoD meeting the intent of the acquisition Goals 1 and 2 of the *Department of Defense Additive Manufacturing Strategy* (OUSD[R&E], 2021b)?

When comparing Air Force spend data from FY2019–FY2020 to the Army's and Navy's spending profiles, we identified the Air Force as the leading agency in overall obligations made toward AM. We found that the Air Force not only leads in total AM obligation amounts, but also leads across the majority of our defined spend categories. With exception to the Maintenance & Support Services category, the Air Force leads in all categories. Moreover, we found that R&D is the category that occupies the highest percentage of AM-related obligations in the Air Force. While our spend analysis indicated that the Air Force is the current leader in total AM obligations among service branches observed, it is important to note that R&D investments comprise a substantial portion of Air Force expenditures (82.2%). This conveys an important reality, that AM technology is not as matured regarding its state of implementation and on-demand capabilities as many of its proponents claim it to be. The Raw Materials category is the lowest area indicating that AM outside of R&D is still not as fully developed in terms of resources being put towards them.

Furthermore, our spend analysis showed there to be a heavy presence of small businesses involved in AM obligations across the DoD agencies observed. The Air Force was noted as the leading agency regarding small business set-asides, awarding most of its AM-related contracts (59%) to small businesses. Moreover, small businesses were found to comprise a substantial portion of the Air Force's top AM suppliers as well, the top 10 AM suppliers making up a majority (52%) of total AM spend, five of which were small businesses. Such prominent levels of small business involvement in AM increase the potential for future competition and business opportunities for nontraditional manufacturers and AM service providers, which is key to integrating AM into the defense industrial base, strengthening the Air Force's application of Goal 1 of the *Department of Defense Additive Manufacturing Strategy*. However, our interviews with experts in the field revealed that many small businesses lack adequate capacity to provide long-term support and maintenance services for their machines, leaving the Air Force's AM acquisition strategy vulnerable. Our data indicated that the Navy's approach is the least vulnerable in terms of its small business composition, with the smallest percentage (33%) of its AM obligations going toward small businesses. This may indicate the Navy possesses a more sustainable approach than both the Army and Air Force regarding the composition of its AM vendor and their long-term support capabilities. This is a double-edged sword. The Navy is behind in small business investment but may be ahead in terms of sustainment for their program. Further exploration into the Navy's AM acquisition practices is needed.

Our spend analysis also revealed that there is a healthy distribution of AM-related procurements across all states, bolstering Goal 1 of the *Department of Defense's Additive Manufacturing Strategy.* This reality also strengthened the belief that the Air Force is meeting the intent of Goal 2, as it shows an effective collaboration and bringing together of stakeholders, an alignment of DoD AM activities to the actions of external entities. Furthermore, we found a healthy number of contracting offices involved in AM-related procurement across three of the four of our defined spend categories, indicating that the Air Force is becoming more experienced and skilled in procuring not only physical 3D printers, but in R&D, maintenance, and support of AM technology. Our raw material category lacked a sufficient number of data points, indicating either that raw material inventories are low and are not strongly integrated into the DoD's industrial base, or the data for raw materials is not adequately tracked. Another explanation for this lack of data is that raw material purchases are made via GPCs, therefore are not reported to or captured in FPDS-NG.

We also found that the states near MIIs were the ones that possessed contracting offices with higher AM obligation rates. While we could not confirm whether these obligation patterns were due primarily to the heavier MII presence in the region or simply due to the higher percentage of 3D printer establishments, we still may conclude that a healthy distribution of 3D printer companies exist across the United States, and that such distribution levels are closely aligned with Air Force AM obligation trends and the location of the MIIs, indicating an effective, coordinated integration and alignment of AM activities.

3. What are the best acquisition practices within the Air Force's additive manufacturing landscape?

Our research uncovered a number of best practices that align with elements of an effective acquisition function (GAO, 2005). Best practices from cornerstones 1, 2, and 4 are presented in Table 12. Our findings are discussed in more detail in Chapter V.

Table 12. Air Force AM Acquisition Best Practices

Cornerstone	Element	Best Practices
1. Organizational Alignment and Leadership (GAO, 2005)	1. Aligning Acquisition with Agency's Mission and Needs	• Strategic alignment with JAMWG • AM Business Model Wargames
	2. Commitment from Leadership	• Additive Manufacturing Marketplace • *AM Contracting Guidebook* • Strong representation at Military AM Summit
	3. Change Management	• CRADAs and partnerships • Exploration of AM category management
2. Policies and Processes (GAO, 2005)	1. Planning Strategically	• Identifying a governing body for AM related questions and decisions early in the process • Collaboration with industry and academia
	2. Effectively Managing the Acquisition Process	• Empowering experts and members of cross-functional teams • Flexibility in acquisition methods
	3. Promoting Successful Outcomes of Major Projects	• Ability to use FAR and non-FAR based acquisition methods depending on the requirement • Working with industry and academia in identifying AM capability gaps
4. Data and Intelligence Management (Dacanay et al., 2020)	1. Data Integrity	• Identifying a governing body for AM related questions and decisions early in the process
	2. Data Analysis	• Empowering experts and members of cross-functional teams

B. RECOMMENDATIONS

This section consists of two parts. First, we provide recommendations based on each GAO cornerstone assessment and respective caution areas. The second part presents recommendations derived from spend analysis findings

1. GAO Framework Analysis

Cornerstone 1 (Organizational Alignment and Leadership) caution areas reflect a lack of a clear definition of AM's function and mission, and ineffective communication and continuous support. To strengthen these factors, we recommend that the Air Force, in collaboration with the JAMWG, publish detailed guidance on the roles and responsibilities of various stakeholders involved in an AM acquisition—to include contracting, program management, technical experts, legal, and public-private partnerships such as America Makes and MITRE. Additionally, as part of JAMWG, AFRL and RSO should establish a technical and contractual support forum for organizations seeking AM requirements. This digital platform should serve as a two-way communication channel where operational units can voice needs and concerns experienced in the acquisition process. AFRL and RSO can use this forum to broadcast revisions of AM acquisition processes that reflect technological advancements and industry practices. We believe these actions will better align acquisition functions with the DoD AM Strategy call for increased integration of AM into the DoD and defense industrial base (OUSD [R&E], 2021).

Cornerstone 2 (Policies and Processes) caution areas focus on the Air Force's lack of AM requirements assessment as well as lack of process monitoring and performance tracking on AM assets and services as an enterprise. This could be attributed to AM adoption being fairly new in the Air Force. As more units in the Air Force acquire AM printers and services, we can look at areas where we can gain standardization and efficiencies in our processes, as well as earn savings by capitalizing on economies of scale. We recommend that the Air Force conduct a category intelligence report (CIR) to determine if creating an AM category or subcategory will add value to the Air Force as a whole.

Air Force leadership can focus efforts on Cornerstone 4 (Data and Intelligence Management) caution errors to improve data integrity and analysis of AM acquisitions. To better track AM procurement data, we recommend an expanded selection of PSCs to fully capture the scope of AM procurement. Details of this recommendation are provided in the next section and supported by observations gathered from our AM spend analysis. We also recommend that JAMWG develop a guide to standardize inputs for AM procurement data. This could include a list of select PSCs, product descriptions, and other fields that assist contracting personnel when inputting data into contract action reports that ultimately flow to FPDS-NG. This action can lead to a more robust and accurate spend analysis, and offer decision-makers better insight into how the DoD procures AM.

2. Spend Analysis

First, we recommend that the Air Force conduct a strategic assessment and review of all PSCs utilized for AM-related procurements to better standardize, simplify, and organize AM-related inputs into FPDS-NG and AFBIT Lite. We identified a total of 48 PSCs in our data cleansing process, all which we determined could fall under one of our four created categories of spend. Moreover, numerous PSC codes were utilized to define identical products. For example, within our spend category of 3D Printers & Scanners alone, 15 PSCs were utilized. A total of 22 PSCs were used for AM-related actions within our R&D category. This is simply too many and creates great difficulty for users to query data accurately and quickly by PSC alone (i.e., why we were forced to utilize key word functions to narrowly filter the data down to solely AM inputs). We recommend that the Air Force simplify its PSC designations for AM-related products in accordance with the framework of our defined spend categories. As CM proponents claim, tracking AM spend data by common categories helps "eliminate redundancies, increase efficiency and effectiveness, and boosts satisfaction with the products and services we deliver" (Bullock, 2017, p. 14). Moreover, having one single PSC per our defined spend categories will provide more value than the vast array of PSCs currently being used, enabling an easier data cleansing process for future tracking and querying of Air Force AM-related data, instead of the guessing game one is currently forced to play in order to filter data by PSCs.

Second, we recommend the development of PSCs that more narrowly target AM-related activities. We found that only one PSC exists within the entire PSC manual that is explicitly labeled with AM terminology, that being code 9630 "Additive Metal Materials." The PSCs commonly utilized for raw materials such as PSC 9330 "Plastic Fabricated Materials" or the those commonly used for 3D printers and scanners such as PSC 3610 "Printing, Duplicating, and Bookbinding Equipment," are too broad in nature and provide no explicit way for users to know if the respective contract action supports TM processes, AM-related activities, or additional operational requirements. Due to this we recommend that new PSCs that are more narrowly tailored to AM be created for users to input into systems like FPDS-NG. This will enable decision-makers to delineate between materials and equipment that are used for TM versus AM and provide leadership with a more accurate state of raw material inventories, a better understanding of our printing-on-demand capabilities and provide more reliable metrics to track overall progress that the Air Force is making regarding its AM-related goals. Regarding raw materials, we assumed that the small amount of data points collected was partially due to raw materials being primarily acquired via a GPC mechanism therefore resulting in many AM raw material inputs not being captured in FPDS-NG or AFBIT Lite as contract actions. For this reason, we were not able to fully capture the state of the Air Force's on-demand printing capabilities, as we could not assess with certainty the number of raw materials each individual unit possesses. For this reason, we recommend that GPC holders be required to explicitly document raw material purchases as "additive" in nature as well as create more stringent reporting mechanisms that enable leadership to better view and track additive raw material inventories.

Third, we recommend mandating stricter FPDS-NG reporting requirements for the model type of 3D printers. Our spend analysis found that terms such as "3D Printer" and "3D Scanner" were many times the only terms listed under the contract description tab. This causes many problems, one being that users cannot accurately assess or benchmark the current pricing schemes to those found in industry, as we cannot determine the model of printer that was purchased. Stratasys Ltd., one of the leading manufacturers of 3D printers, price their uPrint 3D printers at $14,900 and their Fortus 900 mc 3D printers at $379,900 (Kennedy, 2021). With such an extensive range of pricing, it is key for FPDS-NG to have the exact model listed to establish accurate pricing decisions and acquisition strategies. Also, variability across 3D printers is an important consideration from both a compatibility and capability standpoint. The ease of transferring drawings between machines, the type of material used by the machine, the machine's speed, and the type of AM processes the machine utilizes are all aspects that may differ across varying models. Simply put, if the data analyst is unable to determine the specific model of machine procured, it is difficult to provide an informing assessment as to the capabilities and current state of AM across the force.

Fourth, we recommend that a category intelligence report (CIR) be conducted to ensure the transparent and efficient management of AM within Category 5, Industrial Products and Services. As a 2014 OMB memorandum stated, "There is a critical need for a new paradigm for purchasing that moves from managing purchases and price individually across thousands of procurement units to managing entire categories of common spend and total cost through category management" (p. 2). Currently, AM does not possess its own subcategory within Category 5 and similar to the ambiguous PSC designations, the state of TM versus AM becomes difficult to distinguish. The Air Force has recently utilized CIRs over subcategory 5.1 Milling Machines and had success in gaining insight into opportunities for individuals to make more data driven decisions (P. Savard & T. Varner, PowerPoint Slides, June 26, 2020). We believe a CIR will help develop the appropriate considerations that are required for effective management of AM within Category 5.

Furthermore, we recommend that common categories of AM spend be adopted within Category 5, ones that closely matches the categories we created in our spend analysis. If not adopted, any attempt in assessing the current and future state of AM will be limited in nature, being driven by hype and persuasive rhetoric rather than reliable common categories of AM spend data. Common categories of spend will also help ensure that AM procurement is done in an efficient and cost-effective manner, that accurately captures the total cost of ownership of each AM contract action (maintenance costs, cost savings compared to TM, raw material cost, etc.)—not just cost in price at award.

C. AREAS FOR FUTURE RESEARCH

First, we suggest the Human Capital cornerstone of the GAO framework be explored to complete the assessment of the Air Force's AM acquisition function. This could provide better understanding of how to equip future acquisition teams with the appropriate training and workforce. Future research can also use expand on various elements within cornerstone 4 (Knowledge and Information Management) via data calls and more focused interviews from AM-using agencies. Furthermore, this study should be replicated for the Army and Navy to gain further insight into the AM landscape across the entire DoD. Next, we discuss a number of future research areas that we uncovered during our spend analysis.

Second, quantitative data in our spend analysis showed that AM procurement is highly saturated with small businesses. The qualitative evidence gathered in our interviews suggests that a model leaning so heavily on small businesses presents both benefits and challenges to achieving successful AM implementation. However, we lacked solid metrics that enabled us to objectively determine whether such levels are more of an advantage or vulnerability to Air Force AM acquisition strategy. An area of future research would be to find ways in which we can more accurately assess the long-term supportability and capacities of small businesses during the procurement process. If the Air Force desires to have AM implemented successfully in the future, a plan that incorporates and assesses each company's ability to support and provide maintenance services to their machines must be included in the initial acquisition decision.

Third, for this research, we found that there are limited studies that address the full cost of AM and TM value chain. We were only able to find one CBA, and that was conducted by the Army. One of the biggest questions out there is if the use of AM is more cost effective than TM. The answer to that question will drive future acquisition strategies. As the Air Force continue to explore the use and capabilities of AM to support the mission, future areas of study should include quantitative methods such as CBA and total cost of ownership (TCO) calculations in comparing AM and TM.

Fourth, the concept of AM printer brand agnosticism was mentioned a few times during our interviews. Part of our recommendation is producing a CIR for AM to see if standardizing Air Force AM equipment will reduce future issues and added costs caused by too much variability in our equipment. A future area of research could be to discover if AM equipment brand agnosticism or standardization is better for the overall Air Force mission and to determine how acquisition policies and processes need to be adjusted (if at all) to support the mission and our acquisition professionals.

Fifth, we found that the Air Force lacks a comprehensive business model for AM. During our interviews, we learned that some find the idea of a business model helpful and some find it unhelpful. An area of future research is to determine if a business model is appropriate to cover decision-making considerations including IP, certification timeline, TCO, and so forth. to help requirement owners and acquisition professionals determine the best acquisition strategy to support the mission. Another study that can be tied to this is to determine if one business model to acquire AM is appropriate or if there should be three: 1) acquiring AM as a product, 2) acquiring AM as a service, and 3) acquiring AM as hybrid (product and service).

Sixth, it was mentioned in our interviews and literature reviews that AM is still an emerging technology and that new equipment with better capabilities come out every few years or so. In addition, while there may be a lot of vendors selling AM equipment, we also found that smaller businesses struggle to provide maintenance, repair, and training support. We also found that there are different ways to acquire AM: as a product, as a service, or both. A future area of research is to explore whether it is worth investing more in the acquisition of the printers themselves or whether it would be better to wait until the technology matures and meets our AM requirements by acquiring AM as a service

Finally, while our research was Air Force-centric, our findings can be adopted to fit procurement needs specific to all DoD Services seeking to improve AM acquisitions. An appropriate location to share our results would be in the *Additive Manufacturing Contracting Guidebook Phase II* (Draft; NCMS, n.d.), as it is currently undergoing a second revision and being circulated in the DoD for service-specific inputs and review. Ultimately, we hope our research can serve other Services seeking to meet the call for improved contracting processes outlined in the *Department of Defense Additive Manufacturing Strategy*.

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APPENDIX A. FRAMEWORK FOR ASSESSING THE ACQUISITION FUNCTION (GAO, 2005)

Cornerstones	Elements	Critical Success Factors
Organizational Alignment and Leadership	Aligning Acquisition with Agency's Missions and Needs	• Assuring Appropriate Placement of the Acquisition Function • Organizing the Acquisition Function to Operate Strategically • Clearly Defining and Integrating Roles and Responsibilities
	Commitment from Leadership	• Clear, Strong, and Ethical Executive Leadership • Effective Communications and Continuous Improvement
Policies and Processes	Planning Strategically	• Partnering with Internal Organizations • Assessing Internal Requirements and the Impact of External Events
	Effectively Managing the Acquisition Process	• Empowering Cross-Functional Teams • Managing and Engaging Suppliers • Monitoring and Providing Oversight to Achieve Desired Outcomes • Enabling Financial Accountability
	Promoting Successful Outcomes of Major Projects	• Using Sound Capital Investment Strategies • Employing Knowledge-Based Acquisition Approaches
Human Capital	Valuing and Investing in the Acquisition Workforce	• Commitment to Human Capital Management • Role of the Human Capital Function
	Strategic Human Capital Planning	• Integration and Alignment • Data-Driven Human Capital Decisions
	Acquiring, Developing, and Retaining Talent	• Targeted Investments in People • Human Capital Approaches Tailored to Meet Organizational Needs
	Creating Results-Oriented Organizational Cultures	• Empowerment and Inclusiveness • Unit and Individual Performance Linked to Organizational Goals
Knowledge and Information Management	Identifying Data and Technology that Support Acquisition Management Decisions	• Tracking Acquisition Data • Translating Financial Data into Meaningful Formats • Analyzing Goods and Services Spending
	Safeguarding the Integrity of Operations and Data	• Ensuring Effective General and Application Controls • Data Stewardship

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APPENDIX B. FRAMEWORK TO ASSESS A CM FUNCTION (DACANAY ET AL., 2020

Cornerstones	Elements	Critical Success Factors (*) Positive Area (!) Area of Concern
Organizational Alignment and Leadership	Alignment of CM and Agency's Mission Needs	* Appropriate placement and ownership of CM program * Establishment of a joint CM organizational structure * Establishment of organizational CM principles ! Lack of clear definition of CM's function mission
	Commitment from Leadership	* Clear prioritization of CM by leadership * Effective Top-down Communication ! Lack of leadership buy-in
	Change Management	* Core competencies of leadership to drive change * Identification of early adopters ! Lack of drive to challenge resistance by leadership
Policies and Processes	Strategic Planning	* Establishment of governing body or principal forum for establishing strategic direction * Partnership with internal organizations ! Lack of CM collaboration efforts ! Lack of internal and external reporting procedures
	CM Process Management	* Empowerment of cross-functional teams * Management and engagement of suppliers * Establishment of demand management strategies * Establishment of CM program performance measures ! Lack of monitoring and oversight to achieve CM outcomes ! Lack of CM operating procedures

Cornerstones	Elements	Critical Success Factors (*) Positive Area (!) Area of Concern
Strategic Human Capital	Structural Design of Expertise and Capability	* Establishment of centralized support to category managers and other key personnel through development of skills sets needed and maintenance of program guides, tools, templates, and training * Access by personnel to tools and knowledge to use them (decentralized) * Access by personnel to resources outside the agency to assist with tools and dashboards ! Lack of support to CM personnel when roadblocks emerge in performing their duties ! Lack of resources to properly train personnel
	CM Talent Development	* Establishment of CM training program * Establishment of required time frame for completion of CM training * Identification of clear training objectives with feedback loop capability * Identification of key personnel/audience for specific training requirements * Identification of type of training and modality for personnel * Standardization of training to meet professional certification and education requirements ! Lack of ability to provide feedback from trainees about effectiveness of CM courses ! Low prioritization of CM training
Data and Intelligence Management	Data Integrity	* Ownership of a data management strategy * Ability to extract, cleanse, and organize data * Ability to verify & validate data ! Identification of inaccurate data or poor data sources
	Data Storage and Safety	* Ability to safeguard data ! Accessibility issues exist ! Failure to safeguard data
	Data Analysis	* Access to tools to visualize, analyze, interpret data * Ability to generate BI/MI products * Ability to develop and use BI/MI products to generate CM outcomes * Translation of data into meaningful format ! Inability by agencies to translate MI/BI into discernable acquisition actions and decisions

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APPENDIX C. DATA CLEANSING METHODOLOGY KEY TERMS AND CRITERIA USED

Key Term filter utilized the following terms:

3-D Print
3D Print
3-D Scan
3D Scan
Additive
Plastic

Fields/Criteria analyzed across FPDS-NG and AFBIT Lite data sets:

Small Business Determination	Product Service Code	Funding Agency ID	Contracting Office ID
Month of Signed Date	Contract Description	Vendor Name	Extent Competed
Action Obligation Amount	NAICS	Vendor State	CAGE Code
Fiscal Year	DUNS Number	Vendor Zip Code	Vendor Country

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