



**A QUALITATIVE ASSESSMENT OF AIR FORCE LOGISTICIANS'
KNOWLEDGE OF ADVANCED MANUFACTURING TECHNIQUES**

Graduate Research Paper

Robert J. Fekete, Major, USAF

AFIT-ENS-MS-20-J-035

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

The views expressed in this Graduate Research Paper are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government. This material is declared a work of the US Government and is not subject to copyright protection in the United States

A QUALITATIVE ASSESSMENT OF AIR FORCE LOGISTICIANS' KNOWLEDGE
OF ADVANCED MANUFACTURING TECHNIQUES

Graduate Research Paper

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Operations Management

Robert J. Fekete, BS, MPA

Major, USAF

June 2020

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENS-MS-20-J-035

A QUALITATIVE ASSESSMENT OF AIR FORCE LOGISTICIANS' KNOWLEDGE
OF ADVANCED MANUFACTURING TECHNIQUES

Robert J. Fekete, BS, MPA

Major, USAF

Committee Membership:

Lt Col John Dickens, Ph.D.,
Chair (Primary Research Advisor)

Abstract

The 2108 National Defense Strategy (NDS) realigned the Department of Defense's (DoD) priorities from combating violent extremist organizations to preparing for conflicts with near-peer adversaries. However, research has shown that the United States (US) Air Force and the US defense industrial base have limited capability to produce on-demand aircraft spare parts or piece-parts in support of the 2018 NDS, when no stock exists.

The purpose of this research was to assess the familiarity that US Air Force logistics professionals had with advanced manufacturing techniques capable of producing on-demand aircraft spares and piece-parts, and to identify the barriers they perceived to further implementation of these manufacturing techniques throughout the Air Force logistics and sustainment enterprises. Air Force logistics professionals provided responses to a series of interview questions designed to explore their familiarity with, and perceived barriers to, advanced manufacturing techniques. The responses were qualitatively analyzed and the resultant themes were presented and discussed.

This research can help guide education that Air Force logistics professionals should receive about the defense industrial base and manufacturing techniques, guide further implementation of advanced manufacturing technologies, point out potential barriers to implementation, and identify areas for future study.

This paper is dedicated my family, friends, and fellow logisticians, but mostly to my wife, a Ph.D. candidate herself, who looked over my work – all the mistakes are my own!

Acknowledgments

There are several individuals to whom I am especially grateful for making this research project possible. First, I would like to acknowledge my sponsor, Brigadier General Sanford, for his participation and support throughout this project – you continue to set the example for the logistics readiness career field by working with each one of us as individuals – we all see what you do for us and appreciate it! Next, I would like to thank my primary research advisor, fellow logistician, and shredding guitarist, Lt Col Dickens, for his patience, understanding, and guidance. Finally, I would like to emphatically thank the Expeditionary Center’s librarian Pam, for her positive attitude, words of encouragement, and pulling an extreme amount of journal articles to help me complete this research, I could not have done this without you.

Rob Fekete

Table of Contents

Abstract	iv
Acknowledgments	vi
List of Figures	x
List of Tables	xi
 I. Introduction	1
Background	1
Problem Statement	3
Purpose Statement.....	4
Research Questions	5
Research Focus	5
Methodology	6
Assumptions/Limitations	6
Implications.....	7
 II. Literature Review	10
Chapter Overview	10
Literature Search Strategy.....	10
2018 National Defense Strategy	11
State of the Defense Industrial Base	15
Advances in Manufacturing Techniques and Technology.....	23
Computer Numeric Controlled Machinery	24
Additive Manufacturing.....	25

Metamorphic Manufacturing	27
Maturing Manufacturing Techniques and Technology.....	28
Training, Education, and Developmental Programs for Logisticians.....	34
Manufacturing Theories.....	40
Theory of Constraints	40
Theory of Lean Manufacturing.....	42
Six Sigma.....	45
Summary	47
III. Methodology	48
Chapter Overview	48
Participants.....	49
Interview Questions	50
Summary	52
IV. Results and Analyses	53
Chapter Overview	53
Themes.....	54
Familiarity with Advanced Manufacturing Techniques	56
Perceived Barriers to Progressing Advanced Manufacturing Techniques	62
Respondent Demographics	66
Summary	68
V. Conclusion and Recommendations.....	69
Research Limitations	69

Conclusions of Research.....	69
Recommendations for Future Research	74
Bibliography	76

List of Figures

Figure	Page
1. Overall Themes Related to Keywords	54
2. Knowledge of CNC, AM, and MM by Experience	57
3. Percieved CNC, AM, and MM TRL by Experience	59
4. Parts Respondents Believed CNC, AM, and MM Can Manufacture	60
5. Respondents' Grades	66
6. Respondents by AFSC or Series	67
7. Experience Category of Respondents	67

List of Tables

Table	Page
1. Technology Readiness Levels.....	29
2. Manufacturing Readiness Levels.....	31
3. Keyword Count by Assignment Experience.....	55
4. Challenges to Advanced Manufacturing by Experience.....	63
5. Overcoming Challenges to Advanced Manufacturing by Experience.....	65

A QUALITATIVE ASSESSMENT OF AIR FORCE LOGISTICIANS' KNOWLEDGE OF ADVANCED MANUFACTURING TECHNIQUES

I. Introduction

Background

Arguably, the US Air Force has been continually engaged in combat operations since the arrival of the first F-15C fighter aircraft from the 1st Fighter Wing at Langley AFB, VA to the Kingdom of Saudi Arabia on August 7th, 1990 at the start of Operation Desert Shield (Fredriksen, 2011). Since then, the Air Force has flown hundreds of thousands of sorties in support of combat and humanitarian operations worldwide (Haulman, 2011). For the past three decades, the Air Force has conducted its US Code Title 10 force generating activities of organizing, training, and equipping the force, while simultaneously conducting global operations, including patrolling no-fly zones over Northern Iraq; executing airstrikes in the Baltics, Yemen, and Somalia; and delivering life-saving aid to earthquake victims in Iran, Haiti, and Japan (Haulman, 2011). Throughout the past 30 years, the Air Force has prosecuted major air campaigns in Iraq, Afghanistan, and Syria; provided persistent intelligence, surveillance and reconnaissance throughout Africa, South America, and the Philippines; and conducted combat air patrols over the United States, in response to the terrorist attacks of September 11th, 2001 on New York, Pennsylvania, and Washington DC (Haulman, 2011).

Despite a full generation of an unrelenting operations tempo, the Air Force has continued to reduce aircraft inventory and personnel, and the industrial base has correspondingly contracted (Cancian, 2019; Tirpak, 1998). These steep reductions across

the force and industry were based, in part, on the previous National Defense Strategy (NDS) that prioritized counter-extremism, low competition or permissive operating environments, budget uncertainty, and the need to modernize and recapitalize the fleet (2008). During this time, the defense industrial base has radically transformed. From 1994 to 2008, the number of major defense aerospace contractors was reduced from 51 to five (Tirpak, 1998). The rapid proliferation of the Internet in the late 1990s spurred innovation and unprecedented connectivity, while creating an information infrastructure with significant vulnerabilities. This revolution in connectivity, in conjunction with the downsizing of the Air Force, continually shaped the defense industrial base, most notably the defense aerospace industry of today (Hooke, 2005).

Further complicating the problem for the Air Force, is that near-peer competitors, such as China and Russia, have reemerged on the geopolitical stage and overtly seek to challenge the US's military dominance of the past 30 years (DoD, 2018). This concern was so great that the rewrite of the NDS in 2018 reprioritized the focus of the DoD, from fighting global terrorism and extremist organizations, to being prepared for a high-intensity conflict with a near-peer competitor in what the 2018 NDS has dubbed as the great power competition (DoD, 2018). From the highest levels of the executive and legislative branches to major defense contractors and family-owned sub-tier suppliers, industry and government alike are questioning whether or not the modern-day defense industrial base can support the 2018 NDS (Hallman et al., 2020). In the past two years, executive orders, congressional responses, and reports by industry have been circulating with great concern placed on the state of the defense industrial base and its ability to

support the US in a time of war or national emergency (DoD, 2019; Hallman et al., 2020).

On May 13th, 2019, the Office of the Under Secretary of Defense for Acquisition and Sustainment, Office of the Deputy Assistant Secretary of Defense for Industrial Policy, presented its annual report to Congress that assessed the state of the defense industrial base for fiscal year 2018. The report highlighted several areas of concern, explicitly mentioning the complexities associated with the aerospace industry (DoD, 2019). In response to the DoD report, the National Defense Industrial Association (NDIA) released an independent report titled, *Vital Signs: 2020 The Health and Readiness of the Defense Industrial Base*. NDIA graded the defense industry on eight dimensions of support considered critical to the execution of the 2018 NDS and awarded an overall tepid grade of “C” (Hallman et al., 2020). Gaps in capacity, talent, regulations, supply chains, and innovation are just some of the problems plaguing the defense industrial base. The 2018 NDS acknowledged that current war reserve materiel policies were outdated, and, in a conflict with a near-peer, legacy logistics information technology (IT) systems would be attacked, and it questioned the defense industrial base’s ability to surge production to support a protracted conflict.

Problem Statement

Current operational plans do not necessarily account for the potential substantial loss of aircraft early in a violent conflict. Consequently, the Air Force could have few airframes and systems from which to cannibalize spare parts (spares) to keep war efforts going. The need to maximize the employment of every airframe creates a challenge for

the Air Force to generate airpower with a limited aircraft and spares inventory. Coupled with extensive production lead-times for items not currently in stock or no longer manufactured, logistics professionals throughout the Air Force face a daunting challenge to keep aircraft mission capable. Furthermore, should a regional conflict break out with a near-peer competitor, the Air Force would have limited time to blunt enemy action, potentially exposing lead-time gaps in supplies throughout the service's logistics enterprise (DoD, 2018).

Should the Air Force fail to dull enemy action quickly enough, the urgency to end the conflict would still place a premium on the speed of procuring aircraft spares or piece-parts. Given most indicators, the Air Force and the defense industrial base have a minimal capability to rapidly produce aircraft spares and piece-parts, especially as single units or in low numbers, in a manner responsive enough to meet the objectives outlined in the 2018 NDS. This research sought to explore some of the advanced modern manufacturing techniques available to industry that could aid the rapid production of spares and piece-parts in support of the Air Force, and to explore the Air Force logistics personnel's current knowledge of certain techniques, and perceived barriers to their implementation, in an effort to begin to understand the potential problems that can occur in the event of a need to produce many different aircraft parts very quickly, with little lead time.

Purpose Statement

The purpose of this research was to use a qualitative research design to conduct an analysis of themes found in responses to interview questions designed to explore the

current familiarity that Air Force logistics professionals have with advanced manufacturing practices, such as computer numerically controlled (CNC) machinery, additive manufacturing (AM), and metamorphic manufacturing (MM), as methods to rapidly produce on-demand aircraft spares and piece-parts in support of the 2018 NDS. The research also sought to identify some of the barriers that might prevent implementation of advanced manufacturing techniques.

Research Questions

RQ1: How knowledgeable are Air Force logisticians about advanced manufacturing techniques and technologies?

RQ2: What challenges could slow the adoption of these advanced manufacturing technologies?

Research Focus

This research reviews the changes in focus and priorities that have occurred in the last few decades in regards to the strategies of national defense, the current geo-political landscape, and the great power competition. The backgrounds of the currently contracted defense industrial base, and the manufacturing community available for national defense, will also be discussed. The literature review will investigate existing literature associated with the 2018 NDS, the state of the industrial base, advancements in manufacturing technology, maturing manufacturing techniques and technology, education and training available to Air Force logistics professionals, and relevant manufacturing theories. Subsequent chapters will provide the methodology of this research, the interview questions and sampling strategy, the qualitative analysis process, and the themes that

emerged from the interview responses from professional Air Force logisticians. The research will conclude by discussing the themes developed in relation to the research questions, making recommendations based upon those results, and suggesting areas for future study.

Methodology

This research study used a series of written interview questions to gather written response data that was used in a qualitative analysis to determine and present the themes and issues aggregated from the participants' responses. The interview participants were chosen for this research by the researcher in an attempt to provide a wide-ranging sample of Air Force logistics professionals from across the Air Force logistics enterprise.

Assumptions/Limitations

The primary assumption associated with this study was that the participants who responded to the interview questions were representative of the entire population of Air Force logistics professionals. This is an issue of validity in qualitative research, and means that the responses provided by the selection of interview participants can reasonably be assumed to be representative of the average Air Force logistics professionals, so that valid conclusions can be drawn from the themes developed from these responses (Anderson, 2010).

It was generally assumed that the interview participants would have a basic familiarity with the terms associated with advanced manufacturing. For this study, the term aircraft spares was defined as higher level spare part assemblies, such as line-replaceable or shop-replaceable units, and consists of assembly carcasses and piece-parts.

The term piece-parts was defined as single components, such as gears, nuts, bolts, and washers, and refers to the units that comprise aircraft spares.

The first limitation of this study was that the scope of the research was restricted to a small number of active duty and US government employee logistics personnel in the US Air Force. The second limitation was that the researcher had limited knowledge about and access to the training and education currently available to Air Force logistics professionals. Another limitation was the limited time and resources available to the researcher, which prevented the researcher from including more participants in the study. The time and resource limitation also prevented the use of any of the available techniques, such as triangulation, use of contradictory evidence, respondent validation, or constant comparison, to substantiate result validity (Anderson, 2010).

Implications

This research identified gaps in the knowledge that Air Force logistics professionals have about advanced manufacturing techniques, such as CNC, AM, and MM, and identified perceived challenges to implementing advanced manufacturing techniques to produce on-demand aircraft spares and piece-parts. Identifying current knowledge levels and perceived challenges to advanced manufacturing techniques can help guide future research about how to best deploy manufacturing technologies and machinery to meet the objectives of the 2018 NDS. Identifying current knowledge levels and perceived challenges can help direct future research about how to mature and integrate CNC, AM, and MM into the Air Force logistics enterprise, and highlight

opportunities for research into how the Air Force could best partner with industry to rapidly produce on-demand, low-number or single unit spares and piece-parts.

This research can also provide a vector for future studies into the appropriate level of education that Air Force logistics professionals should receive on advanced manufacturing technologies and the defense industrial base, when they should receive it, and the types of assignments for which such education would be most appropriate.

Teaching Air Force logisticians about how private industry may be capable of manufacturing individual aircraft spares and piece-parts could help better prepare them to support the 2018 NDS in the event of high-intensity conflict. Knowledge of private industry practices could better position Air Force logistics professionals for assignments with increased responsibility within the US military logistics and materiel enterprise, particularly for assignments where the Air Force directly interfaces with the industrial base. Familiarity with advanced manufacturing techniques and the future of aerospace manufacturing would benefit Air Force logisticians assigned to positions within the aircraft maintenance depots, Air Force wholesale and retail supply chains, the Defense Logistics Agency (DLA), field and intermediate-level maintenance, Systems Program Offices (SPO) and product support centers, and combatant command and warfighting staffs.

Stakeholders

As a general practice, stakeholders are assessed by their levels of interest, influence, and risks they present to a project or objective for the purposes of engagement and communication management (Hitt et al., 2001). Key stakeholders related to this

research include the US government, most notably the executive and legislative branches; the DoD and the services; major defense companies, such as Boeing, Northrup-Grumman, Raytheon, and General Dynamics; other original equipment manufacturers (OEM); sub-suppliers and subcontractors; the Air Force logistics enterprise, including senior leaders and policymakers; field level maintenance; intermediate repair facilities; depot maintenance; contract maintenance teams and supporting activities; DLA, as a procurer of common piece-parts across the DoD; the Defense Contract Management Agency, as the entity responsible for administering and overseeing defense contracts; and coalition partners and nations that purchase US weapons systems and spares through foreign military sales programs. The vitality of the defense industrial base brings with it a vast multitude of stakeholders with a high interest in the defense industrial base's ability and speed to produce aircraft spares. The broad area of stakeholders makes the adoption of advanced manufacturing techniques difficult, in part, due to competing priorities, bureaucracy, misaligned incentives, limited touch points and visibility, and personal agendas.

II. Literature Review

Chapter Overview

Much has been written about the defense industrial base, the challenges it has faced in the past, and the issues it faces moving forward. Correspondingly, much has been written about the education and training of Air Force members, and how to best develop the force. For the purpose of this research, this literature review will discuss the 2018 NDS; the state of the industrial base, both organic and contract; innovations in manufacturing; the codification of levels of readiness and relevant theories and practices that apply to all manufacturing systems, methodologies, and processes. This literature review will also explore the relevant education and training that Air Force logisticians receive about the defense industrial base and manufacturing, as well as developmental programs that are related to the aerospace industry.

Literature Search Strategy

The literature for this review was obtained using multiple internet search engines, databases, websites, and the US Air Force Expeditionary Center's (USAF EC) library located at Joint Base McGuire-Dix-Lakehurst, NJ. Google, Google Scholar, EBSCO, ScienceDirect, and the Institute of Electrical and Electronics Engineers were the primary internet search engines and databases used to query terms and term combinations to identify germane scholarship. The key terms and combinations that were searched included, *defense industrial base*, *aerospace industry*, *additive manufacturing*, *metamorphic manufacturing*, *computer numerically controlled machinery*, *national*

defense strategy, congressional testimony, military supply chain, aircraft spares, piece-parts, maturing technology, technology readiness level, and innovations in manufacturing. The Air Force's electronic publications website provided the career field education and training plans (CFETP) for the logistics officer career fields, and pertinent Air Force Instructions (AFI), while the Air Force Personnel Center's (AFPC) MyPers homepage provided documents relevant to special programs. The Defense Acquisition University (DAU) website provided information about acquisitions certifications, acquisitions program management, maturing technology, and manufacturing processes related to a defense acquisition program. The USAF EC library and inter-library exchange program provided several books on advanced manufacturing techniques and previously written graduate research papers.

2018 National Defense Strategy

The 2018 NDS, produced by Defense Secretary Jim Mattis under President Donald Trump's Administration, made specific mention that "inter-state strategic competition, not terrorism, is now the primary concern of US national security" (DoD, 2018, p. 1). This change is in stark contrast to the 2008 NDS, signed by Defense Secretary Robert Gates late into the George W. Bush Administration, that noted, "for the foreseeable future this environment will be defined by violent extremist ideology that seeks to overturn the international state system" (DoD, 2008, p.2). However, a change in focus to the Pacific and a resurgent China has been anticipated by the DoD for quite some time. The Defense Strategic Guidance, signed by President Barack Obama in January 2012, dictated that "while the US military will continue to contribute to security globally,

we will of necessity rebalance toward the Asia-Pacific region" (DoD, 2012, p.2). Despite this guidance and the last NDSs being only ten years apart, this new strategy will unquestionably change the approach of the DoD, supporting agencies, views of the public, and the activities of the defense industrial base.

The 2018 NDS described the global security environment as "increasingly complex, characterized by overt challenges to the free and open international order" (DoD, 2008, p. 2). This NDS cited China and Russia as near-peer competitors with malevolent intentions to influence, coerce, or occupy countries in their immediate geographic areas to upend post World War II international order and alliances. The 2018 NDS bemoaned the eroding US military's edge in every warfighting domain and made mention of the need of the DoD to change its mindset from operating in permissive environments with relatively low casualties to operating in contested environments where losses are to be expected and planned for accordingly. In January of 2019, Elbridge A. Colby, Director of the Defense Program at the Center for a New American Security, testified before the Senate Armed Services Committee that China and Russia have plausible theories of victory where they operate subversively in "grey zones," presumably through state-sponsored proxies, while employing strong anti-access/area denial (A2/AD) capabilities, and fielding capable and lethal maneuver forces, underpinned by a credible nuclear deterrent. This scheme of maneuver would allow Russia or China to immediately overwhelm and seize the territory of a US ally or interest, slow any US response, and then shape the environment such that a US victory would be "too difficult, dangerous,

and politically demanding for Washington and its allies to undertake, or undertake successfully" (Implementation of the National Defense Strategy, 2019, p. 4).

To counter the aggressive actions of Russia and China, the 2018 NDS outlined that the US military must build a more lethal force, strengthen alliances and attract new partners, and reform the DoD for higher performance and affordability. To win militarily, Colby testified that the US military must adopt a new warfighting approach, noted in the 2018 NDS as the Global Operating Model. This new warfighting paradigm assumes that the US will be in immediate contact with the enemy, as opposed to the previous generation of encounters such as Operations Desert Storm, Allied Force, and Iraqi Freedom, which allowed the US to build up forces and establish multi-domain superiority before conducting the land war or occupation (Implementation of the National Defense Strategy). The Global Operating Model called for a four layer approach; 1) a contact layer, where activities are shaped in the "grey zone;" 2) a blunting layer, where enemy action is delayed, prevented, or minimalized; 3) a surge layer, where US forces can mass and arrive with decisive combat power; and 4) a homeland layer, where the US continues to defend the homeland (Implementation of the National Defense Strategy). To enable this four-layer approach to modern warfighting, the 2018 NDS called for a lethal, agile, resilient, and ready force to make Russia and China have to choose between "unfavorably escalating the conflict or settling on terms favorable to the US" (Implementation of the National Defense Strategy, p. 4). This model suggests that any near-peer conflict that is to be blunted and resolved favorably will be violent, but short in duration. Furthermore, the 2018 NDS described Iran and North Korea as destabilizing rogue states that threaten

American regional interests and acknowledged that terrorism and extremist activity still pose potential harm to the US at home and abroad. Simply put, the 2018 NDS claimed that the US must address all the threats, but made clear that the priority is great power competition with China and Russia.

Recent aggression from Russia and China can be easily observed, emphasizing the sense of urgency and bringing real-world attention to the warnings contained in the 2018 NDS. Initiated by a crippling cyber-attack, in 2014, the Russian Federation annexed the peninsula of Crimea, following local political unrest. Although the conflict was of relatively low intensity, the armed invasion allowed Russia to seize strategic air and seaports, and a significant naval base with access to the Black Sea (Cecire, 2014).

Additionally, the buildup and militarization of Chinese man-made islands, adjacent to the Spratly Islands in the South China Sea, is particularly disconcerting for the US and regional allies, and threatens freedom of navigation and trade in the Southern Hemisphere. According to the former director of the Asia Maritime Transparency Initiative at the Center for Strategic and International Studies research group, Mira Rapp-Hooper, the Chinese seek to reinforce territorial assertions, which threatens to unsettle over \$1 trillion of commerce. In accordance with international law, the US military continues to sail and fly around the man-made islands, each time prompting an angry and defiant response from the Chinese government, highlighting the tensions in the region (Watkins, 2015).

The 2018 NDS directed the DoD down a new path that places more importance on great power competition than rogue states and terrorism, while still accounting for

other threats. The enemy seeks to exert influence in their immediate geographic area by fomenting discord and executing rapid military action, while expanding A2/AD capabilities, before the US can react. The new US paradigm of warfighting suggests that the DoD needs to counter subversive activities to immediately slow the adversary's military actions, allowing the buildup of forces for a decisive victory. This guidance is radically different from the rogue state and counter-insurgency doctrine of the past 30 years. How the DoD responds to the new guidance will drive changes in force structure and presentation, requirements, capabilities, and ultimately how the defense industrial base must adapt to support this new paradigm.

State of the Defense Industrial Base

The state of the defense industrial base needs to be analyzed to support the 2018 NDS's reprioritization to prepare for high-intensity conflict where losses are expected. Significant challenges exist and must be studied and understood, and manufacturing gaps mitigated, if the industrial base is to support the US military going forward in the new geopolitical landscape. Risk abounds in the current US manufacturing capability. Furthermore, the DoD's organic industrial base must be continually integrated with the commercial sector, and public law must be taken into consideration to best facilitate interaction. Innovations in manufacturing and material sciences must also be matured and leveraged to maximize support in future conflicts.

On July 21, 2017, President Trump issued executive order 13806, titled Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States. This executive order stated that a healthy and robust

defense industrial base is essential to US economic strength and national security and that long supply chain lead-times are of particular concern (Exec. Order No. 13806, 2017).

The executive order (2017) detailed the loss of 60,000 US factories and 5 million manufacturing jobs since the year 2000, and it directed the DoD and Departments of Commerce, Labor, Energy, and Homeland Security to produce a report evaluating the state of the industrial base.

The resulting 2019 DoD Industrial Capabilities Report (ICR) presented to Congress and the President concluded that the industrial base is profitable and has been growing since 2012, however, significant challenges exist to every service and industry (DoD, 2019). Risks identified by the ICR included sole and single-source providers; fragile suppliers, marketplaces and capacity; foreign dependency; diminishing manufacturing sources and material shortages (DMSMS); gaps in US human capital; erosion of manufacturing infrastructure; and product security. Specific risks to the aerospace sector included prime contractor and sub-supplier consolidation, long development times, shortages of trade and skilled workers, and competition for software engineers as aircraft become increasingly software-intensive. To illustrate a primary risk detailed in the ICR, the US has only four US forging houses that exist and are capable of casting "large, single-pour aluminum and magnesium sand castings," and these single-source forging houses face continuous financial risks and the potential for bankruptcy, because a large portion of their business corresponds to the uneven defense acquisition cycle (DoD, 2019, p. 35).

The organic defense industrial base provides the US military with integral logistics capabilities essential to sustaining approximately 440,000 vehicles, 780 strategic missiles, 278 combatant ships, and almost 14,000 aircraft, with the preponderance of the enterprise residing within the depot repair system (DoD, 2019). Referred to as the "Core Law," 10 USC. §2464 Core Logistics Capabilities, mandated that the DoD maintain core logistics capabilities, including personnel, facilities, equipment, and tooling, necessary to ensure the DoD's timely ability to respond to a contingency or national emergency. Moreover, 10 USC. §2466, Limitations on the Performance of Depot-Level Maintenance of Materiel, stated that not more than 50 percent of depot-level maintenance funds can be awarded to contracted repair of DoD materiel, which is commonly called the 50/50 Law (Kobren, 2018). The Core and 50/50 laws have a significant effect on weapons system support and the resulting partnership with the defense industrial base. The DoD's repair depots are a source of supply for warfighting units in terms of both weapons system overhaul and repair, as well as spares support. To ensure compliance with the law, while supporting the supply chain, depots are often required to generate time-consuming workarounds that add to the already existing long procurement lead-times of spares and piece-parts, especially aircraft spares. Additionally, the DoD organic industrial base faces the same human capital challenges as their commercial counterparts in finding and training tradespeople and software engineers, while dealing with the issue of an increasingly aging and retirement-eligible workforce (DoD, 2019).

The NDIA's independently conducted report, produced with data science company Govini in response to President Trump's executive order and the resulting

report to Congress, showed a downward trend in production inputs, innovation, industrial security, supply chain responsiveness, and political and regulatory activity from 2016 clearances (Hallman and Smith, 2020). The report blamed the erosion of the industrial base on a multitude of factors, which were exacerbated by government shutdowns, the lack of production inputs, and difficulties onboarding personnel, particularly the lengthy time of completing security clearances (Hallman and Smith, 2020). The NDIA did note upward trends in competition, demand, and production capacity and surge readiness, indicating a profitable, strong domestic defense market; however, cybersecurity, especially for small upstream sub-suppliers, remained a significant challenge (Hallman and Smith, 2020).

Unquestionably, manufacturing has become more software intensive, both in terms of organizations sharing information and in programming of manufacturing machinery (Naylor and Maletz, 1986). Katie Arrington, Chief Information Security Officer at the Office of the Undersecretary of Defense for Acquisition and Sustainment, noted, "the Pentagon's supply chain currently consists of about 300,000 companies, and about 290,000 of those have no cybersecurity requirements whatsoever" (Lee, 2020, para. 6). Arrington also stated that the strategies and security paradigms of 2020 cannot be the same in 2025, suggesting an ever-evolving field of finding and patching cyber vulnerabilities posing a never-ending challenge for cybersecurity personnel (Lee, 2020). Of note, small suppliers, with limited resources, may be difficult to motivate to secure their IT systems, which is of concern as suppliers, sub-suppliers, and OEMs seek to better integrate their information sharing with their supplier base and the DoD (Lee, 2020). To

meet this challenge, the DoD is modifying acquisition regulations, renegotiating critical contracts to ensure cybersecurity, and working to create a supplier-base cybersecurity certification standard with outside credentialing entities and auditors (Lee, 2020). Firms will not be allowed to certify themselves. The DoD is exploring using existing organizations such as the Defense Contract Management Agency (DCMA) to shepherd companies along and make cybersecurity a requirement for doing business with the US government (Lee, 2020). Industry, however, is not close to being fully secure, and it would be impossible to conduct business without these companies (Lee, 2020). The ICR noted, for both the public and private sectors, challenges in cultivating, recruiting, and retaining science, technology, engineering, and mathematics (STEM) personnel, and those same concerns are also detailed by the NDIA. A recent report from the Ronald Reagan Institute lamented an aging STEM workforce with difficulties attracting new talent, primarily because the private sector, e.g., Silicon Valley, offered better compensation with which the government cannot compete. Furthermore, the report discussed the lack of diversity and abundance of foreign STEM students, particularly from adversarial countries, such as China, as a contribution to the coming shortfall of STEM talent and a significant threat to the need of the industrial base to innovate, produce, and sustain defense products (Task Force on 21st-Century National Security Technology and Workforce, 2019).

At the 2019 Interservice Industry Training, Simulation, and Education Conference in Orlando, Florida, Vice Chief of Staff of the Air Force, General Stephen Wilson stated that compared to the US, China had "produced eight times the STEM graduates and they

are predicting that in the next five years that the number of STEM graduates will be 15:1" (Tadjdeh, 2020, para. 21). Additionally, former Secretary of the Navy, Richard Spencer, told reporters at the Halifax International Security Forum in Nova Scotia, Canada that the race for technology is "going to be a horse race – one year we will be ahead, the next year China will be ahead " and the ultimate difference-maker will be "grey matter," alluding to the US STEM workforce (Tadjdeh, 2020, para. 24). To help overcome the US's STEM workforce shortages, the Reagan Institute report made several recommendations. The report advised creating a partnership program for a strong innovation base; a national STEM corps similar to the military's Reserve Officer Training Corps; a specific and an adequately vetted STEM visa program to encourage friendly international students to remain in the United States and work on national security programs; and additional reforms for how the DoD conducts business with the private sector, through encouraging technological risk, innovation, and growing the STEM workforce with a focus on national security issues (Banks, 2019; Tadjdeh, 2020). The concerns regarding properly educated human resources being available for the private defense industrial base should also be mirrored by the Air Force's logistics and industrial enterprises. The Air Force can reasonably expect to contend with similar challenges in maintaining well-trained and educated logistics professionals to support the changing needs highlighted by the 2018 NDS.

Serious concerns abound about the defense industrial base's ability to surge production in the event of a significant conflict with a near-peer competitor. The small number of major defense contractors, mainly the oligopoly of Boeing, Lockheed Martin,

Northrup-Grumman, General Dynamics, Raytheon, and BAE Systems have been encouraged to operate as efficiently as possible since the end of the Cold War, and, therefore, cut excess production capacity in order to reduce costs to the DoD (Harper, 2020). Should the US experience significant attrition of ships and aircraft within the first year of a major conflict, it is doubtful that industry could retool or stand up new production lines to produce major end-items or full weapons systems in a timely manner. It is also unlikely that industry could field an entirely new sophisticated weapons systems early in a conflict or quickly enough to make up for significant losses. In some cases, companies lack the competency for specific requirements, for example, Northrup-Grumman is the only major manufacturer producing strategic bombers. In other cases, the Pentagon's budget process, or cumbersome and risk-averse acquisition procedures, prevent the rapid fielding of new technologies (Harper, 2020). As alluded to in the 2018 NDS, the speed of the adversary and the corresponding speed of the US will have a significant effect on the outcome of a conflict. The evolution of technology, materials, and innovation has reduced the cycle time of warfare, producing a first-mover advantage. Many of the reactionary policies and institutions of the US are simply not aligned with the 2018 NDS and the defense industrial base will be challenged to overcome those misalignments. It is important to begin identifying areas of most concern to preventing adequate responsiveness from the defense industrial base and developing plans to address deficiencies now, before engaging in a large-scale conflict.

However, recent history shows that the industrial base has been able to meet emerging and urgent requirements as they occur. The DoD had recent success, during

Operations Iraqi Freedom and Enduring Freedom, at rapidly expanding production capacity of the industrial base to produce the relatively low-technology Mine Resistant Ambush Protected Vehicle (MRAP; Friedman and Truver, 2014). Although Assistant Secretary of Defense for Acquisition Kevin Fahey describes the MRAP as essentially a "really big tuck," five manufacturers were able to field over 40 variants of the MRAP and deliver over 24,000 vehicles to the theaters of operation, saving an untold number of US and coalition service members' lives (Friedman and Truver, 2014). Despite his concerns about the state of the industrial base, Fahey stated, "when you end up with a requirement that is funded, how quickly they can ramp up" (Harper, 2020, para. 58). Although the US Marine Corps initiated the MRAP program in 2004, the MRAP was not declared the DoD's top acquisition priority until May 2007, with deliveries spiking in February 2008, according to the Government Accountability Office's (GAO) 2008 report on the rapid acquisition of the MRAP. The MRAP's arguably ambiguous production timeline does not adequately answer the question of whether or not the defense industrial base could surge production with short notice however, and certainly does not account for more technologically advanced weapons systems with longer procurement lead times and an expansive supply base.

Reports on the current state of the defense industrial base are of concern, but are not without positive outlooks and areas of opportunity (Lee, 2020). Congress and the DoD must make a concerted effort, despite how difficult it may be, to adjust the way the US does business with industry and change its culture, almost in its entirety. Furthermore, policymakers and the DoD must look to new capabilities, emerging technologies,

including disruptive manufacturing technologies, as a means of leverage if the 2018 NDS is to be supported for the foreseeable future.

Advances in Manufacturing Techniques and Technology

As aerospace manufacturers transitioned from the Industrial Age to the Information Age, the defense industrial base experienced significant revolutions in manufacturing technologies, materials, and processes, offering novel opportunities to affect the future of warfighting. Whether it is through a more distributive network that is harder for the enemy to attack, or by producing parts closer to the demand signal to reduce cycle time, advanced manufacturing techniques have the potential to largely supplant traditional manufacturing processes. They offer responsive and customizable single, or low volume, batch products, along with economic advantages, and it would benefit Air Force logisticians to be familiar with these advancements in manufacturing (Ford and Despeisse, 2016). This section will discuss the recent revelations of the three digital waves of manufacturing and describe CNC, AM, and MM technologies. These advances in manufacturing have differing technological maturity levels, but have the potential to have a profound impact on the aerospace industry and the defense industrial base, particularly when these manufacturing techniques are used in conjunction.

These advancements are not without challenges, however. In the case of aircraft spares and piece-parts, especially when a manufacturer no longer exists, the application of advanced manufacturing techniques is challenging, and relies on other processes, such as redesign or reversed engineering of parts (Plewa, 2019). Redesigning or reverse-engineering a product involves scanning, repairing, feature identifying, optimization, and

verification of the part (Montero et al., 2018). Consistently producing items of the same quality or specifications across different machines in different locations and environments remains a challenge to be overcome. Conversely, these sophisticated manufacturing techniques bring with them the potential to enhance or strengthen properties of aircraft spares and piece-parts that otherwise could not be accomplished with traditional manufacturing methods (Uriondo et al., 2015). As the industrial base attempts to efficiently produce aircraft spares and piece-parts at a cost-effective rate for both the OEM and the Air Force, there is little doubt that logisticians would benefit from being familiar with what these newer techniques and what new manufacturing technology has to offer for aircraft sustainment.

Computer Numeric Controlled Machinery

Before CNC techniques, machinery was operated manually through mechanical means such as a wheel, press, chuck and die, or die-cast with incremental adjustments made by the machine operator to manufacture items to specification. To ensure the quality of the mechanically produced items, personnel used measurement instruments such as micrometers, calipers, and scales on manufactured parts, suggesting the skill of the individual machine operator played a significant role in the error rate, rework, or a potential waste of the product (Ni, 1997). Developed in the 1950s, CNC machines are commonly thought of as computer-controlled lathes, drill presses, and other boring tools, however, computer-controlled fabrication machinery also encompasses water jet cutters, laser fusing, hydroforming, 3D printers, plasma torches, spindles, electronic discharge machines, and mills. Modern-day embroidery and fabric-weaving machines are

computer-controlled. CNC aided machines precisely move raw materials or blanks such as wood, metal, plastic, polymer, ceramic, or composites about multiple axes, spinning, rotating, or on a moving platform, allowing the formation of the preprogrammed product shapes to be manufactured with exceptional precision and quality (Lynch, 1997).

Additionally, CNC machines allow a manufacturing platform to serve as multiple machines in one, or a "cell" of clustered machines, as the manufacturing of the product is driven by algorithms programmed into the machine's computer. These multiple algorithms help to ensure maximum machine usage while taking up minimal space (Bramlet, 2007). CNC machines have multiple uses and are attractive to the aerospace industry as the demand for air travel has expanded over the past decade, with growth expected to double in the next 15 years, driving the industry to expand manufacturing automation to meet the demand of customers (Möllera et al., 2017). Undoubtedly, the defense industrial base will benchmark and apply the automation techniques of the aerospace industry.

Additive Manufacturing

AM often referred to as 3D Printing, or rapid prototyping, is the process of adding together successive layers of source materials, such as ceramics, metals, polymers, or plastics in powder or liquid form, to create a three-dimensional product. Adding thin layers over previous layers makes the manufacturing process additive as opposed to subtractive processes such as milling or shaving a piece of wood or metal into a shape that creates waste from the raw material or blank. AM uses computer-aided design software or other digital modeling programs and incrementally combines materials to

fabricate items, often with complex geometric shapes similar to that of an item created in a cast or mold. Through extensive research, AM has been able to produce structurally complex formations such as lattice supports, as well as to create items that require minimal finishing, or items to be used in a combination of additive and subtractive processes (Guo and Leu, 2013). AM is capable of producing special internal features that would be expensive or difficult to replicate in conventional manufacturing processes, without retooling, and at higher speed and a lower cost, especially for low-volume production runs (Ahtiluoto and Coatanea, 2019). International standards organization ASTM International, defines additive manufacturing as the "process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (2017, p. 2).

In 2013, the National Aeronautical and Space Administration (NASA) partnered with Aerojet Rocketdyne and successfully printed and tested a rocket injector during a procedure that produced 20,000 pounds of thrust at Glenn Research Center in Cleveland (Plafke, 2013). In 2015, the Federal Aviation Administration approved General Electric AM techniques to produce parts for an aircraft engine, and as of 2018, GE Aviation boasts producing over 23,000 flight quality AM parts (Rutkofsky et al., 2018). As AM technology matures, it brings with it the possibility to produce low-cost, on-demand, aircraft spares and piece-parts, as evidenced by commercial logistics provider United Parcel Service's (UPS) partnership with 3D printing startup Fast Radius (O'Neill, 2018). UPS wanted to produce low batch number, on-demand aircraft spares that were closer to their transportation hubs, and become part of the AM market, which is expected to grow

to \$21 billion by 2020 (Rutkofsky et al., 2018; Sejersgaard-Jacobsen, 2020). AM is not without its challenges, however. Consistent quality, reproducibility, extensive code-writing, and machine operator training are obstacles to maturing AM techniques (Proff and Staffe, 2019). Additionally, materials needed for AM are unique, which has limited the proliferation of AM machines. These limitations have slowed its transition from laboratories and experimental facilities to the factory floor, and it is still relatively new to the aerospace industry (Lyons, 2012).

Metamorphic Manufacturing

Referred to as the third wave of digital manufacturing, the concept of MM, or robotic blacksmithing, is still in its infancy. As defined by the 2019 report from the Minerals, Metals and Materials Society (TMMS), MM is the "closed-loop, numerically controlled, incremental forming to achieve simultaneously complex shapes, and specific engineering properties and local microstructures" (xxiii). MM relies on five dimensions to fabricate an item, including sensors, thermal control, actuators and forming mechanisms, robotic systems, and computational control. Sensors monitor the geometry and acoustics of the material; thermal controls include adjusting the thermal properties of the material and surrounding environment, including heat treating; actuators and forming mechanisms press, hammer, and mold the material; robotic systems manipulate, move, and position the material, and computations control and make real-time decisions about the entire process (TMMS, 2019). These fundamental elements are combined to create optimized, robust, and fatigue-resistant product shapes using the already understood thermal properties of the source material, similar to the way a blacksmith molds,

hammers, and shapes intensely heated iron or metal, and then places the material into a cooling element to harden or heat treat. MM is envisioned as a precision-input, rapid process with "the incremental thermo-mechanical deformation of a metalsmith with the precision and control of intelligent machines and robotic systems" (Long, 2020, para. 2). MM is similar to AM in that redesign, reverse engineering, and digitization of the item to be manufactured may be necessary. MM shows the most promise to be used for metal forming, as metal is inexpensive to fashion. When manufacturing single-piece complex metal forging or castings, die creation is one of the most expensive parts of the tooling line. Subsequently, dies must be switched, maintained, and stored, which adds steps to the process and additional expense for companies (Daehn and Taub, 2017). There is no literature on MM producing any item other than a prototype piece-part or a proof of concept component. This lack of literature suggests that the concept of MM is developing. However, MM has the potential to compliment CNC and AM as progress towards creating customized, intricate parts and, ultimately, aircraft spares and piece-parts.

Maturing Manufacturing Techniques and Technology

Efforts to apply the three digital waves of manufacturing techniques and technology to the production of low volume batches of aircraft spares and piece-parts will undoubtedly require a maturation process. The DoD Technology Readiness Assessment (TRA) Deskbook described the TRA as an independent and formal metrics-based system that assesses the maturity of critical hardware and software technologies to be used in a system (2009). The TRA assesses vital technological elements as part of larger systems

or major acquisition programs, particularly programs that are developing and maturing technologies for broad implementation. As part of the technology assessment process, the DoD has adopted the NASA Technology Readiness Level (TRL) scale created in 1974 by researcher Stan Sadin (Héder, 2017). The TRL scale assesses the readiness of technology to be incorporated into a systems acquisition program and was formally adopted by NASA in 1989 and updated throughout the 1990s (Banke, 2010). The European Space Agency adopted a similar scale based on the NASA measures in 2008, lending international and scientific credence to the scale's utility (European Space Administration, 2008). As noted from the DAU, the DoD scale consists of nine levels with each TRL representing progress and evolution towards maturity (see Table 1).

Table 1. Technology Readiness Levels (DAU, 2018)

Level	Definition	DoD Acquisition Guide Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in	Basic technological components are integrated to establish that they will work together. This is

	laboratory environment.	relatively “low fidelity” compared to the eventual system. Examples include integration of “ad hoc” hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

TRLs create a common language, help program managers assess technological program risk, and inform decisions. TRLs have been widely successful in communicating the status of technologies across a myriad of interdependent and integrated organizations (Mankins, 2007). Based on the success of TRL, the DoD partnered with industry

adopting a Manufacturing Readiness Level (MRL) scale in 2005, which similarly provides a common terminology and relatively simple assessments of manufacturing techniques and technology, or process maturity, for suppliers and sub-suppliers (Dietrichab and Cudney, 2011). A 2010 GAO report lauded MRL as a best practice in identifying manufacturing gaps and managing risk. The GAO report mentioned that both the Army and Air Force have reported MRLs as a significant contributor to hundreds of millions of dollars in reduced program costs, improved schedule, and better performance of products (2010). However, the uneven application of MRL across all major acquisitions programs hampers implementation and standardization efforts (GAO, 2010). A result of MRLs success, was that it drove changes to acquisition policy, where the MRL process is now incorporated into major decision points and milestones in large acquisition programs. As noted in the 2010 GAO report and informed by DCMA, the MRL scale is defined by ten readiness levels (see Table 2).

Table 2. Manufacturing Readiness Levels (DAU, 2018)

Level	Definition	DoD MRL Description
1	Basic Manufacturing Implications Identified	Basic research expands scientific principles that may have manufacturing implications. The focus is on a high-level assessment of manufacturing opportunities. The research is unfettered.
2	Manufacturing Concepts Identified	This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined military needs.
3	Manufacturing Proof of Concept Developed	This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.

4	Capability to produce the technology in a laboratory environment	This level of readiness acts as an exit criterion for the MSA Phase approaching a Milestone A decision. Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.
5	Capability to produce prototype components in a production relevant environment	Mfg. strategy refined and integrated with Risk Management Plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development.
6	Capability to produce a prototype system or subsystem in a production relevant environment	This MRL is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the EMD Phase of acquisition. Technologies should have matured to at least TRL 6. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself.
7	Capability to produce systems, subsystems, or components in a production representative environment	System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. Technologies should be on a path to achieve TRL 7.
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	The system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. This level of readiness

		is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation.
9	Low rate production demonstrated; Capability in place to begin Full Rate Production	The system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes .
10	Full Rate Production demonstrated and lean production practices in place	Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level.

The uniform understanding and common nomenclature that the TLR scale provides can help facilitate conversations between DoD and the defense industrial base on how to best mature and apply the three digital waves of manufacturing for both initial weapons system production, and sustainment after fielding. Assessments by the TRL scale can be used to inform the development of innovative manufacturing processes that have to potential to supplant single-source suppliers such as the forging houses mentioned in previous paragraphs. The TRL scale enables critical communication about the maturity and readiness of advanced manufacturing techniques, such as CNC, AM, and MM, to all stakeholders, and the potential to rapidly produce aircraft spares and

piece-parts is pertinent to the support of the 2018 NDS. The interview responses analyzed later in this paper include references to TRLs and MRLs.

Training, Education, and Developmental Programs for Logisticians

An important and convenient place for Air Force logistics professionals to learn about new practices, such as advanced manufacturing techniques, would be from the training and education that is provided by the Air Force for all logistics career fields. The training and education are governed by a career field education and training plan (CFETP), unique to each career field. The CFETP is a comprehensive document that identifies education and training requirements, provides assignment guidance, and establishes minimum core task proficiency for basic, senior, and master career field certifications. The CFETP instills rigor in the force development process and articulates the requirements that each logistician must meet to be considered fully qualified and to advance through their career. The CFETP also details competitive developmental programs, DAU training modules, and academic courses that logistics professionals should consider joining or completing.

The Air Force logistics officers' career fields consist of the Air Force Specialty Codes (AFSC) of 21A, aircraft maintenance; 21M, munitions and missile maintenance, and 21R, logistics readiness. The 21A CFETP identified two core tasks related to the local manufacturing of a component for basic level career field certification. The tasks included familiarity with local manufacturing processes and understanding of policies and procedures (Department of the Air Force, 2017). The types of technologies, machinery, or methodologies used in the local manufacture of components were not

mentioned. The 21A CFETP also referenced Air Force Materiel Command's professional maintenance certification program (PMxCP). The PMxCP was designed for maintenance professionals and referred to the concept of maintenance support as the ability to manufacture and retain or restore materiel in a serviceable condition, and the need to incorporate manufacturing into maintenance practices at the organizational, intermediate, and depot levels (Department of the Air Force, 2017). To receive the senior level career field certification, the 21A CFETP required personnel to complete DAU's Production, Quality, and Manufacturing (PQM) 101, PQM 201A, and PQM 201B courses (Department of the Air Force, 2017). No specific mention of advanced or innovative manufacturing technologies was made in the 21A CFETP, nor was there any reference to career broadening developmental programs.

The 21M CFETP articulated that munition and missile maintenance officers are liaisons to OEMs, and identified one core task of understanding local manufacturing procedures for basic level career field certification (Department of the Air Force, 2019). The 21M CFETP did not directly mention innovative, advanced, or disruptive manufacturing technologies, such as CNC, AM, or MM. The 21M CFETP made reference to several developmental programs, most notably the Logistics Career Broadening Program (LCBP), Education with Industry (EWI) fellowships, and the Acquisition and Logistics Exchange Tour (ALEET), which will be described later in this chapter.

The 21R CFETP did not articulate any core tasks directly related to manufacturing or interfacing with the defense industrial base. The 21R CFETP did,

however, have one core task related to understanding the relationship between SPOs and the Air Force Sustainment Center, tangentially implying that those in the career field need to understand the defense industrial base and how it relates to weapons system sustainment (Department of the Air Force, 2017). The 21R CFETP also did not explicitly mention any education or training related to advanced manufacturing or interfacing with industry, but did provide a general reference to courses offered through the DAU. Similar to the 21M career field, the 21R CFETP also referenced the developmental programs of the LCBP, EWI, and the ALEET as opportunities for 21R personnel to expand their knowledge of industry, weapons system acquisition, and depot-level sustainment.

A review of the position classification flysheet for government series (GS) 0346, logistics management specialist, revealed that professionals involved in the integrated logistics support (ILS) of a weapons system have frequent association with counterparts in industry and other technical partners (Office of Personnel Management, 1987). The document cited that logistics management specialists involved in ILS have extensive contacts with technical personnel such as engineers, maintenance planners, and project managers, yet the document did not refer to any manufacturing technology, technique, or methodology (Office of Personnel Management, 1987). The flysheet also did not mention any required education or training in regards to manufacturing or interfacing with industry. The GS-0346 flysheet did not mention any experiential or career field developmental opportunities or programs.

Although standard assignments throughout the logistics and materiel enterprise exist for Air Force professionals, logisticians serving in developmental assignments that

place an emphasis on interacting with industry and, by extension, have the most contact with manufacturing processes, are primarily those that are competitively selected for a Special Exchange Experience (SPEED) program (AFPC, 2019; Department of the Air Force, 2017). The SPEED programs most applicable to this research are the LCBP, EWI fellowships, and the ALEET program. According to the AFPC personnel delivery services memorandums for 2018 and 2019, the Air Force selected a total of 32 officers, from among all the logistics career fields, for assignment to a SPEED program each year.

The LCBP is a unique two-year assignment to an aircraft depot, the DLA, or the F-35 Joint Program Office, where Air Force logisticians gain knowledge and experience in weapon systems acquisition and sustainment. The LCBP is a premier developmental program designed to mature logistics officers as future leaders in the logistics and materiel enterprise and is governed by AFI 36-2111 (Department of the Air Force, 2017). Throughout their tour, Air Force logisticians will inevitably interface with industry and gain insight into the manufacturing process (Department of the Air Force, 2017). For logisticians assigned to the LCBP in aircraft depots, the program rotates personnel through three primary areas, which are supply chain management, depot maintenance, and a product support center or SPO (Department of the Air Force, 2017). Logistics professionals assigned to the LCBP have the opportunity to attend the Air Force fundamentals of acquisition course and be awarded the acquisition officer's badge. The positions filled by participants in the LCBP are coded as acquisition critical billets, in accordance with the Defense Acquisition Workforce Improvement Act (DAWIA) of 1990. This billet type allows logisticians to achieve an acquisitions professional

development program (APDP) level one certification in the category of lifecycle logistics, while assigned to the program (Department of the Air Force, 2017).

The SPEED guide described EWI fellowships as ten-month career broadening programs where logistics professionals learn about state-of-the-art technology and management practices, while being assigned to work with companies such as Delta, UPS, FedEx, and Amazon (AFPC, 2019). EWI fellowships provide logisticians an immersive, hands-on learning experience to better understand industry and to be able to better articulate Air Force concerns and requirements to commercial partners (AFPC, 2019). EWI fellowships allow for Air Force logisticians to become familiar with industry best practices and innovations and then bring that knowledge back the Air Force logistics enterprise, upon completion of the fellowship. By design, EWI fellowships are assignments that directly interface with industry. For logisticians assigned to work with a manufacturing company or within a manufacturing section of a company, there is a high potential that the logistician will learn about any advanced manufacturing technologies that the company is using.

The ALEET program was described as an “initiative designed to facilitate the career broadening between the acquisition and operational logistics career fields,” and was created to enhance awareness between product centers, most commonly SPOs, and logisticians in the field (AFPC, 2019, p. 20). Air Force logistics professionals assigned to the ALEET program earn an ADPD level two certification in either program management or lifecycle logistics, and they assist the acquisition cycle by providing user perspectives to the product development and support processes (AFPC, 2019). As members assigned

to a SPO, ALEET program participants are all but assured to interact with industry and have a high potential to be involved in, or experience, manufacturing processes of major defense contractors and OEMs.

As a point of comparison, this literature review would be incomplete without an analysis of the AFSC 63A, acquisition manager CFETP. SPEED programs such as the LCBP and the ALEET place a high emphasis on APDP certifications and working within the acquisition community. Additionally, acquisition program managers are often assigned to product centers and SPOs, working alongside the logistics officers selected for these programs. The 63A CFETP described acquisition program managers as having purview over every aspect of a defense acquisition program, including production, manufacturing, logistics support, and quality assurance (Department of the Air Force, 2012). The 63A CFETP made references to manufacturing in the sense of DMSMS, developmental test and evaluation support, and program risk management. The 63A CFETP identified seven core tasks related to manufacturing management and two core tasks associated with industry that are required to be completed in the first assignment of an acquisition manager. Second assignment 63A personnel are required to complete an additional four core tasks related to manufacturing, as noted in the CFETP. The 63A CFETP also mentioned competitively selected EWI fellowships and the ALEET program as opportunities for additional development. However, for acquisition managers selected for ALEET, the 63A personnel are assigned to an aircraft or missile maintenance unit, as opposed to 21A personnel being assigned to a product center or SPO (AFPC, 2019).

Manufacturing Theories

To make the manufacturing of on-demand aircraft spares and piece-parts responsive to the needs of the customer, cost-effective for the Air Force, and profitable for industry, several theories of manufacturing emerge, and apply to the three digital waves of manufacturing. Theory of Constraints (TOC), Lean Manufacturing, and Six Sigma are perhaps the most widely employed theories by the government, commercial, and defense-industrial bases and, as such are applicable to this research. The DoD and the industrial base have a symbiotic relationship, and maintaining a proper balance is critical to supporting the 2018 NDS. The DoD needs industry to remain profitable, incentivized, motivated, and capable of producing aircraft spares, piece-parts, sub-assemblies, and weapons systems. The defense industrial base can help ensure profitability by reducing operating costs through the application of manufacturing theories. The next portion will provide an overview of the Theory of Constraints, Theory of Lean Manufacturing, and Six Sigma statistical process controls to show how production can be increased, and operating costs reduced.

Theory of Constraints

Eliyahu M. Goldratt popularized TOC in his 1984 book titled *The Goal*. TOC applies to both the private and public defense industrial bases, and the literature suggests that industry is far ahead of the DoD in applying the theory. However, the Air Force logistics enterprise has recently established the Tesseract organization within the Headquarters Air Force staff, with one of its goals being bringing TOC training to the service's logistics enterprise, particularly field and base-level maintenance and logistics

units. Tesseract is made up of logistics Airmen working closely with the acquisition community, Rapid Sustainment Office, and Business Systems Enterprise Office, to apply TOC across the Doctrine, Organization, Training, Materiel, Leadership, and Education, Personnel, Facilities, and Policy solution spaces as defined by the Joint Staff, Joint Capabilities Integration Development System process. As noted by Tesseract, aerospace manufacturing has benefitted from TOC for decades, citing Delta Airline's application of TOC to help transform the airline over the past decade (SAF/AQ, 2019). Goldratt contended that organizations can be measured by throughput, expense, and inventory (Goldratt and Cox, 1984). TOC is an iterative management philosophy of continuous process improvement (CPI) focusing on and enhancing the throughput of the weakest part of a production system, referred to as the bottleneck or constraint (Şimşita et al., 2014). TOC postulates that every system has at least one bottleneck that prevents the system from reaching maximum performance and, therefore, by definition, is sub-optimized (Goldratt, 1990). As a method of CPI, TOC primarily consists of five steps. The steps include identifying the constraint and exploiting it to ensure that it works at maximum capacity; subordinating or slowing processes prior to the constraint; alleviating the constraint or expand its capacity; if possible remove the constraint; and then repeat the steps again to identify and mitigate the next constraint (Goldratt and Cox, 1984). Constraint identification shows decision-makers, where the bottleneck is in the system or process, while exploiting the constraint ensures that the bottleneck is operating at maximum throughput. Subordinating precursor activities prevents the constraint from becoming overwhelmed, and in the case of manufacturing, prevents the buildup of work

in progress (WIP) or unfinished goods throughout the system. One of the primary goals of TOC is to ensure continuous flow or to create value-added inputs that produce an output at each activity in the system (Davis et al., 2015). Flow is accomplished through continuous management and employee engagement and physically accomplished with the use of right-sized production and buffer stock. Today, TOC is almost always used in conjunction with the popular manufacturing theories of Six Sigma, which focuses primarily on the use of statistical controls, and lean manufacturing, which focuses on reducing waste in the process.

Theory of Lean Manufacturing

The theory of lean manufacturing, referred to as Lean, has its origins in the automotive manufacturing industry at Toyota in the 1970s and matured throughout the following decades. The Toyota Production System (TPS) is a CPI philosophy that recognizes and enhances the interaction of personnel with technical processes throughout the manufacturing system to eliminate "muda," the Japanese word for waste (Krafcik, 1988). Lean is a transformational set of theories, philosophies, and practices that incrementally look to create value and eliminate waste, thereby increasing quality and reducing production costs (Do, 2017). Lean consists of five principles. The first is defining value, most notably that the customer ultimately defines value in what they are willing to pay for, sometimes referred to as the voice of the customer. The next step is value stream mapping, which is a process of identifying the steps and activities in a process that either add value or do not add value. Non-valued steps or processes are considered waste. Lean then looks to create flow, ensuring the process or system

smoothly continues to produce value-added products or results. Lean creates a "pull system" that is defined as having the right number of items or products at the right place and time to reduce inventory or WIP, referred to as Just-in-Time inventory. Finally, Lean aspires for perfection, and the process is continually evaluated to identify and eliminate new or previously unaddressed areas of waste. Given Lean's focus on waste, the term must be defined. Detailed by the German trade website Everlean, the TPS determined waste to consist of overproduction, waiting, transportation, over-processing, excess inventory, unnecessary motion, and defects. Overproduction is arguably the most significant type of waste (2019). If there is no demand for something that is produced, then there is almost no value in producing the item in the first place. Waste in the form of waiting, either personnel or machines awaiting input or sitting idle in anticipation of work, do not add value to the process or end product. Unnecessary transportation, the physical movement of products or WIP, also does not add value to the end product. Over-processing or processing more than is required or demanded by the customer elongates the production system and increases operating expenses without added benefits to the producing organization. Excess inventory is defined as carrying too much inventory, or WIP, and causes the organization to incur capital and carrying costs that reduce the overall value of the product and present a financial risk. Unnecessary motion in a system adds unneeded time to the complete process and may impede flow. Defects require additional time to be repaired, reworked, or refinished and can consume additional raw materials. Additionally, throughout the production process, waste leads to the potential for underutilized personnel and, as such, are unrealized capacity, increasing the potential

for personnel turnover due to problems associated with under usage or boredom (Myerson, 2012).

Another cornerstone of Lean is a concept known as the 5Ss. According to the Lean Six Sigma Definition website glossary, 5S stands for sorting, setting, shinning, standardizing, and sustaining places and activities in a work center. Sorting is organizing a workspace and removing unnecessary items and materials. Setting, also called straightening, is placing items in an optimal location to ensure production and enhance flow. Shining, also called sweeping, is continually cleaning the work area to ensure employee safety and productivity. Standardizing procedures, workspaces, and schedules ensures employees are informed, and sustaining or self-discipline, seeks to continually maintain the efforts of 5S, train others, and make additional improvements when possible (Omogbai and Salonitis, 2017).

Lean is an especially important concept in the US where manufacturing is costly, and in the case of major weapons systems, it is a politically sensitive endeavor. Given that the defense industrial base has many regulatory restrictions and often must procure, produce, or manufacture assemblies and subassemblies throughout the different parts of the US, practicing Lean is valuable to an OEM and their upstream suppliers. The benefits of Lean manufacturing include increased productivity and mixed complexities without a reduction in quality, reduced lead times, reduced inventory and WIP, reduced shop space, increased sustainability and employee satisfaction, reduced operating costs, improved customer satisfaction, and increased profits. Lean theories are still applicable in the digital age and relevant to innovative manufacturing methodologies. Lean theories apply

to manufacturing systems that produce items in mass, as well as small production runs that may only produce a single item and is therefore pertinent to the evolution of the defense industrial base's support to the 2018 NDS.

Six Sigma

Six Sigma combines many management practices, theories, and philosophies and is a rigorous, focused, and highly effective implementation of proven statistical quality principles and techniques designed to identify and reduce variation (Pyzdek, 2019). Made popular by engineer Bill Smith at Motorola in the 1980s, Six Sigma aims to achieve customer satisfaction and to combine initiative with methodology. Six Sigma differs from other quality practices, especially the practice of Total Quality Management, because it combines the distinct view of the customer's expectations and the quality/price tradeoffs customers are willing to make (Tennant, 2001). Quality has two characterizations, potential and actual, and Six Sigma aims to produce a defect-free product 99.99966 percent of the time or per opportunity (Pyzdek, 2019).

Six Sigma uses measurements of supplier input to a process (SIPOC) to deliver outcomes to a customer. The SIPOC allows for identifying processes, inputs, and attributes that are critical to quality to satisfy the voice of the customer. To assist in this, Six Sigma relies on a structured problem-solving process known as DMAIC, an acronym for define, measure, analyze, improve, and control (George et al., 2005). Like TOC and lean, DMAIC is reliant on the robust participation of executives, senior leadership, mid-level management, and employees engaged in the work process.

According to the 2005 Lean Six Sigma Pocket Toolbook, the five steps of DMAIC included defining and validating that a problem exists; measuring and identifying key inputs, metrics, and value-added activities; analyzing processes to determine critical inputs and activities; identifying root causes, and prioritizing tasks; improvement or development of solutions and implementation plans, known as defining the "to be" state; and then controlling, or the process of implementing controls such as standard work, mistake proofing, and training. Six Sigma makes heavy use of statistical tools, charts, and visual data representation to inform decision-makers and quality managers. Instruments such as control, run, and Gantt charts are used in conjunction with root cause analysis tools such as fishbone diagrams, force field and Pareto analysis, and scatter plots to provide insights to processes and their relationship to quality. Moreover, Six Sigma employs failure mode and effects analysis tools, regression analysis and modeling, analysis of variation, simulations, and Poke-Yoke error-proofing implementation as just some of the methods for analyzing systems and improving process outputs. According to the online corporate Pyzdek Institute:

Companies operating at three or four sigmas typically spend between 25 and 40 percent of their revenues fixing problems. This is known as the cost of quality, or more accurately, the cost of poor quality. Companies operating at Six Sigma typically spend less than five percent of their revenues fixing problems. (Pyzdek 2019, para. 5)

Significant benefits of Six Sigma include problem identification and remedy, reduced cycle time, elimination of product defects, improved compliance, standardization, and increased customer satisfaction through participation and delivering on expectations (Pande and Holpp, 2001).

Summary

The literature reviewed revealed the difficulties and challenges involved in implementing or further progressing advanced manufacturing technologies into the defense industrial base as a whole, and it can be assumed that those same challenges would also apply to the Air Force logistics and materiel enterprises. An important beginning step to implementation of these kinds of advanced techniques would be to provide appropriate professionals within the logistics career fields with education and training about these techniques and their benefits and challenges. Given the priorities of the 2108 NDS, an exploration of the education and knowledge that Air Force logistics professionals currently possess regarding advanced manufacturing techniques is an optimal subject on which to base this research. Although the education and training provided to logisticians covered a vast range of subjects tangentially related to the defense industrial base and manufacturing, a review of the literature revealed a gap in the knowledge of how Air Force logistics professionals could use advanced manufacturing technologies, such as CNC, AM, and MM, to produce low volume or single-unit aircraft spares and piece-parts to support the 2018 NDS. The next chapter will detail the data collection process and the methodology used for the analysis to determine key words, themes, and challenges that Air Force logistics professionals identified.

III. Methodology

Chapter Overview

The purpose of this chapter was to describe the data collection methods, the data sources, and the processes used in the analysis of key words, themes, and challenges from that data. The purpose of the analysis was to explore the level of familiarity that Air Force logistics professionals have with advanced manufacturing techniques, such as CNC, AM, and MM, based upon assignment experience and APDP certification. The analysis also identified key words and themes related to on-demand aircraft spare or piece-part production using advanced manufacturing techniques, and it detailed the perceived challenges to further implementing advanced manufacturing techniques throughout the logistics and sustainment enterprises of the Air Force. The resulting data was then used to form the basis of the recommendations presented later in this research.

Professionals from across the Air Force logistics enterprise were queried, through a set of written interview questions, about their general familiarity with the three digital waves of manufacturing, and the components that advanced manufacturing techniques can produce. Additionally, Air Force logisticians were asked about the obstacles that they perceived to maturing and implementing CNC, AM, and MM techniques as an avenue to produce low volume batches of aircraft spares and piece-parts. The responses that were received were then aggregated into one document and manually searched for key words and phrases to identify themes and encode the findings. The researcher determined key words after reading all of the interview responses. The responses were then further

divided by interview questions, and the answers were grouped by respondents with common assignment experience, as described in the following paragraphs.

Participants

The population of this research was primarily Air Force logistics officers and civilians employed in the Air Force's logistics enterprise. The purposive sampling strategy entailed forwarding interview questions via electronic mail to potential respondents who were in known leadership positions across differing Air Force logistics organizations. In some cases, the interview questionnaires were then forwarded to subordinates in the respondents' organizations, leading to additional respondents through convenience sampling. Given the large variety of assignment types throughout the logistics enterprise, a minimum threshold of two respondents, with wholesale, retail, and acquisition experience, per each assignment type was set. The researcher kept the participants' responses and information confidential by removing any potentially identifying indicators throughout the analysis.

The Air Force logistics professionals queried held the AFSCs of 21A, aircraft maintenance; 21M, munitions and missile maintenance; 21R, logistics readiness; 2A7X1, metals technology; GS-0346, logistics management specialist; and GS-1601, industrial production manager. For assessing possible differences in education, participants were categorized as having wholesale experience, an acquisition certification, or retail-only experience. For this research, wholesale experience was defined as having been assigned, or permanently detailed to, an aircraft depot or air logistics complex; the 448th Supply Chain Management Wing; DLA; legacy Air Force Global Logistics Support Center

organizations outside of the 635th Supply Chain Operations Wing; or the LCBP or ALEET programs. Individuals with acquisition certifications were defined as those having attained a minimum level-1 APDP certification in either the categories of lifecycle logistics or program management. All participants that held an acquisition certification also had wholesale experience. All other assignments and special duties were considered retail experience.

The interview questions were sent to professionals with either wholesale or retail experience, both wholesale and retail experience, and those with an APDP certification. Sixteen respondents, ranging in grades from Senior Master Sergeant to Colonel and GS-12 to NH-04, commonly considered a GS-13 to GS-15 equivalent, returned answers.

Interview Questions

The interview questions were developed after a review of the literature revealed a gap in logistics professionals' education about advanced manufacturing techniques. The literature also revealed areas where the defense industrial base had eroded in the last several decades, and discussed the slow pace of the adoption of advanced manufacturing techniques. The interview questions were based on the concept that producing on-demand aircraft spares and piece-parts could be significantly beneficial to the Air Force's ability to support the 2018 NDS.

Interview questions were disseminated via electronic mail to 41 Air Force logistics professionals throughout the logistics enterprise. The following interview questions were employed:

1. Are you familiar with the concepts of Computer Numerical Control (CNC) machining, Additive Manufacturing (AM), and Metamorphic Manufacturing (MM)?
2. What do you feel is the Technology Readiness Level for CNC, AM, or MM to support the DoD's need to produce on-demand aircraft spares or piece-parts?
3. Would the DoD benefit from an organization that can quickly integrate parts of industry to rapidly produce aircraft spares or piece-parts on-demand, with little lead time and in small batches or single units?
4. Do you believe a complex aircraft spares or piece-parts can be manufactured using CNC, AM, MM technologies as opposed to castings, forgings, or other traditional methods?
5. What type of parts can be manufactured quickly and in low numbers using CNC, AM, and MM as opposed to castings, forgings, or other traditional manufacturing methods?
6. Traditional manufacturing processes aside (tooling, training, etc.), rapidly producing an aircraft spare or piece-part on-demand brings with it many challenges, including intellectual property rights, first-article testing, harden critical item testing, exotic or rare materials procurement, to name a few. What other challenges do you foresee?
7. What framework and timeline would you propose to take advantage of emerging manufacturing technologies to produce on-demand aircraft spares and piece-parts?

Assignment experience categories were assigned to respondents to identify possible patterns in the responses. The key words and phrases that were searched and encoded included the words or terminology related to, *structure, risk, risk aversion, test/testing, engineer/engineering, cost, invest/investment, return on investment (ROI), approve/approval, safety, safety of flight, funds/funding, quality, certify/certification, quality, and airworthiness.*

Summary

The qualitative methodology for this research study consisted of developing and disseminating a series of interview questions to Air Force logistics professionals spread throughout the logistics enterprise. The participants were then categorized by assignment experience and APDP certification to identify any patterns or differences in their responses. The results and analyses chapter of this research presents the themes that emerged, assesses the education that Air Force logisticians had about advanced manufacturing techniques, details any perceived barriers to further adopting advanced manufacturing techniques, and presents recommendations and areas for future research.

IV. Results and Analyses

Chapter Overview

The production, storage, and distribution of aircraft spares and piece-parts creates a variety of challenges for the Air Force, particularly in times of conflict in contested environments. For example, “the military faces a need of spare parts for a variety of equipment in widespread locations, which leads to complex logistics and causes repeated bottlenecks in the spare part supply chain” (Joaquin et al., 2019, p. 109). Logistics professionals with knowledge of advanced manufacturing techniques are well suited to meeting such complex challenges, particularly in the event of aircraft attrition in a high-intensity conflict. This chapter analyzed the interview responses of the logistics professionals and developed themes to explore the study’s research questions about the knowledge levels of current Air Force logistics professionals regarding advanced manufacturing techniques and barriers they perceived to implementing advanced techniques. The results of the qualitative interview analysis revealed several gaps in the education of logisticians on the advanced manufacturing techniques of CNC, AM, and MM, regardless of assignment or acquisition experience. Throughout the responses, several overarching themes emerged, including funding, quality, safety of flight, manufacturing approval processes, need for culture change, and risk management concerns associated with the production of aircraft parts using CNC, AM, or MM techniques. These themes were reiterated throughout each interview question response, and especially in the perceived challenges to further implementing advanced

manufacturing techniques, such as CNC, AM, and MM, as means to produce on-demand aircraft spares and piece-parts.

Themes

The 16 interview questionnaires contained a combined 4,097 words in response to all seven questions and revealed several common themes and keywords (see Figure 1). When repeated themes or related ideas appeared multiple times in a response to a single question, the similar concepts were consolidated for the analysis.

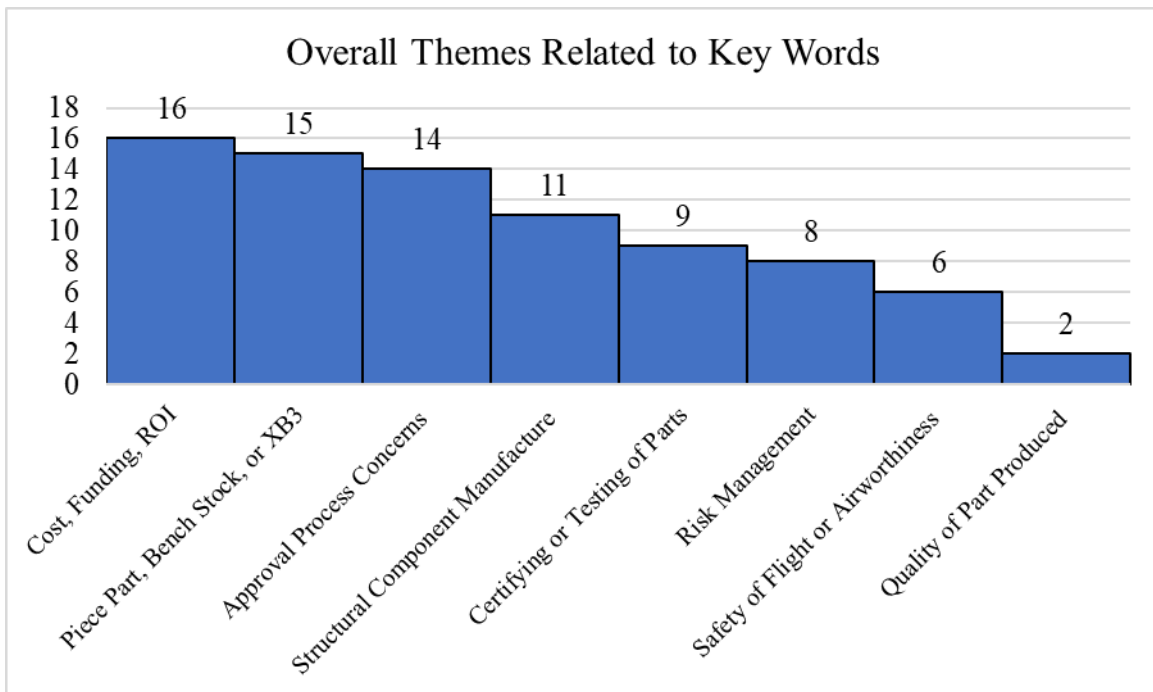


Figure 1. Overall Themes Related to Keywords

The raw number of keywords found throughout the interview responses was also noted and they were grouped by assignment experience (see Table 3).

Table 3. Keyword Count by Assignment Experience

Key Word	Wholesale w/Acq	Wholesale w/o Acq	Retail-Only	Total
Structure/Structural	4	2	5	11
Risk	3	1	5	9
Engineer/Engineering	0	6	1	7
Cost	2	1	4	7
Test	5	2	1	8
Approve/Approval	0	4	2	6
Safety	5	0	0	5
Investment/ROI	1	0	3	4
Funds/Funding	0	5	1	6
Quality	1	0	2	3
Certify/Certification	1	0	1	2
Airworthiness	0	0	1	1

Several responses included concerns and challenges related to the cost of equipment, training, and processes involving CNC, AM, and MM techniques and whether or not there was sufficient ROI if advanced manufacturing technology was further implemented. Additional themes that were identified included the current use of advanced manufacturing techniques to produce piece-parts; bench stock or expendability, recoverability, repairability code (ERRC) XB3; and generic structural items, such as ribs or supports. Furthermore, respondents identified challenges working within a risk-averse or overly bureaucratic culture, specifically referencing the engineering or SPO approval process for producing, certifying, and testing items manufactured using advanced techniques. Other themes identified throughout the responses included the safety of flight, the quality of manufactured components, and the need to partner with industry to bring advanced manufacturing as close as possible to the demand signal. Cost, funding,

or ROI were identified 16 times throughout the responses, while bench stock, piece-parts, or ERRC XB3 items were identified on 15 occasions. Respondents identified concerns with the manufacturing approval process 14 times, the manufacture of structural components 11 times, and the certification of testing of manufactured components nine times. Themes related to risk management were identified eight times, and safety of flight and airworthiness concerns were mentioned on six occasions. The production quality of any manufactured component was identified twice by respondents.

A raw count of key words found throughout the interview responses (see Figure 1 and Table 3) revealed that *structure/structural* was the primary word(s) related to the themes identified by the respondents and was identified 11 times. Other key words identified throughout the text were *risk*, identified nine times; *engineer/engineering* and *cost*, each identified seven times; *test*, identified on eight occasions; *approve/approval*, identified six times; *safety*, identified five times; *investment* or *ROI*, identified on four occasions; *funds/funding*, identified six times; *quality*, identified three times; *certify/certification*, identified twice; and *airworthiness* was identified on one occasion.

Familiarity with Advanced Manufacturing Techniques

Regarding the first research question that addressed Air Force logistics professionals' knowledge of advanced manufacturing, interview response analysis revealed that all 16 respondents were familiar with CNC and AM technologies (see Figure 2). One respondent, who had only retail experience, noted that he or she was only "conceptually" familiar with AM and stated "I do not know if I ever used an item produced using AM techniques." Another respondent with wholesale experience stated

that “we use CNC currently for manufacturing parts that go in our [missile] silos.” Five respondents claimed to be familiar with the concept of MM, however none of the respondents elaborated on their experience with, or use of, the technique. Of the respondents familiar with MM, two had acquisition experience, one had wholesale experience without an acquisition certification, and two respondents had only retail experience.

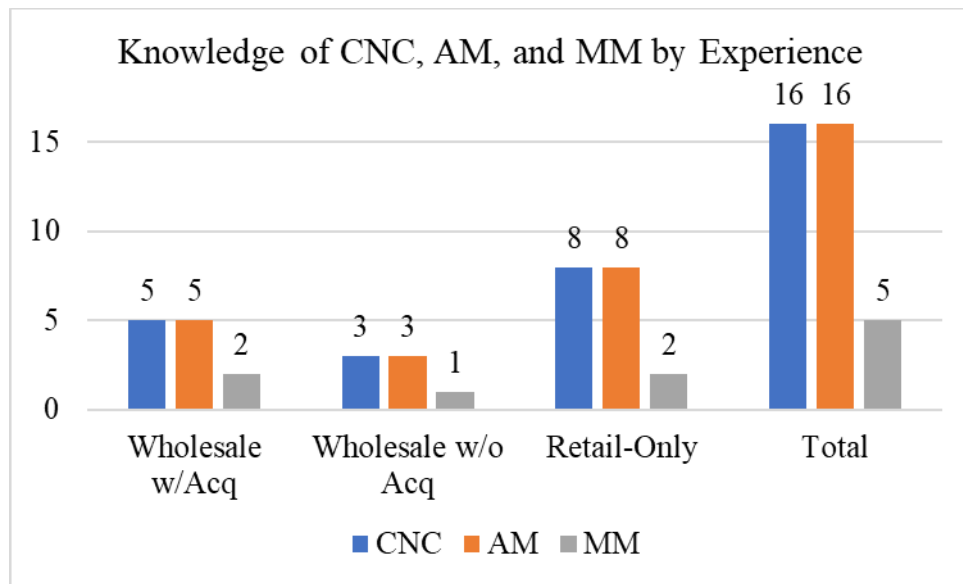


Figure 2. Knowledge of CNC, AM, and MM by Experience

The responses were further analyzed to determine the average perceived advanced manufacturing techniques' TRLs by respondent experience type (see Figure 3). All the respondents perceived CNC to be the most mature and advanced manufacturing technique, with an overall TRL average of eight. One respondent, with only retail experience, said, “CNC would seem to be the most ready, perhaps as high an eight.” AM

was considered the next most mature with an average TRL of six. However, several respondents added caveats to their assessments. An interview respondent, with only retail experience, said that he or she would assess the TRL of AM as “a qualified [five], that is to say that AM for plastics, resins and other like materiel, but I don’t know how far metal printing has evolved.” Respondents perceived MM to be the least mature technology with a TRL of four.

None of the assignment experience groups had a difference of over two levels for an assessed TRL. The TRL assessments corresponded to the relative time each manufacturing technique had been employed by the aerospace industry and defense industrial base, even if the actual TRL itself could be debated for each manufacturing technique.

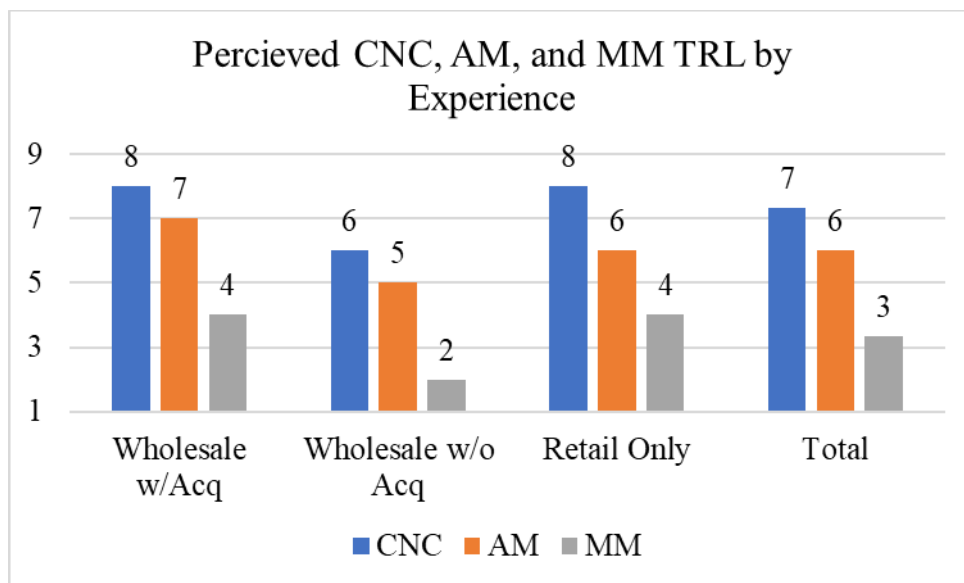


Figure 3. Percieved CNC, AM, and MM TRL by Experience

Of the logistics professionals queried, 13 of the 16 respondents were of the belief that the DoD would benefit from an agency that is capable of quickly pulling together the necessary entities of the defense industrial base to support a rapid, on-demand, low volume or single-unit production of an aircraft spare or piece-part in the event of a near-peer conflict or national emergency. Of note, the three respondents that dissented were limited to retail-only experience and reasons given were that such organizations already existed throughout the logistics enterprise, that such an organization would be viewed as a tiger team and such teams are not always the answer, and disbelief that industry would be willing to participate in such an endeavor. Of the positive responses, one respondent, with only retail experience, said that the Reverse Engineering and Critical Tooling (REACT) lab at the Ogden Air Logistics Complex “can partially do this now, but they are not postured for AF-wide support.”

All 16 respondents believed that CNC, AM, and MM techniques were capable of producing complex aircraft parts, however, analysis of the answers suggested that Air Force logisticians believed manufacturing simple parts was more appropriate (see Figure 4). The logisticians’ focus on producing simple components, rather than more complex parts, using an advanced technique could be related to the TRL of a particular advanced manufacturing methodology, or perhaps the responses were based on some of the respondents’ personal experiences with advanced manufacturing techniques.

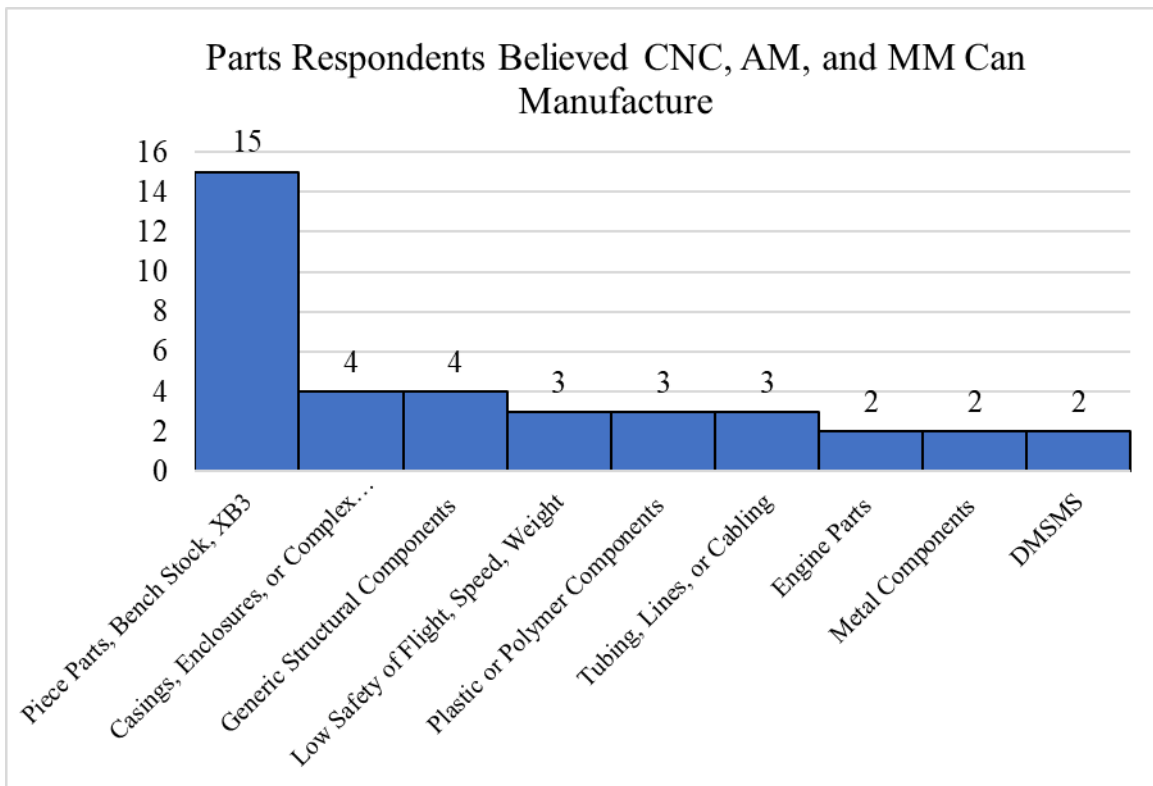


Figure 4. Parts Respondents Believed CNC, AM, and MM Can Manufacture

One respondent, with only retail experience, said, “complex aircraft parts have been CNC manufactured... [at the] field-level for over 20 years. AM has gained more interest over the last [five] years and polymer AM has been implemented at multiple locations.”

Items consistent with piece-parts or ERRC XB3, such as nuts, bolts, screws, shims, light and lens covers, dials, fasteners, fittings, receptacles, and switches, were mentioned 15 times throughout the interview responses and were items most commonly associated with AM techniques in retail, or base-level maintenance organizations.

Components made of plastics, polymers, metal, or engine parts were also associated with AM machines and mentioned on seven occasions. Manifolds, casing, enclosures, and

generic structural items, such as ribs, stringers, and load bearing components, were generally thought of as being manufactured via CNC machinery, and were also prevalent in the responses and identified eight times. One respondent, with wholesale experience, mentioned that an organization they were once a part of solved a fleet-wide issue for the T-38 aircraft by “using CNC and ‘hogging out’ a new part from a block of aluminum.”

Other ideas presented for CNC, AM, and MM techniques included producing tubing, cabling or lines, DMSMS components, items with low safety concerns, low speed requirements, or that are lightweight which combined for the remaining eight components that respondents believed advanced manufacturing is capable of producing. One respondent, with both wholesale experience and an acquisition certification, said, “I have seen AM used to make smaller plastic parts or tools that are not typically involved in safety of flight.”

There was no discernable pattern or difference in experience for the responses received, leading to the conclusion that all respondents, regardless of assignment experience, viewed advanced manufacturing techniques as currently best suited for relatively simple items, despite believing that such techniques were capable of producing complex items. This conclusion, however, was not completely consistent with the literature on the topic.

The literature was persistent in its mentioning of the capability and potential for advanced manufacturing techniques to produce complex aircraft parts faster, and with better precision than traditional manufacturing techniques, and the literature was also consistent in providing proof-of-concept case studies on the manufacturing of simplistic

items (Joshi and Sheikh, 2015). For example, using AM, the German Federal Armed Forces reproduced a symmetrically structured flanged shaft with nothing more than the original part, from which they created the technical data package, showcasing the potential of the technique of an intricate component (Montero et al., 2018). Additionally, in 2017, a group of undergraduate students at Ohio State University modified and reprogrammed a traditional CNC milling machine to metamorphically manufacture a horseshoe truss from a sphere of plasticine (Daehn, 2019). These case studies were consistent with the interview answers, as they illustrate that advanced techniques are currently adept at producing simple items but contain the promise of more complex components as the technology matures. Additionally, the Ohio State University example is consistent with the answers received, as the plasticine material used can be viewed as congruent with the plastics and polymers mentioned throughout the interview responses. Moreover, aircraft spares or piece-parts to be produced via AM with alloys or less common metals, such as titanium or nickel, were also supported throughout the literature and consistent with the responses in the generic forms of metal parts, engine parts, and load bearing components (Uriondo et al., 2015).

Perceived Barriers to Progressing Advanced Manufacturing Techniques

The second research question addressed by this research concerned the perceived barriers of Air Force logistics professionals to implementing advanced manufacturing techniques, such as CNC, AM, and MM. The perceived barriers to progressing and implementing advanced manufacturing techniques varied considerably across the set of

interview responses, but were internally consistent with themes identified in response to other questions throughout questionnaire (see Table 4).

Table 4. Perceived Challenges to Advanced Manufacturing

<i>Challenge</i>	<i>Wholesale w/o Acq</i>	<i>Wholesale w/Acq</i>	<i>Retail Only</i>	<i>Total</i>
Structural Stability		1		1
Institutional Resistance		2		2
Safety of Flight Concerns		1		1
Testing or Certification	1	2		3
Risk-Averse Culture		1	2	3
Infrastructure Close to the Demand Signal		1		1
Part Size		1		1
Training	1	1		1
Engineering Approval	2			2
SPO Approval	1		1	2
Challenges working with OEM			2	2
Cost or Funding of Equipment	1		1	2
Lifecycle Management Tracking			1	1
Quality Control			1	1
Environmental Control			1	1
ROI of Equipment			1	1
Digital Security			1	1

Safety, testing, quality, and the stability of the manufactured components were challenges identified by each experience group, being mentioned six times throughout the responses, and can be interpreted as one of the predominant concerns logistics professionals had about implementing advanced manufacturing techniques to support on-demand aircraft spares and piece-parts. One respondent, with wholesale experience and an acquisitions

certification, stated his or her concern was “legitimate safety of flight...and rigorous testing of these products.” The engineering and SPO approval processes, along with educating and overcoming a risk-averse culture, can be viewed as another challenge that respondents saw to integrating advanced manufacturing techniques into the Air Force logistics enterprise. These perceived barriers were identified seven times by the respondents, and when considered with the other identified challenge of organizational resistance, the tone of the responses suggested that Air Force logistics professionals were of the belief that overcoming these obstacles would be daunting. As one respondent, with wholesale experience, stated, “one of our greatest challenges in the [intercontinental ballistic missile] arena is gaining cognitive engineering approval for any new process or part manufacture.” Another respondent, with wholesale experience, opined that the major barriers to implementing advanced manufacturing techniques was “cost and us, the latter because we again have a hard time accepting risk. This requires culture change and I’m skeptical.” The themes of quality and approval were consistent with the aerospace industry’s two principal concerns of lightweight and safe components, and, therefore, displayed that the Air Force’s logistics professionals shared the same concerns as their counterparts throughout the defense industrial base (Joshi and Sheikh, 2015).

The responses were then examined to develop themes to overcoming the challenges identified to implementing advanced manufacturing techniques by respondents’ experience levels (see Table 5).

Table 5. Overcoming Challenges to Advanced Manufacturing by Experience

<i>Theme</i>	<i>Wholesale w/Acq</i>	<i>Wholesale w/o Acq</i>	<i>Retail Only</i>	<i>Total</i>
Develop strategies to overcome organizational resistance	1	1	1	2
Concentrate on constrained parts	1		1	2
Partner with industry to develop technologies	2	1	1	4
Build a test case on a specified system	1		1	2
Need to implement advanced manufacturing ASAP - 3 years	2	1	2	4
Need a top down driven approval process		1	1	2
Overcome funding challenges			2	2

In order to overcome the challenges that were identified, interview respondents twice identified a need to develop a strategy to overcome institutional resistance. Respondents also identified a need to partner with industry within the next three years to begin implementing advanced manufacturing technologies on a larger scale, which was articulated on four occasions. Respondents twice recommended adequately funding the advancement of CNC, AM, and MM, and developing a test case using an unmanned system or ground equipment to test using advanced manufacturing techniques. Respondents also mentioned on two occasions that CNC, AM, and MM should concentrate on constrained or DMSMS parts as a proof-of-concept to overcome barriers. No discernable patterns in assignment groups were identified in the answers given.

Respondent Demographics

Of the 41 interview questionnaires sent to logistics professionals, 17 responded, for a 41 percent return rate. However, one response was discarded because the respondent was not a logistician or otherwise directly involved in the Air Force's logistics enterprise. At the time the responses were received, seven respondents held the grade of major, three colonel, two lieutenant colonel, one captain, one senior master sergeant, one GS-12, and one NH-04 (see Figure 5).

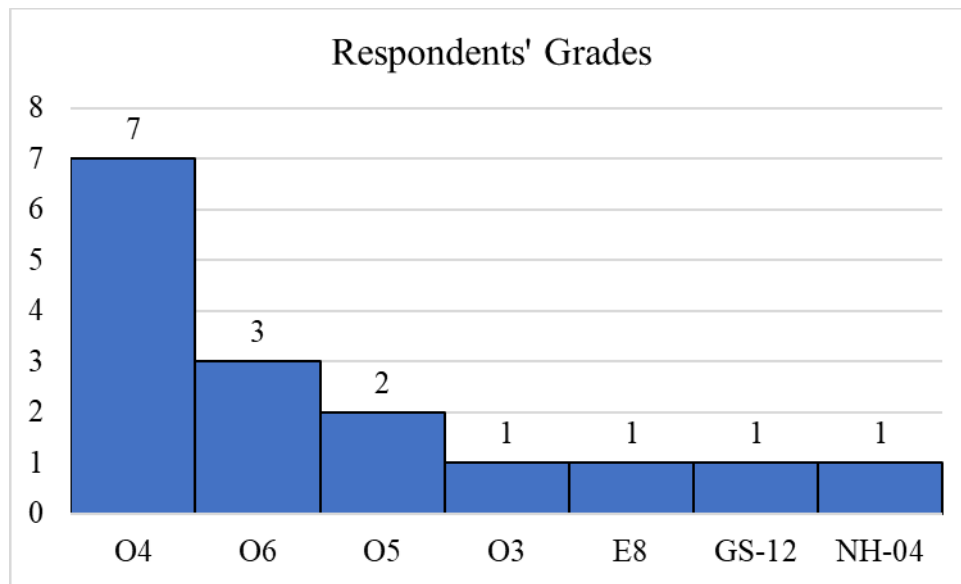


Figure 5. Respondents' Grades

Nine of the respondents held the AFSC of 21R logistics readiness officers, four 21A Aircraft maintenance officers, two 21M munitions maintenance officers, one 2A7X1 metals technology craftsman, one series GS 0346, logistics specialist, and one GS 1601 industrial production manager (see Figure 6).

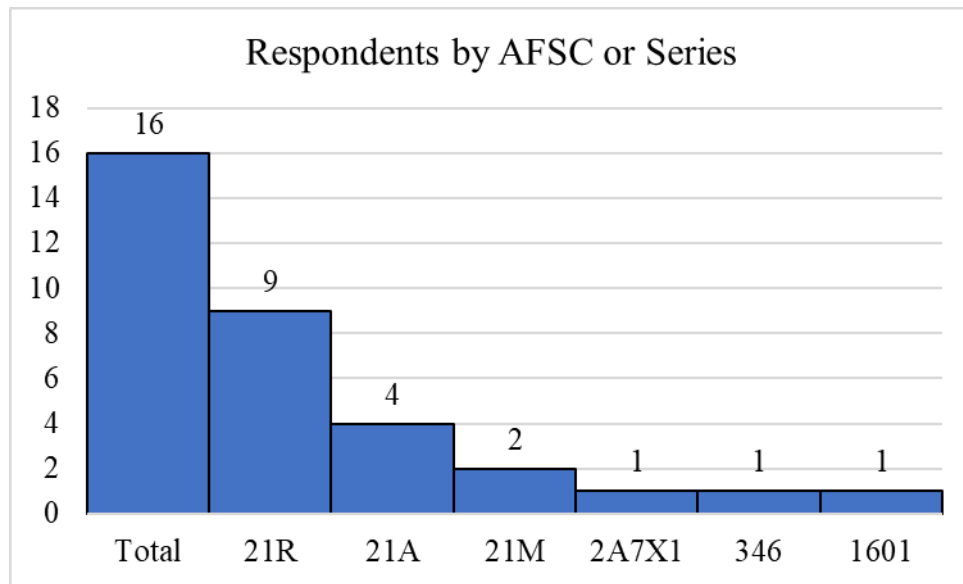


Figure 6. Respondents by AFSC or Series

Two interview respondents were qualified as both a logistics readiness and aircraft maintenance officers. The respondents were also sorted into categories by experience type (see Figure 7).

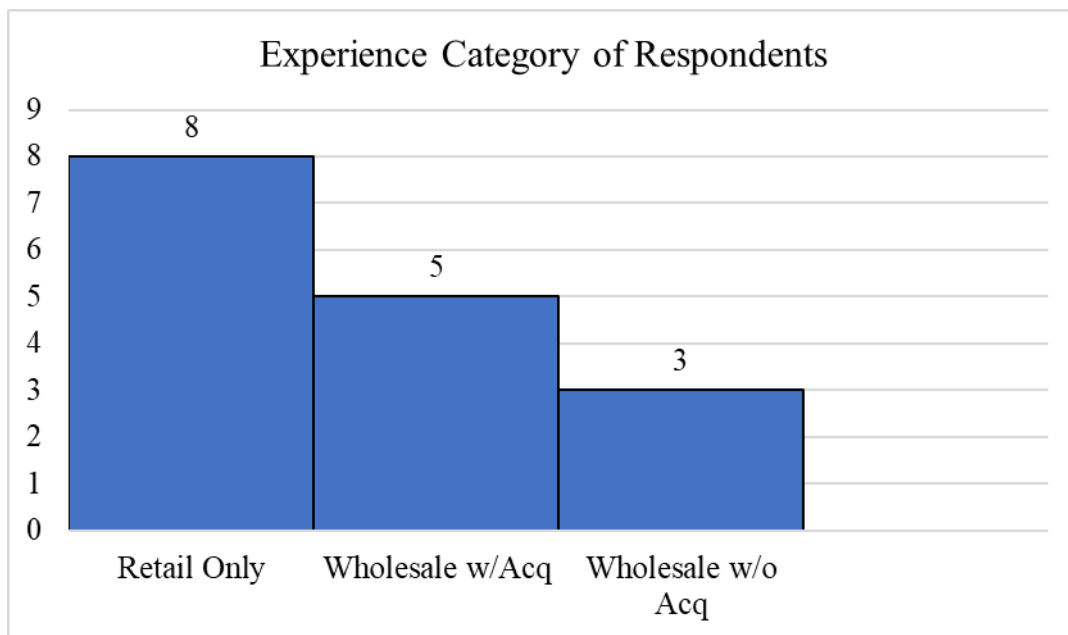


Figure 7. Experience Category of Respondents

Eight respondents had wholesale experience, with five of those respondents having attained a DAWIA APDP certification of at least level 1. All five of the respondents with both an APDP certification and wholesale experience were LCBP graduates. Three of the eight respondents with wholesale experience did not hold an acquisition certification. The remaining eight respondents had only retail experience and had not attained an APDP certification.

Summary

The respondents all shared common or overlapping themes and displayed similar familiarity with advanced manufacturing techniques regardless of AFSC, series, grade, assignment experience, or APDP certification. All respondents viewed subtractive manufacturing processes as being the most mature, and all viewed AM as an avenue to produce relatively simple aircraft spares or piece-parts, while no other specific references were made to the process of MM by any participant. All respondents saw the potential of advanced manufacturing techniques to produce complex on-demand aircraft spares and piece-parts, but also shared concerns about establishing quality and certification standards consistent with themes routinely identified in AM literature (Uriondo et al., 2015). Respondents identified the primary barriers to further implementing advanced manufacturing techniques as being related to the manufacture approval process and overcoming a risk averse culture. Additionally, respondents viewed funding as a major challenge, and suggested these barriers needed to be addressed within the next three years.

V. Conclusion and Recommendations

Research Limitations

In order to maintain the institutional review board exemption for this research, the interview questions could only be submitted to Air Force active duty or Air Force government employees and logistics personnel. This limited the scope of the research by restricting it to a relatively small number of potential participants. Another limitation was that the researcher had limited knowledge about, and access to, the training and education currently available to Air Force logistics professionals. Further research would benefit from a more extensive review of the current education and training content regarding advanced manufacturing that Air Force logistic professionals receive. The research was also done with time and resources limitations, which prevented the researcher from including more participants in the study, and prevented the learning and use of qualitative analysis software to aid in the analyses, as well as the use of any of the available techniques, such as triangulation, use of contradictory evidence, respondent validation, or constant comparison, to substantiate result validity (Anderson, 2010).

Future research should address some of these limitations and should consider ensuring that participants included in the research are as representative of the entire population of Air Force logistics professionals as possible to improve research validity.

Conclusions of Research

RQ1: Familiarity with Advanced Manufacturing Conclusions

The responses to the interview questions and the themes that were identified showed that Air Force logistics professionals, regardless of assignment experience or

APDP certification, were only partially familiar with advanced manufacturing techniques. The qualitative analysis of Air Force logistics interview responses revealed that the Air Force logistics had limited education about advanced manufacturing techniques. These findings were consistent with the review of the different CFETPs and flysheets and opens the aperture to ask why innovative manufacturing techniques are not part of an Air Force logistics professionals' standard education and training.

Given some of the responses to the interview questions were only partially consistent with the literature, and that they showed no discernable patterns across the demographics, the Air Force should consider placing a greater emphasis on advanced manufacturing techniques when the logistics CFETPs are next rewritten. Additionally, if manpower and funding allow, the Air Force should consider providing more opportunities to interface with the defense industrial base, starting early in logistics officers' careers, to include possibly assigning newly commissioned officers directly into wholesale or materiel organizations as a first assignment. The Air Force logistics community should consider creating educational, developmental, and assignment milestones specifically related to retail, wholesale, and acquisition experience, education, and training. Additionally, logistics professionals should be regularly rotated through the different assignment types to ensure that a continual exchange of perspectives, ideas, and experiences are brought to each area. A concerted assignment, education, and training rotation would soften the divide between assignment types, combat competency stove piping, and prevent career brandings as a specific type of logistician. If the population of

logisticians allows, the Air Force should consider expanding existing opportunities and increasing the pool of eligible personnel for SPEED programs, or possibly develop additional SPEED programs, that interface with industry for mid-career and senior logisticians. Developing a continuum of industrial and manufacturing education, training, and assignments, would help create consensus relating to challenges that the Air Force and the defense industrial base face. It would also better enable the development of solutions, like how to produce on-demand aircraft spares and piece-parts in support of a high intensity conflict, as indicated in the 2018 NDS.

RQ2: Perceived Challenges to Implementing Advanced Manufacturing Techniques

The analysis of the interview responses concluded that a general consensus was not achieved in what Air Force logistics professionals perceived to be the primary challenges to further implementing advanced manufacturing techniques. However, the themes of funding, a risk-averse manufacturing approval process, and risk-averse culture, warrant special consideration and were found in the responses to nearly every question. Every demographic alluded to challenges involving the funding of advanced manufacturing machinery, equipment, and training. Additionally, every demographic of respondent mentioned a risk-averse engineering and SPO approval processes, embedded in an overarching risk-averse culture of the Air Force's materiel enterprise. As such, the Air Force should consider creating an advanced manufacturing task force (AMTF) to addresses challenges identified by the interview participants.

An AMTF could seek solutions to fund advanced manufacturing machinery, equipment, and training at the base level, or it could create an intermediate level of

manufacturing, similar to that of the current network of central repair facilities for aircraft commodities that the Air Force established in recent years. This intermediate level of manufacturing would be specifically designed to overcome engineering and production obstacles, with the mission of rapidly producing on-demand spares and piece-parts in small volumes or single units. A series of dedicated intermediate manufacturing facilities, presumably based on the manufacturing method used or on geographic location, would be located closer to the demand signal and not impede or otherwise add to the workload of the manufacturing efforts taking place at the aircraft depots or burden the defense industrial base with low volume spares or piece-parts manufacturing orders. These intermediate level manufacturing facilities could not only be used to produce low volume spares and piece-part batches on-demand, but could also be used to further mature advanced manufacturing technologies, and would provide developmental assignment opportunities for Air Force logistics professionals as an additional benefit. It is assumed that a small number of strategically located intermediate manufacturing facilities would be more economical than purchasing machinery and providing training for each base, and thus afford sufficient ROI for the Air Force logistics enterprise.

Additionally, the AMTF should consider developing a new education and action plan that incorporates advanced manufacturing techniques and risk mitigation strategies, targeting engineers and product support managers within the materiel enterprise. The education and action plan would help overcome unnecessary risk aversion and burdensome bureaucracy, with an emphasis placed on the manufacturing approval process. To lend credibility to the education and action plan, the AMTF could partner

with the aerospace industry and companies such as Southwest and Delta. It could also use examples from existing innovative organizations already within the Air Force, such as REACT, AFWERX, and the Air Force Rapid Sustainment Office, to develop learning materials, duplicate best practices, and benchmark training techniques. By partnering with industry and existing entities, the AMTF could bring a sense of innovation to the materiel enterprise and provide a framework for the engineering and product support communities to accept the appropriate level of risk when reviewing and approving manufacturing requests. Additionally, the AMTF could seek to partner with advanced manufacturing organizations, such as American Lightweight Materials Manufacturing Innovation Institute and TMMS, to help further engender a spirit of innovation into the acquisition and sustainment processes and help mature and eventually scale sophisticated manufacturing techniques throughout the logistics and materiel enterprises. These combined partnerships can be facilitated by the AMTF and have a high potential to transform the materiel enterprise's culture from being risk-averse and bureaucratic to one that is responsive and innovative.

As the defense industrial base attempts to recover from its NDIA "C" rating, a strong partnership between industry and the Air Force stands to greatly benefit both parties. This research presented several ways to bridge the knowledge gap that Air Force logistics professionals had about advanced manufacturing and provided suggestions to better interface with the defense industrial base. This research also identified perceived barriers to further implementing advanced manufacturing technologies, and recommended strategies to overcome those obstacles. To meet the goals set out in the

2018 NDS, Air Force logisticians will need to be better educated on techniques available to produce on-demand aircraft spares and piece parts. Additionally, logistical barriers will need to be overcome, and the defense industrial base must become more responsive to the demand signal, if the US is to prevail in a high intensity conflict.

Recommendations for Future Research

This research identified several areas that should be considered for future study. Subjects such as the placement of advanced manufacturing machines, the effects of CNC, AM, and MM on spares' cycle times and demand data, and the projected manpower reductions or burdens on the Air Force logistics enterprise, all provide areas of opportunity for exploration. Additionally, researchers can consider how much education Air Force logisticians should have concerning the defense industrial base, spares, and piece-parts manufacturing, and at what point in their careers and to what level logisticians should be educated. Furthermore, researchers can study which positions within the logistics enterprise these more educated logisticians should hold, when they hold them, and how logisticians should rotate between retail, wholesale, and acquisition assignments. This research can help inspire other studies relating to how to change a risk-averse engineering culture, or how to incorporate accepting an appropriate level of risk in a SPO or product support center. Finally, future research can explore how advanced manufacturing techniques should be leveraged to support, rewrite, or revise war plans, particularly war plans where high attrition is expected, as this most directly relates to the 2018 NDS.

Bibliography

- Ahtiluoto, Matti, Asko Ellman, and Erik Coatanea. Model for Evaluating Additive Manufacturing Feasibility in End-Use Production. *Proceedings of the Design Society: International Conference on Engineering Design*, 1(1) (2019), 799-808.
- Anderson, Clair. Presenting and Evaluating Qualitative Research. *American Journal of Pharmaceutical Education*, 74(8) (11 October 2010), 141-148.
- Air Force Personnel Center. Personnel Services Delivery Memorandum 18-88, 2019 Academic Advanced Degree (AAD) Special Experience Exchange Duties (SPEED) Selection Board Results. Joint Base San Antonio-Randolph TX, 2 November 2018.
- Air Force Personnel Center. Personnel Services Delivery Memorandum 19-83, 2020 Academic Advanced Degree (AAD) Special Experience Exchange Duties (SPEED) Selection Board Results. Joint Base San Antonio-Randolph TX, 29 October 2019.
- Air Force Personnel Center. Advanced Academic Degree/Special Experience Exchange Duty Selection Process Guide. Joint Base San Antonio-Randolph TX, 1 April 2020.
- Banke, Jim, "Technology Readiness Levels Demystified." *National Aeronautics and Space Administration*. 20 August 2010. Retrieved 15 December 2019.
- Banks, Jim, "Rep. Banks Announces Release of Reagan Task Force Report on Strengthening America's National Security Innovation Base." *Press Release*. 4 December 2019.
- Bramlet, Christina, "How CNC Led To Cells." *Modern Machine Shop*. 2 September 2007. Retrieved on 15 December 2019.
- Cancian, Mark F. "U.S. Military Forces in FY 2020: Air Force." Unpublished Report. Center for Strategic and International Studies, Washington DC, 21 October 2019.
- Cecire, Michael, "The Russian Invasion of Ukraine." *Foreign Policy Research Institute*. 2 March 2014. Retrieved on 16 January 2020.
- Daehn, Glenn. "'Robotic blacksmithing': A technology that could revive US manufacturing." *The Conversation*. 11 December 2019. Retrived 4 May 2020.

- Daehn, Glenn and Alan Taub. "Metamorphic Manufacturing (a.k.a. Robotic Blacksmithing): The Third Wave of Digital Manufacturing." Unpublished Presentation. Lightweight Innovations for Tomorrow, Detroit MI, 26 October 2017.
- Davis, Connie, Justin Hassen, Laura Griggs, Elaine Frock, and Denise Bryant. *The Air Force Sustainment Center Presents the Art of the Possible*. Hill Air Force Base: 367th Training Support Squadron, 2015.
- Department of the Air Force. *Acquisition Managers 63A & 1101*. CFETP 63AX & 1101. Washington DC: HQ USAF, 1 August 2012.
- Department of the Air Force. *The Logistics Career Broadening Program*. AFI 36-2111. Washington DC: HQ USAF, 17 February 2017.
- Department of the Air Force. *AFSC 21AX Aircraft Maintenance Officer*. 21AX CFETP. Washington DC: HQ USAF, 25 May 2017.
- Department of the Air Force. *AFSC 21RX Logistics Readiness Officer*. 21RX CFETP. Washington DC: HQ USAF, 30 June 2017.
- Department of the Air Force. *AFSC 21MX Munitions and Missile Maintenance Officer*. 21MX CFETP. Washington DC: HQ USAF, 16 July 2019.
- Department of Defense. *Technology Readiness Assessment (TRA) Deskbook*. Director, Research Directorate and Office of the Director and Defense Research and Engineering: Washington DC, 2009.
- Department of Defense. *National Defense Strategy*. Washington DC, June 2008.
- Department of Defense. *Sustaining US Global Leadership: Priorities for the 21st Century Defense*. Washington DC, 3 January 2012.
- Department of Defense. *Summary of the 2018 National Defense Strategy of the United States*. Washington DC, 2018.
- Department of Defense. *Industrial Capabilities*. Office of the Under Secretary of Defense for Acquisition and Sustainment and Office of the Deputy Assistant Secretary of Defense for Industrial Policy annual report to congress. Washington DC. 2019.
- Dhital, Dipesh, "Airline Industry 2019." AviationOutlook.com. 16 July 2019. Retrieved 16 January 2020.

- Dietrichab, David M. and Elizabeth A Cudney. Methods and considerations for the development of emerging manufacturing technologies into a global aerospace supply chain. *International Journal of Production Research*, 49(10) (2011) 2819-2831.
- Do, Doanh, “*The Five Principles of Lean.*” The Lean Way. 5 August 2017. Retrieved 3 April 2020.
- European Space Administration. *Technology Readiness Levels Handbook for Space Applications*. Issue 1. 6 September 2008.
- Ford, Simon and Melanie Despeisse. “Additive manufacturing and sustainability: an exploratory study of the advantages and challenges,” *Journal of Cleaner Production*, 137 (2016), 1573-1587.
- Fredriksen, John C. *The United States Air Force: A Chronology*. Santa Barbra: ABC-CLIO, 2011
- Friedman, Norman and Scott C. Truver. “This Truck Saved My Life! Lessons Learned from the MRAP Vehicle Program.” Unpublished Report. Defense Acquisition University, Fort Belvoir VA, 30 June 2014.
- Goerge, Michael L., David Rowlands, Mark Price, and John Maxey. *Lean Six Sigma Pocket Toolbook*. New York: McGraw-Hill Book Company, 2005.
- Goldratt, Eliyahu M. *Essays on the Theory of Constraints*. Great Barrington: North River Press, 1998.
- Goldratt, Eliyahu M. and Jeff Cox. *The Goal*. Great Barrington: North River Press, 1984
- Goldratt, Eliyahu M. and Jeff Cox. *What is this thing called the Theory of Constraints?* Great Barrington: North River Press, 1990.
- Government Accountability Office. *Rapid Acquisition of Mine Resistant Ambush Protected Vehicles*. GAO-08-884R. Washington DC, 15 July 2008
- Government Accountability Office. *Best Practices DoD Can Achieve Better Outcomes by Standarizing the Way Manufacturing Risks are Managed*. GAO-10-439. Washington DC, 22 April 2010.
- Guo, Nannan and Ming C. Leu. Additive manufacturing: technology, applications and research needs. *Frontiers of Mechanical Engineering*, 8(3) (2013), 215-243.

- Hallman, Wesley and Christopher Smith, "Vital Signs 2020: Defense Industrial Base's Report Card Reveals 'C' Grade." *National Defense*. 21 January 2020. NationalDefenseMagazine.org. Retrieved on 14 February 2020.
- Hallman, Wesley, Christopher Smith, and Corbin Evans. "Vital Signs 2020 The Health and Readiness of the Defense Industrial Base." Unpublished Report. National Defense Industrial Association, Arlington VA, 5 February 2020.
- Harper, Jon, "Vital Signs 2020: Industrial Base Could Struggle to Surge Production in Wartime." *National Defense*. 24 January 2020. NationalDefenseMagazine.org. Retrieved on 14 February 2020.
- Haulman, Daniel L. "USAF Named operations 1947-2006." *Air Force Historical Support Division*. 30 August 2011. Retrieved 4 May 2020.
- Héder, Mihály. From NASA to EU: The evolution of the TRL scale in Public Sector Innovation. *The Innovation Journal*, 22(2) (2017), 1-23.
- Hitt, Michael A., R. Edward Freeman, and Jeffrey S. Harrison. *The Blackwell Handbook of Strategic Management*. Hoboken: Wiley, 2001.
- Hooke, Richard, Global Aerospace and Defence Leader. "The Defense Industry in the 21st Century." Unpublished Paper. PricewaterhouseCoopers, London UK, 2005.
- Implementation of the National Defense Strategy: Hearing before the Armed Services Committee, Senate, 166th Cong. 1 (2019) (Testimony of Elbridge A. Colby).
- Joshi, Sunil C. and Abdullah A. Sheikh. 3D printing in aerospace its long-term sustainability. *Virtual and Physical Prototyping*, 10(4) (2015), 175-185.
- Kobren, Bill, "Core and the 50-50 Rule – A Study in Contrasts." *Defense Acquisition University*. 4 September 2008. Retrieved on 8 November 2019.
- Krafcik, John F. Triumph of the Lean Production System. *Sloan Management Review*, 30(1) (1988), 41-52.
- Lee, Connie, "Vital Signs 2020: Small Businesses Concerned About New Cybersecurity Certification." *National Defense*. 23 January 2020. NationalDefenseMagazine.org. Retrieved on 14 February 2020.
- Long, Lane, "Metamorphic Manufacturing: The "Third Wave" of Digital Manufacturing." *Engineering.com*. 2 January 2020. Retrieved on 16 January 2020.

- Lynch, Mike, “Key CNC Concept #1—The Fundamentals Of CNC” *Modern Machine Shop*. 1 April 1997. Retrieved on 3 April 2020.
- Lyons, Brett. Additive Manufacturing in Aerospace Examples and Research Outlook. *The Bridge Frontiers on Engineering*, 42(1) (2012), 13-19.
- Mankins, John C. Technology readiness assessments: A retrospective. *Acta Astronautica*, 65(9) (2007), 1216-1223.
- Möllera, Christian, Hans C. Schmidt, Philip Koch, Simon-Markus Kothe, Jörg Wollnak and, Wolfgang Himtz. *Procedia Manufacturing*, 14 (January 2017), 17-29.
- Montero, Joaquin, Kristin Paetzold, Mathias Bleckmann, and Jens Holtmannspoetter. “Re-design and re-manufacturing of discontinued spare parts implementing additive manufacturing in the military field,” *DESIGN 2018 International Design Conference*. 1269-1278. Dubrovnik, Croatia, 24 May 2018.
- Montero, Joaquin, Kristin Paetzold, Mathias Bleckmann, and Jens Holtmannspoetter. “Enhancing the Additive Manufacturing process for spare parts by applying Agile Hardware Development principles,” *2019 IEEE 10th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)*. 109-116. Cape Town, South Africa, 17 February 2019.
- The Minerals, Metals & Materials Society. “Metamorphic Manufacturing: Shaping the Future of On-Demand Components.” Unpublished Report. TMMS, Pittsburgh, PA, 2019.
- Myerson, Paul. *Lean supply chain and logistics management*. New York: McGraw-Hill Book Company, 2012.
- Naylor, Arch W. and Mark C. Maletz. The Manufacturing Game: A Formal Approach to Manufacturing Software. *IEEE Transactions on Systems, Man, and Cybernetics*, 16(3) (1986), 321-334.
- Ni, Jun. CNC Machine Accuracy Enhancement Through Real-Time Error Compensation. *Journal of Manufacturing Science and Engineering*, 119(4B) (1997), 717-725.
- Office of Personnel Management. Position Classification Flysheet for Logistics Management Series, GS-0346. TS-78. January 1987.
- Omogbai, Oleghe and Konstantinos Salonitis. “The Implementation of 5S Lean Tool Using System Dynamics Approach.” *Procedia CIRP*, 60 (10 May 2017), 380-385.

- O'Neill, Mike, "From Idea to 3-D in a Day: UPS and Fast Radius." *Technologies and Operations Management*. Harvard Business School. 12 November 2018. Retrieved on 3 April 2020.
- Pande, Pete S. and Larry Holpp. *What is Six Sigma*. New York: McGraw-Hill Book Company, 2001.
- Petersen, Bent, André Laplume, and Joshua Pearce. Global value chains from a 3D printing perspective. *Journal of International Business Studies*, 47(5) (2016), 595-609.
- Plafke, James. "NASA successfully tests 3D-printed rocket injector, showcases viability of 3D printing." *ExtremeTech*. 29 August 2013. Retrieved on 4 May 2020.
- Plewa, Kat, "3D printing and reverse engineering: how to improve your production." *Sculpteo*. 10 December 2019. Retrieved on 11 November 2019.
- Proff, Harald and Andreas Staffe. "Challenges of Additive Manufacturing: Why companies don't use Additive Manufacturing in serial production." Unpublished Report. Deloitte Touche Tohmatsu Limited, London UK, February 2019.
- Pyzdek, Thomas. "The Six Sigma Revolution." *Pyzdek Institute*. 21 December 2000. Retrieved on 3 April 2020.
- Rutkofsky, Marni, Tara DiJulio, Darby Becker, Jeff Connor, Mark Besonen, Shaun Wootton, Michael Fitzpatrick, Karen Kerr, and Steve Taub. "The Additive Journey: The Time is Now." Unpublished Whitepaper. GE Additive, Cincinnati OH, 2 October 2018.
- SAF/AQ, AF/A4, AFLCMC. *Tesseract Charter*. Washington DC: HQ USAF, December 2019.
- Sejersgaard-Jacobsen, Michelle, "Interview with UPS: how will 3D printing impact the Supply Chain?" *3Dnatives*. 19 November 2018. Retrieved 4 May 2020.
- Simpson, Timothy W., Christopher B. Williams, and Michael Hripko. Preparing industry for additive manufacturing and its applications: Summary & recommendations from National Science Foundation workshop. *Additive Manufacturing*, 13 (2017), 166–178.

- Şimşit, Zeynep T., Noyan S. Günay, and Özalp Vayvay. Theory of Constraints: A Literature Review. *Procedia - Social and Behavioral Sciences*, 150 (2014), 930-936.
- “Standard Terminology for Additive Manufacturing Technologies.” *ASTM International*. 9 September 2017. Retrieved on 8 March 2020.
- Tadjdeh, Yasmin, “Vital Signs 2020: Defense Sector Straining to Attract STEM Talent.” *National Defense*. 22 January 2020. *NationalDefenseMagazine.org*. Retrieved on 14 February 2020.
- Task Force on 21st-Century National Security Technology and Workforce. “The Contest for Innovation: Strengthening America's National Security Innovation Base in an Era of Strategic Competition.” Unpublished Report. Ronald Reagan Presidential Foundation & Institute, Washington DC, 2 December 2019.
- “Technology Readiness Levels.” *AcqNotes Defense Acquisitions Made Easy*. Defense Acquisition University. 22 June 2018. Retrieved on 7 October 2019.
- Tennant, Geoff. *Six Sigma: SPC and TQM in Manufacturing and Services*. Burlington: Gower Publishing Company, 2001.
- “Test & Evaluation.” *AcqNotes Defense Acquisitions Made Easy*. Defense Acquisition University. 6 June 2018. Retrieved on 7 October 2019.
- Tirpak, John. A., “The Distillation of the Defense Industry.” *Air Force Magazine*. 1 July 1998. Retrieved on 16 January 2020.
- Uriondo, Adrian, Manuel Esperon-Miguez, and Suresh Perinpanayagam. The present and future of additive manufacturing in the aerospace sector: A review of important aspects. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 229(11) (2015), 2132–2147.
- Watkins, Derek, “What China Has Been Building in the South China Sea.” *New York Times*. 27 October 2015. Retrieved on 11 November 2019.

REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY) 07/09/2020		2. REPORT TYPE Graduate Research			3. DATES COVERED (From - To) July 2019 - June 2020	
4. TITLE AND SUBTITLE A Qualitative Assessment Of Air Force Logisticians' Knowledge of Advanced Manufacturing Techniques				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Fekete, Robert J., Major				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way Wright-Patterson AFB OH 45433-7765					8. PERFORMING ORGANIZATION REPORT NUMBER AFIT-ENS-MS-20-J-035	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Logistics Agency-Aviation Attn: Brigadier General David Sanford 8000 Jefferson Davis Hwy Richmond, VA 23297 David.Sanford@dla.mil					10. SPONSOR/MONITOR'S ACRONYM(S) DLA Aviation/CC	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Statement A. Approved for Public Release; Distribution Unlimited						
13. SUPPLEMENTARY NOTES This work is declared a of the U.S. Government and is not subject to copyright protection in the United States.						
14. ABSTRACT Research has shown that the US Air Force and the US defense industrial base have limited capability to produce on-demand aircraft spare parts or piece-parts in support of the 2018 National Defense Strategy, when no stock exists. This purpose of this research was to assess the familiarity that US Air Force logistics professionals have with advanced manufacturing techniques capable of producing on-demand aircraft spares and piece-parts, and to identify the barriers they advanced manufacturing techniques. The responses were qualitatively analyzed and the resultant themes were presented and discussed.						
15. SUBJECT TERMS Defense Industrial Base, National Defense Strategy, Advanced Manufacturing, Additive Manufacturing, Metamorphic Manufacturing, On-Demand Manufacturing						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Lt Col John M. Dickens AFIT/ENS	
U	U	U	UU	94	19b. TELEPHONE NUMBER (Include area code) (937) 255-3636 x4319 john.dickens@afit.edu	